CS 240H NOTES: FUNCTIONAL SYSTEMS IN HASKELL

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1. Basics: 4/1/14

This course is taught by David Mazières and Bryan O'Sullivan, who together have done a lot of systems programming and research and Haskell. Meanwhile, the CA, David Terei, is a member of the Haskell language standards committee...

The goal of this class is to learn how to use Haskell to program systems with reduced upfront cost. Haskell is typically taught in the context of programming language research, but this course will adopt a systems perspective. It's a surprisingly flexible and effective language, and since it was created by and for programming language resources, there are lots of interesting things to do, and it's extremely flexible (if you want to try something new, even if it's syntactical, this is as easy as using a library, unlike most programming languages).

The first week of this class will cover the basics of Haskell, though having some prior experience or a supplement (e.g. *Real World Haskell* or *Learn You a Haskell*) is helpful. After the basics, we will cover more advanced techniques. The class grade will be based on attendance and participation, with scribing one of the lectures, and also three warm-up programming assignments and a large final project and presentation, in groups of one to three people.

Now, let's talk about Haskell.

In order to use Haskell, one will want to install the Haskell platform or `cabal`, along with the Haskell compiler, `ghc`. The simplest program is

```
main = putStrLn "Hello, world!"
```

Unsurprisingly, this is a "Hello, world!" program. One can compile it, e.g. `ghc -o hello hello.hs`, but also load it into an interpreter `ghci` (in this regard, Haskell is much like Lisp).

The first thing you've noticed is the equals sign, which makes a binding, e.g.

```
x = 2        -- Two hyphens introduce a comment.
y = 3        -- Comments go until the end of a line.
main = let z = x + y -- let introduces local bindings.
       in print z
```

This program will print 5.

Bound names can't start with uppercase letters, and are separated by semicolons, which are usually automatically inserted as above. Functions can even be bound, e.g.:

```
add x y = x + y   -- defines function add
five = add 2 3                -- invokes function add
```

This is a good way to define functions.

Haskell is a pure functional language. Thus, unlike variables in imperative languages, Haskell bindings are immutable: within a given scope, each symbol can be bound only once. In other words, the following is an error:

```
x = 5
x = 6 -- Error, cannot re-bind x
```

Bindings are thus order-independent.

Another interesting fact is that bindings are lazy: definitions of symbols are only evaluated when they're needed. For example:

```
safeDiv x y =
    let q = div x y      -- safe as q isn't evaluated if y == 0
    in if y == 0 then 0 else q
main = print (safeDiv 1 0) -- prints 0
```

Notice this is completely different from C-like languages!

Another interesting aspect of bindings, which goes hand-in-hand with order-independence, is that bindings are recursive, so each binding is in scope within its own definition.

```
x = 5                   -- not used in main!

main = let x = x + 1    -- introduces a new x, defined in terms of itself
       in print x       -- loops forever, or stack overflows
```

In C, this would print 6, but here, `x` refers to itself! The runtime sometimes is able to detect the loop, however.

This means that writing things in Haskell requires thinking differently! For example, here's a factorial program in C:

```
long factorial(int n) {
    long result = 1;
    while (n > 1)
        result *= n--;
    return result;
}
```

But in Haskell, one uses recursion.

```
factorial n = if n > 1 then n * factorial (n-1)
                       else 1
```

However, the C function requires constant space, but the Haskell version requires *n* stack frames! But Haskell supports optimized tail recursion; if a function ends with a call to itself (i.e. is tail-recursive), then it can be optimized into a loop. However, the definition provided above isn't tail-recursive.

Using an accumulator, the factorial function can be made tail-recursive.

```
factorial n = let loop acc n' = if n' > 1
                                then loop (acc * n') (n' - 1)
                                else acc
              in loop 1 n
```

This uses an *accumulator* to keep track of the partial result. It's a bit clunky, but can be tidied up with Haskell's incredible concision. For example, one can use guards to shorten function declarations, e.g.

```
factorial n = let loop acc n' | n' > 1 = loop (acc * n') (n' - 1)
                              | otherwise = acc
              in loop 1 n
```

The guards (pipe symbols) are evaluated from top to bottom; the first one that evaluates to `True` is followed. `otherwise` is defined to be `True`, but it makes the code easier to read. One might also introduce a `where` clause, which is like `let` but can support multiple guarded definitions, and is thus convenient for use around guards.

```
factorial n = loop 1 n
    where loop acc n' | n' > 1     = loop (acc * n') (n' - 1)
                      | otherwise = acc
```

You'll notice that there will be plenty of inner functions, and their arguments are related to that of the outer functions. But it's easy to confuse `n` and `n'`, so the following code compiles and throws a runtime error!

```
factorial n = loop 1 n
    where loop acc n' | n' > 1     = loop (acc * n) (n' - 1) -- bug, should be n'
                      | otherwise = acc
```

One way to work around that is to use a naming convention in which the outermost variable has the longer name; then, bugs like this are caught at compile time, due to scope.

Haskell is strongly typed, so we have tyles such as `Bool`, which is either `True` or `False`; `Char`, which is a Unicode code point; `Int`, a fixed-size integer; `Integer`, an arbitrary-sized integer; `Double`, which is like a `double` in C; and also functions. A function from type `a` to tybe `b` is denoted `a -> b`. We also have tuples: `(a1, a2, a3)`, including the unit `()` (a zero tuple, kind of like `void` of C).

It's good practice to write the function's type on top of a function, e.g.

```
add :: Integer -> (Integer -> Integer)
add arg1 arg2 = arg1 + arg2
```

Well, here's something interesting. The arrow associates to the right, so these parentheses aren't strictly necessary, but they make an important point: all functions accept only one argument, so the above function takes an integer and returns a function! For example, `add 2 3` is parsed as `(add 2) 3`, and `add 2` is a function. Often, this behavior (called currying) is optimized out by the compiler, but can be useful. The compiler can infer types, and in the interpreter this can be queried by `:t`.

```
*Main> :t add
add :: Integer -> Integer -> Integer
```

The user can also define data types, using the `data` keyword.

```
data PointT = PointC Double Double deriving Show
```

This declares the type `PointT` with a constructor `PointC` containing two `Double`s. The phrase `deriving Show` means that it can be printed, which is useful in the interpreter. Types and constructors must start with capital names, but live in different namespaces, so they can be given the same name.

Types may have multiple constructors, and said constructors don't actually need arguments (which makes them look sort of like `enum`s in C).

```
data Point = Cartesian Double Double
           | Polar Double Double
             deriving Show

data Color = Red | Green | Blue | Violet deriving (Show, Eq, Enum)
```

Now, we can do things like `myPoint = Cartesian 1.0 1.0` and so on.

One extracts this data using `case` statements and guards, as in the following example:

```
getX, getMaxCoord :: Point -> Double
getX point = case point of
               Point x y -> x        -- if only the Point x y constructor is around
getMaxCoord (Point x y) | x > y      = x
                        | otherwise = y

isRed :: Color -> Bool
isRed Red = True          -- Only matches constructor Red
isRed c   = False         -- Lower-case c just a variable
```

The latter notion is called pattern matching, which detects which constructor was used to create the object. For another example, consider the following:

```
whatKind :: Point -> String -- Cartesian or polar constructor as above
whatKind (Cartesian _ _) = "Cartesian"
whatKind (Polar _ _)     = "Polar"
```

This underscore indicates that the value is unused, or something we don't care about. The compiler can actually infer and optimize based on that. It's bound, but never used, which is quite helpful, especially given that the compiler warns about unused variables.

Exercise 1.1. Given the following types for a rock-paper-scissors game:

```
data Move = Rock | Paper | Scissors
     deriving (Eq, Read, Show, Enum, Bounded)

data Outcome = Lose | Tie | Win deriving (Show, Eq, Ord)
```

Define a function `outcome :: Move -> Move -> Outcome`. The first move should be your own, the second your opponent's, and then the function should indicate whether one won, lost, or tied.

Solution.

```
outcome :: Move -> Move -> Outcome
outcome Rock Scissors            = Win
outcome Paper Rock               = Win
outcome Scissors Paper           = Win
outcome us them | us == them     = Tie
                | otherwise      = Lose
```

There are plenty of other ways to do this.

Types, much like functions, can accept parameters, but type parameters start with lowercase letters. For example, within the standard Prelude:

```
data Maybe a = Just a
             | Nothing

data Either a b = Left a
                | Right b
```

`Maybe` is used to indicate the presence of an item, or some sort of error, and `Either` can provide more useful error information, etc. In this case, the convention is for `Right` to indicate the normal value, and `Left` some sort of sinister error. The interpreter can reason about these types, too:

```
Prelude> :t Just True
Just True :: Maybe Bool
Prelude> :t Left True
Left True :: Either Bool b
```

Often, one uses the underscore pattern matching mentioned above with these parameterized types to pass exceptions along. For example,

```
addMaybes mx my | Just x <- mx, Just y <- my = Just (x + y)
addMaybes _ _                                = Nothing
```

Equivalently (and more simply),

```
addMaybes (Just x) (Just y) = Just (x + y)
addMaybes _ _               = Nothing
```

Lists. Now, we have enough information to define lists, somewhat like the following.

```
data List a = Cons a (List a) | Nil

oneTwoThree = (Cons 1 (Cons 2 (Cons 3 Nil))) :: List Integer
```

But since lists are so common, there are some shortcuts: instead of `List Integer`, one writes `[Integer]`, and the `Cons` function is written `:`, and is infix. The empty list is called `[]`, so instead we could have written `oneTwoThree = 1:2:3:[]`. Alternatively, there is nicer syntax:

```
oneTwoThree' = [1, 2, 3]  -- comma-separated elements within brackets
oneTwoThree'' = [1..3]    -- define list by a range
```

Strings are just lists of characters.

Here are some useful list functions from the Prelude:

```
head :: [a] -> a -- first element of a list
head (x:_) = x
head []    = error "head: empty list"

tail :: [a] -> [a]             -- all but the first element
tail (_:xs) = xs
tail []     = error "tail: empty list"

a ++ b :: [a] -> [a] -> [a]  -- infix operator to concatenate lists
[] ++ ys     = ys
(x:xs) ++ ys = x : xs ++ ys

length :: [a] -> Int         -- This code is from language specification.
length []    =  0            -- GHC implements differently, because it's not tail-recursive.
length (_:l) =  1 + length l

filter :: (a -> Bool) -> [a] -> [a] -- returns a subset of a list matching a predicate.
filter pred [] = []
filter pred (x:xs)
  | pred x     = x : filter pred xs
  | otherwise  = filter pred xs
```

Note the function `error :: String -> a`, which reports assertion failures. `filter` is a higher-order function, i.e. one of its arguments is also a function. For example, one might define a function `isOdd :: Integer -> Bool` and then filter a list of `Integer`s as `filter isOdd listName`.

In addition to `deriving Show`, one has `deriving Read`, allowing one to parse a value from a string at runtime. But parsing is tricky: there could be multiple possible values, or ambiguity. For example, suppose we have the following declaration:

```
data Point = Point Double Double deriving (Show, Read)
```

Then, the following would happen in the interpreter.

```
*Main> reads "invalid Point 1 2" :: [(Point, String)]
[]
*Main> reads "Point 1 2" :: [(Point, String)]
[(Point 1.0 2.0,"")]
*Main> reads "Point 1 2 and some extra stuff" :: [(Point, String)]
[(Point 1.0 2.0," and some extra stuff")]
*Main> reads "(Point 1 2)" :: [(Point, String)] -- note parens OK
[(Point 1.0 2.0,"")]
```

Notice that `reads` returns a list of possibilities, along with the rest of the string. This is asymmetrical from `show`.

This isn't a language property, but the best way to search for functions (and their source code!) is Hoogle, at `http://www.haskell.org/hoogle/`. This is a good way to look up functions, their type signatures, and so on. Looking at the source is a great way to learn the good ways to do things in Haskell; in particular, notice just how short the functions are. Haskell has a steep learning curve, but it's pretty easy to understand what code is doing.

For another example of functional thinking, here's a function to count the number of lowercase letters in a string.

```
import Data.Char    -- brings function isLower into scope

countLowerCase :: String -> Int -- String is just [Char]
countLowerCase str = length (filter isLower str)
```

This looks absurd in C, but since Haskell is lazily evaluated, it doesn't actually copy the string; in some sense, values and function pointers are the same under lazy evaulation. But, of course, this can be written more concisely:

```
countLowerCase :: String -> Int
countLowerCase = length . filter isLower
```

Here, `f . g` means $f \circ g$ mathematically: this is function composition: `(f . g) x = f (g x)`. But now, the argument isn't necessary. This can be used like a concise, right-to-left analogue to Unix pipelines. This is known as point-free programming.

Conversely, if one wants the arguments but not the function, you can just use lambda expressions. The notion is `\`*variables* `->` *body*. For example:

```
countLowercaseAndDigits :: String -> Int
countLowercaseAndDigits =
    length . filter (\c -> isLower c || isDigit c)
```

This is useful for small functions that don't need to be used in more than one place.

Another neat syntactic trick is that any function can be made prefix or infix. For functions that start with a letter, underscore, digit, or apostrophe, prefix is the default, but they can be made infix with backticks, e.g. `1 ‘add‘ 2`. For anything else, infix is default, adding parentheses makes them prefix: `(+) 1 2` and so on. Infix functions can also be partially applied:

```
stripPunctuation :: String -> String
stripPunctuation = filter (‘notElem‘ "!#$%&*+./<=>?@\\^|-~:")
-- Note above string the SECOND argument to notElem ^
```

2. Basics 2: 4/3/14

Fixity. Most operators are just library functions in Haskell; only a very few are reserved by the language syntax (specifically, `..`, `:`, `::`, +, \, |, `<-`, `->`, `@`. `~`, `=>`, and `--`). So there's nothing to stop someone from defining their own operators. One can specify operators' associativity and "fixity" with commands such as `infixl`, `infix`, `infixr`, and so on, which determine the associativity (and precedence is given by a number).

Here are some `infixr 0` operators.

-
  ```
  ($) :: (a -> b) -> a -> b
  f $ x = f x
  ```

  This is just function application with the lowest precedence, so it's useful for things like

  ```
  putStrLn $ "the value of " ++ key ++ " is " ++ show value
  ```

- `seq :: a -> b -> b` returns the second argument, but forces the first to evaluate, which actually has to be built into the compiler.
- `$!` combines `$` and `seq`. This is useful: in the recursive factorial programs implemented last lecture, the accumulator could contain $O(n)$ thunks, thanks to lazy evaluation. Using the above can help with that:

  ```
  factorial n0 = loop 1 n0
      where loop acc n | n > 1     = (loop $! acc * n) (n - 1)
                       | otherwise = acc

  factorial n0 = loop 1 n0
      where loop acc n | n > 1     = acc ‘seq‘ loop (acc * n) (n - 1)
                       | otherwise = acc
  ```

Cabal and Hackage. Hackage is a large collection of Haskell packages, which will probably be useful for the project later in this course. Cabal is a tool for browsing Hackage and installing packges; run `cabal update` to create a file `$HOME/.cabal`, and within the config file, we're recommended to set `documentation: True` and `library-profiling: True`.

Modules and importing files. Haskell groups top-level bindings into modules. The default module name is `Main`, which contains the `main` function where programs start. All other modules M must reside in the file M`.hs`. At the top of a source file for module `ModuleName`, one can write `module ModuleName where` or `module ModuleName (...) where`, where the list of exported symbols is in the parentheses. Then, one can `import ModuleName` to access its functions, or use `qualified` or `hiding` to export only some symbols (or suppress some symbols) to prevent namespace conflicts.

With this, here's a complete program:

```
module Main where
import System.IO

greet h = do
  hPutStrLn h "What is your name?"
  name <- hGetLine h
  hPutStrLn h $ "Hi, " ++ name

withTty = withFile "/dev/tty" ReadWriteMode
```

```haskell
main = withTty greet
```

Notice that the do notation is necessary because pure functions can't print or read text from a terminal... but real programs find that somewhat useful. Then, this do block allows one to sequence IO actions, such as

- `pattern <- action` binds `pattern` (a variable or constructor pattern) to the result of *executing* `action`.
- `let pattern = value` (no `in` necessary) binds `pattern` to `value`, which should be a pure value.
- Just calling an action executes it, and discards the result (or returns it, at the end of a block).

GHCI input is like a do block, in that one can use the above syntax.

Note that `do`, `let`, and `case` don't parse after a prefix function unless one uses parentheses, e.g. `func (do...)`. Thus, it's convenient to use `func $ do` instead, to keep track of fewer parentheses.

What's the type of an IO action?

```haskell
main :: IO ()
greet :: Handle -> IO ()
hPutStrLn :: Handle -> String -> IO ()
hGetLine :: Handle -> IO String
```

`IO` is a parameterizeed type; `IO a` indicates an I/O action that produces a type `a` if executed. Unlike `Maybe`, we don't actually see the constructor, and it's just a little bit magical.

It seems reasonable in some languages to write something like `main = hPutStrLn stdout(hGetLine stdin)`, because `hPutStrLn` expects a type `String`, but gets type `IO String`. So how do we work around that? We can't use `case`, because there's no visible constructor.

Well, there's another way to look at `IO`. `hGetLine` and `hPutStrLn` return actions that can change the world. In some sense, the world is passed along as an argument, and the result is a modified world, `world'`! Then, the do block builds a compound action from these other actions; when executed, it applies `IO a` actions to the world, and then extracts values of type `a`. In some sense, the whole program is like this, for the `main` function.

Short note on compiling: using `ghc`, one can create an executable like in C. But GHCI can read object code, so one can type `ghci ./greet.hs`, and it reads the object file. But then, it doesn't have access to the internal symbols and functions, so the command prompt lacks an asterisk; use an asterisk in the `:load *filename` command to override this.

Now, what if we want I/O actions to return things? Every line in a do block must have type `IO a`, so we need a trivial `IO` action. This is the `return :: a -> IO a` function, which is badly named, because it's a function, not a control-flow statement. It doesn't terminate a do block, even though it is often used to return values from do blocks.

```haskell
greet :: Handle -> IO String
greet h = do
  hPutStrLn h "What is your name?"
  name <- hGetLine h
  hPutStrLn h $ "Hi, " ++ name
  return name
```

There's also point-free I/O composition, using `>>=` (pronounced "bind") rather than `.`. This composes right-to-left, and can be used to get rid of `name` in the above code:

```haskell
greet h = do
  hPutStrLn h "What is your name?"
  hGetLine h >>= hPutStrLn h . ("Hi, " ++)
```

Interestingly, do is just syntactic sugar for the bind operator; the above is processed as

```haskell
-- Desugared version of original greet:
greet h = hPutStrLn h "What is your name?" >>= \_ ->
          hGetLine h >>= \name ->
          hPutStrLn h ("Hi, " ++ name)
```

The value is thrown away if it's not used for anything, which is what the underscore means.

Here's another example, which obtains a `MOve` type for playing rock, paper, scissors as in last lecture:

```haskell
getMove :: Handle -> IO Move
getMove h = do
  hPutStrLn h $ "Please enter one of " ++ show ([minBound..] :: [Move])
  move <- hGetLine h
  case parseMove input of Just move -> return move
                          Nothing   -> getMove h
```

Here are some more polymorphic functions from the Prelude:

```haskell
id :: a -> a
id x = x

const :: a -> b -> a -- ignores second argument
const a _ = a

fst :: (a, b) -> a -- first thing in a 2-tuple
fst (a, _) = a

snd :: (a, b) -> b -- second thing in a 2-tuple
snd (_, b) = b
```

There's a function `print a = putStrLn (show a)`, but we don't know how to express its type right now.

There are two kinds of polymorphism: the first, *parametric polymorphism*, does the same thing for all types, e.g. `id`. These work for every possible type. But there's also *ad hoc polymorphism*, which does different things to different types. For example, `1 + 1` and `1.0 + 1.0` compute different things. `show` is another example of an ad hoc polymorphic function. These ad hoc polymorphic functions are called methods, and declared within classes.

```haskell
class MyShow a where
    myShow :: a -> String
```

Then, for each type for which this is defined, one provides an instance declaration:

```haskell
data Point = Point Double Double
instance MyShow Point where
    myShow (Point x y) = "(" ++ show x ++ ", " ++ show y ++ ")"
```

All right, what's the type of `myShow`?

```haskell
myPrint x = putStrLn $ myShow x

*Main> :t myPrint
myPrint :: MyShow a => a -> IO ()
```

This is what is known as a context. This seems a bit laborious, and there's no way to write `deriving myShow` as with the standard typeclasses.

The syntax given above can be used for functions; and if there are multiple such restrictions, use parentheses:

```haskell
myPrint :: MyShow a => a -> IO ()

sortAndShow :: (Ord a, MyShow a) => [a] -> String

-- In standard library
-- Determines whether a given element is in the given list, so it needs to know
-- when two objects are equal.
elem :: (Eq a) => a -> [a] -> Bool
elem _ []     = False
elem x (y:ys) = x==y || elem x ys

add :: (Num a) => a -> a -> a
add arg1 arg2 = arg1 + arg2
```

The context is in some sense hiding some implicit dictionary arguments, of how exactly to call the functions.

The Dreaded Monomorphism Restriction (DMR). Suppose `superExpensive :: Num a => Int -> a` is some expensive function whose result we want to cache. Then, we might call `cachedResult = superExpensive 5`, which will be a thunk that is executed once, and then done. Then, `cachedResult` has type `Integer`, so it's a good thing that `cachedResult` doesn't have type `Num a => a`; were this the case, it would require the context to be provided each time, and thus recompute everything. Note that the type of `0` is `Num a => a`, because it can be any numeric type, so this is a good thing to know.

In this case, the compiler can't always infer everything:if something looks like a function, a statement will infer ad hoc and parametric types, but if it looks like anything else, there will only be parametric inference unless it's explicitly declared. To look like a function, something should bind to a single symbol rather than a patter (e.g. `f`, not `(Just x)`). Moreover, it should have an explicit argument, i.e. `f x = ....` Types are first inferred from use elsewhere (such as type signatures), then some educated guessing. But if that doesn't work, compilation may fail.

In practice, this boils down to the following:

```
-- Compiler infers: show1 :: (Show x) => x -> String
show1 x = show x

show2 = show         -- fails
show3 = \x -> show x -- fails
```

But all of these will work if you declare explicit type signatures for these functions! There's a moral here.

Notice that this turns a runtime error (which would be really slow for the caching example) into a compiler error.

Superclasses and Contexts. One class can require classes to be members of another. For example, Ord instances don't make sense without an Eq instance, so Ord declares Eq as a superclass, using a context.

```
class Eq a => Ord a where
    (<), (>=), (>), (<=) :: a -> a -> Bool
    a <= b = a == b || a < b -- default methods can use superclasses
    -- and so on
```

One might also want instances to have contexts:

```
instance (MyShow a) => MyShow [a] where
    myShow [] = "[]"
    myShow (x:xs) = myShow x ++ ":" ++ myShow xs
```

There are also classes of parameterized types. For example, Functor is a class of parameterized types on which you can map functions (e.g. lists, where the function is mapped onto every element; Maybe, where it's mapped onto the Just). Here's the declaration:

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

instance Functor Maybe where
    fmap _ Nothing  = Nothing
    fmap f (Just a) = Just (f a)

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

instance Functor [] where
    fmap = map

nstance Functor IO where
    fmap f io = io >>= return . f
    -- equivalent to:  do val <- io; return (f val)
```

Now, one can use fmap in any of these contexts, e.g.

```
greet h = do
  hPutStrLn h "What is your name?"
  fmap ("Hi, " ++) (hGetLine h) >>= hPutStrLn h
```

So what happens if one tries to make Int into a functor? Then, fmap :: (a -> b) -> Int a -> Int b, which produces a compilation error: Int isn't a parameterized type. Thus, we can classify types into those that require zero parameters (e.g. Int, Double, ()), those that require one parameter (Maybe, IO, []), those that require two constructors (Either, (,)), and so on. Parameterized types (i.e. at least one parameter) are called type constructors.

One can reason about these with some new notation. * is a kind of type constructor with no parameters. * -> * is the kind of type with one parameter, and * -> * -> * is a type constructor with two arguments of kind *. Thus, Functor must accept kind * -> *.

Monads. The moment you've all been waiting for... the entire first two lectures have been working towards this point.

return and >>= are actually methods of a class called Monad.

```
class Monad m where
    (>>=) :: m a -> (a -> m b) -> m b
    return :: a -> m a
    fail :: String -> m a   -- called when pattern binding fails
    fail s = error s        -- default is to throw exception

    (>>) :: m a -> m b -> m b
    m >> k = m >>= \_ -> k
```

This has pretty far-reaching consquences; for example, one could use do blocks for non-I/O purposes, and a lot of library code works with the general Monad class, rather than just I/O.

Well, why would you want to do that? It turns out monads appear in a bunch of places. For example, Maybe is a monad:

```
instance  Monad Maybe  where
    (Just x) >>= k = k x
    Nothing >>= _  = Nothing
    return = Just
    fail _ = Nothing
```

This is pretty useful, because multiple Maybe statements can be combined with do notation, as in the following example, where one processes a form.

```
extractA :: String -> Maybe Int
extractB :: String -> Maybe String
-- ...
parseForm :: String -> Maybe Form
parseForm raw = do
    a <- extractA raw
    b <- extractB raw
--  ...
    return (Form a b ...)
```

This is a good way to do exception handling! Moreover, because Haskell is lazy, expensive computations after an error will be skipped: computation stops at the first Nothing.

Another example of monads in the real world is a security library which implemented a restricted I/O monad. Then, the entire standard library works well with this.

Algebraic Data Types. Some data types have a lot of fields:

```
-- Argument to createProcess function
data CreateProcess = CreateProcess CmdSpec (Maybe FilePath)
    (Maybe [(String,String)]) StdStream StdStream StdStream Bool
```

This is pretty tangled; instead, one can use an algebraic data type, that allows one to label fields, akin to a struct in C.

```
data CreateProcess = CreateProcess {
  cmdspec   :: CmdSpec,
  cwd       :: Maybe FilePath,
  env       :: Maybe [(String,String)],
  std_in    :: StdStream,
  std_out   :: StdStream,
  std_err   :: StdStream,
  close_fds :: Bool
}
```

3. Testing and Quickcheck: 4/8/14

Today's lecture is by Bryan O'Sullivan, who has been involved in Haskell for twenty years, and has written one of the major standard references, *Real World Haskell*.

There are several "states of the art" for testing software:

- An Excel spreadsheet full of different tests to be done by hand. Really.
- Unit testing, where

  ```
  public class TestAdder {
      public void testSum() {
          Adder adder = new AdderImpl();
          assert(adder.add(2, 2) == 4)
          assert(adder.add(5, 6) == 11)
          // and so on
      }
  }
  ```

- Integration testing checks that various components of a program work together.

- Fuzz testing feeds random input to a program. This might have been used to discover the recent major security bug in OpenSSL.

Unit tests are only useful up to a point: people get bored quickly, and also tend to miss important corner cases. That's why people often turn to computers, which are more patient than people. For example, UTF-16 is the ugly cousin of UTF-8, locked up in a castle such that nobody has to think about it. It's a variable-length encoding and relatively obscure, so there have been several security exploits based on incorrect assumptions people make about it. Basically, it's real-world, obscure, yet important, so good unit testing is particularly crucial.

In Haskell, `Char` represents a Unicode point, so `encodeChar` should have type `Char -> [Word16]` (after importing `Data.Char`) (or `Char -> Either (Word16, (Word16, Word16))`, if you want to be fancier). Then, we can build up some unit tests.

```
import Data.Char (ord) -- it's good practice to explicitly specify what you import
import Data.Bits ((.&.), shiftR) -- low-level bit-hacking functions

ord :: Char -> Int

fromIntegral :: (Integral a, Num b) => a -> b

encodeChar :: Char -> [Word16]
ehcodeChar x
    | w < 0x10000 = [fromIntegral w]
    | otherwise   = [fromIntegral a, fromIntegral b]
        where w = ord x
        -- low-level bit operations go here
```

Now, we can do unit testing with `Test.HUnit`. How do you pronounce `HUnit`? Bryan O'Sullivan doesn't know. This is basically a port of `JUnit`, the granddaddy of all automatic unit testing frameworks.

Here's an example of a bad test.

```
import Test.HUnit

badTest = do
    assertEqual "sestertius encode as one code unit"
      -- above the critical value of 0x10000
      1 (length (encodeChar '\x10198'))
```

This, of course, fails if you run it, as it should; this symbol has two words.

But now we can parameterize and generalize the test:

```
testOne char = do
    assertEqual "ASCII values have one code point"
      1 (length (encodeChar char))

goodTest = do mapM_ ['\x0'..'\x7f']
```

But explicitly parameterizing these takes a while, and is somewhat inefficient. Thus, `Test.QuickCheck` exists. The idea is that, especially for combinatorial things for which it would be very hard and time-consuming to explicitly test everything, it can automate randomized testing. For most types, QuickCheck starts with small test cases (which is nice, so that bugs found are more likely to be minimal), and then builds up to bigger ones. But only 100 tests isn't really enough to find a character in the 2-word range, so QuickCheck isn't telling the whole story yet.

QuickCheck generates random values using a typeclass called `Arbitrary`. This is a multipurpose abstraction useful in many ways in Haskell.

```
-- Generator type
data Gen a

-- Used to generate values, abstracted away from where we can see ot
class Arbitrary a where
    arbitrary :: Gen a

-- Generate a random value within a range
-- Random is a typeclass, which means it's meaningful to choose a random value.
choose :: Random a => (a, a) -> Gen a
-- For example, choosing a random Bool
instance Arbitrary Bool where
    arbitrary = choose (False, True)
instance Arbitrary Char {- all of the chars go here... -}
```

Now, we can denote a class Testable if propositions about it can be tested:

```
-- Protection for a Gen
data Property = MkProperty (Gen a)

-- The set of types that can be tested
class Testable prop

instance Testable Bool -- the body code isn’t interesting magical. What is:
instance (Arbitrary a, Show a, Testable prop) => Testable (a -> prop)
```

In other words, any function that can accept an Arbitrary function and return a proposition is really testable! Thus, something is testable if it's a terminal return type (a Bool) or something that returns a Testable. Thus, we can create functions of arbitrarily many arguments Testable. This is pretty deep magic.

Now, we can say more about our testing code:

```
prop_encodeOne :: Char -> Bool
prop_encodeOne c = length (encodeChar c) == 1
```

Now we can just call quickCheck prop_encodeOne, which runs 100 (or more or less, if you specify) random tests. There's also verboseCheck, which provides more information about the passed tests.

The test is broken, even if one increases the number of tests. Let's look at the source.

```
module Test.QuickCheck.Arbitrary where

instance Arbitrary Char where
    arbitrary = chr ‘fmap‘ oneof (choose (0,127), choose (0,255))
```

Well, it's no longer 1985, so we want to have more diverse Chars around. We want a type that is almost exactly like Char, except with a different Arbitrary instance. This is what the newtype keyword does.

```
newtype BigChar = Big Char -- constructor
                deriving (Eq, Show) -- so we reuse these existing instances
```

Now, we want to write a new Arbitrary instance which chooses values between 0 and 0x10ffff. So we want to use choose, which means making BigChar an instance of Random:

```
import Control.Arrow (first) -- a function that maps a function to the first element of a tuple
import System.Random

instance Random BigChar where
    random = first Big ‘fmap‘ random
    -- and so on. A little bit of yak shaving, so to speak. Somewhat boilerplate
```

But there's a GHC language extension that works around this! GHC usually only can derive standard typeclasses from newtype, but this allows it to infer things about non-standard typeclasses. It almost always works.

```
{-# LANGUAGE GeneralizedNewtypeDeriving #-}
newtype BigChar = Big Char deriving (Eq, Show, Random) -- just works. Splendid!
```

Now we can write more comprehensive tests:

```
instance Arbitrary BigChar where
    arbitrary = chose (Big ’0’, Big ’\x10FFFF’)

prop_encodeOne3 (Big c) = length (encodeChar c) == 1
```

Now, this fails almost instantly, and tells us what counterexample it failed on.

This changes the unit test policy of hand-coding variations on a theme to the QuickCheck way of expecting a property to universally hold true and randomly checking inputs. This is almost entirely focused on random values, but there are other libraries (e.g. SmallCheck) that can be used to find bugs that appear with extremely low probability.

One problem is that random values tend to be large; are there smaller inputs that could cause the bug to happen again? This makes the bug easier to understand; finding the smallest input is known as shrinking.

Writing a function called shrink takes an Arbitrary value and generates a list of smaller Arbitrary values. For example:

```haskell
{-# LANGUAGE GeneralizedNewtypeDeriving #-}

import System.Random
import Test.QuickCheck
import Data.Char

newtype BigChar = Big Char
                deriving (Eq, Show, Random)

instance Arbitrary BigChar where
    arbitrary        = choose (Big '0', Big '\x10FFFF')
    shrink (Big c)   = map Big (shrinkChar c)

shrinkChar c = map chr $ shrink $ ord c
```

Now that this setup all exists, we can look at ways of choosing test values. One could generate them directly:

```haskell
prop_encodeOne2 = do
    c <- choose ('\0', '\xFFFF')
    retrn  length (encodeChar c) == 1
```

Second, one could generate any values and filter those that don't make sense (e.g. using `suchThat`). This ends up being similar, but more verbose. However, it's generally more efficient to just generate the values one needs, and do no filtering.

Exercise 3.1. Write and test a `decodeUtf16 :: [Word16] -> [Char]` function.

At this point, we've seen the `Functor` class, with `fmap` used to lift a pure function into a functor. In general, the idea of "lifting" is to take a concept and transform it to work in a different, more general, setting. For instance, one can lift with monads:

```haskell
liftM :: (Monad M) -> (a -> b) -> m a -> m b
liftM f action = do
    b <- action
    return (f b)
```

This `liftM` is a cousin of `fmap`: they do very similar things. Basically, `liftM` executes some action, and applies `f` to it, and `fmap` does something that is effectively the same. Notice their type signatures:

```haskell
fmap  :: (Functor f) => (a -> b) -> f a -> f b
liftM :: (Monad m)   => (a -> b) -> m a -> m b
```

It turns out that lifting pure functions into monads is extremely common, so `Control.Monad` provides lots of combinator functions `liftM2` to `liftM5` which lift functions of 2 through 5 arguments. This allows us to tighten `Arbitrary` instances from

```haskell
data Point a = Point a a -- as in last weeks' lectures

instance (Arbitrary a) => Arbitrary (Point a) where
    arbitrary = do
        x <- arbitrary
        y <- arbitrary
        return (Point x y)
```

to

```haskell
import Control.Monad (liftM2)
instance (Arbitrary A) => Arbitrary (Point a) where
    arbitrary = liftM2 Point arbitrary arbitrary
```

It just works.

QuickCheck also allows one to shrink tuples, using a predefined function that allows one to shrink pairs of data points. More interestingly, one could generate arbitrary recursive data structures:

```haskell
data Tree a = Node (Tree a) (Tree a)
            | leaf a
              deriving (show)

instance (Arbitrary a) => Arbitrary (Tree a) where
    arbitrary = choose (liftM Leaf arbitrary, liftM2 Node arbitrary arbitraray)
```

There are analogues of this in plenty of other languages, but many of them have jankier type inference, making it sometimes less effective. For the rest of this class, provide QuickCheck tests along with the rest of a submitted project.

4. Exception Handling and Concurrency: 4/10/14

In Haskell, concurrency and exceptions are related, because of Haskell's concept of asynchronous exceptions. These are a lot prettier than the corresponding concepts in, say, C++.

We have so far seen a few functions that return any type, e.g. `undefined :: a` (used to build code up and test individual functions, suppressing type errors from other code) and `error :: String -> a`. These are language-level constructions; to use exceptions directly, call `import Control.Exception`. (In older versions of ghc, one need to hide an earlier `catch` function, so `import Prelude hiding (catch)`; this is probably not necessary anymore).

Thus, we hae an `Eception` typeclass, and the following functions:

```
class (Typeable e, Show e) => Exception e where ...
throw :: Exception e => e -> a
throwIO :: Exception e => e -> IO a
catch   :: Exception e => IO a -> (e -> IO a) -> IO a
```

The `Typeable` typeclass requires the `DerivingDataTypable` language extension, as in the following code; this will be discussed more in depth in a future lecture. The following code creates an error catching function, which invokes a handler when an error is received by `catch`.

```
{-# LANGUAGE DeriveDataTypeable #-}

import Prelude hiding (catch) -- if necessary, but still good practice.
import Control.Exception
import Data.Typeable

data MyError = MyError String deriving (Show, Typeable)
instance Exception MyError

catcher :: IO a -> IO (Maybe a)
catcher action = fmap Just action ‘catch‘ handler
    where handler (MyError msg) = do putStrLn msg; return Nothing
```

Note that the type of `handler` can't be inferred, so it will be necessary to create a constructor or use a type signature. The constructor pattern `e@(SomeException _)` matches all exceptions, rather than just `MyError`.

The typeclass `Exception` has two methods, `toException :: e -> SomeException` and `fromException :: SomeException ->` (which determines whether it's the correct exception we are looking for).

Haskell's pure functionality makes this more interesting: exceptions can be thrown in pure code, but must be caught within `IO`. This is because the world state may change in exception handling, and also because there's ambiguity in the order of evaluation, e.g. in `(error "one") + (error "two")`. Nondeterminism is allowed, but within the `IO` monad. Then, `throw` produces a thunk that throws an exception, but is lazily evaluated; `throwIO` is strict, so in the following code, only the first exception is reached.

```
do x <- throwIO (MyError "one")   -- this exception thrown
   y <- throwIO (MyError "two")   -- this code not reached
   return (x + y)
```

In general, `throwIO` is better, but there are some exceptions,[1] the pure `throw` is useful for unimplemented code and error creation, e.g. how `undefined` is defined in the Prelude.

Sometimes this interacts weirdly with laziness.

```
pureCatcher :: a -> IO (Maybe a)
pureCatcher a = (a ‘seq‘ return (Just a))
                ‘catch‘ \(SomeException _) -> return Nothing

pureCatcher $ 1 + 1
Just 2
*Main> pureCatcher $ 1 ‘div‘ 0
Nothing
*Main> pureCatcher (undefined :: String)
Nothing
*Main> pureCatcher (undefined:undefined :: String)
Just "*** Exception: Prelude.undefined
```

[1] No pun intended.

This is because evaluating a constructor of a list doesn't evaluate the head or tail, so seq(undefined:undefined) () just returns () again, since it just evaluates the constructor. To force evaluation of every element when constructing, use deepseq in the library of the same name (for many common data types), or match on the constructor ([] or (x:xs)) to actually look at everything.

```
seqList :: [a] -> b -> b
seqList [] b     = b
seqList (a:as) b = seq a $ seqList as b
```

Some more useful functions: try returns Right a if it works normally, and Left e if an exception occurred. finally and onException run clean-up actions within IO; finally in all cases, and onException only when there's an exception.

```
try :: Exception e => IO a -> IO (Either e a)
finally :: IO a -> IO b -> IO a      -- cleanup always
onException :: IO a -> IO b -> IO a  -- after exception
-- In both cases, result b of cleanup action is discarded.
```

Though these are all nice, language-level exceptions are cumbersome outside of the IO monad; in other monads, it might be better to use the fail method that is part of the Monad typeclass. For example, in Maybe, fail _ = Nothing, while in other monads, this might thrown an exception.

Threads. Haskell's threads are lightweight and user-level, and actually are more useful than threads in other languages! They live in Control.Concurrent. A new thread is created with forkIO :: IO () -> IO Threadid, which creates a new thread and returns its ID. Here are some other useful functions:

```
throwTo :: Exception e => ThreadId -> e -> IO ()
killThread :: ThreadId -> IO ()   -- = flip throwTo ThreadKilled
threadDelay :: Int -> IO ()       -- sleeps for # of  s e c
myThreadId :: IO ThreadId
```

As an example of some code, here's a timeout function, which evaluates an action or aborts after a certain number of microseconds. There's a builtin in the library System.Timeout.

```
data TimedOut = TimedOut UTCTime deriving (Eq, Show, Typeable)
instance Exception TimedOut

timeout :: Int -> IO a -> IO (Maybe a)
timeout usec action = do
  -- Create unique exception val (for nested timeouts)
  -- the unique value is just the current time
  expired <- fmap TimedOut getCurrentTime

  ptid <- myThreadId
  -- Idea: child thread tracks the time, and kills the thread
  -- if time runs out.
  let child = do threadDelay usec
                 throwTo ptid expired
      parent = do ctid <- forkIO child
                  result <- action
                  killThread ctid
                  return $ Just result
  -- uses catchJust in case the parent has to deal with other exceptions
  catchJust (\e -> if e == expired then Just e else Nothing)
            parent
            (\_ -> return Nothing)
```

An MVar is a mutable variable that is either full or empty (something in it, or not), and allows threads to communicate via shared variables.

```
newEmptyMVar :: IO (MVar a)  -- create empty MVar
newMVar :: a -> IO (MVar a)  -- create full MVar given val

-- These block a thread until the MVar becomes available.
takeMVar :: MVar a -> IO a
putMVar :: MVar a -> a -> IO ()

-- non-blocking versions
tryTakeMVar :: MVar a -> IO (Maybe a) -- Nothing if empty
```

```
tryPutMVar :: MVar a -> a -> IO Bool   -- False if full
```

If an MVar is empty, putMVar fills it with a value, and if it's full, takeMVar empties it. If several try to access these, they're blocked to accessing them one at a time. These are akin to channels in Go, and may be less intuitive than mutexes and condition variables, but are a lot less error-prone.

In use, here's a benchmarking program.

```
import Control.Concurrent
import Control.Exception
import Control.Monad

pingpong :: Bool -> Int -> IO ()
pingpong v n = do
  mvc <- newEmptyMVar    -- MVar read by child
  mvp <- newEmptyMVar    -- MVar read by parent
  let parent n | n > 0 = do when v $ putStr $ " " ++ show n
                            putMVar mvc n
                            takeMVar mvp >>= parent
               | otherwise = return ()
      child = do n <- takeMVar mvc
                 putMVar mvp (n - 1)
                 child
  tid <- forkIO child
  -- no matter what happens, clean up the child thread
  parent n `finally` killThread tid
  when v $ putStrLn ""

-- *Main> pingpong True 10
--  10 9 8 7 6 5 4 3 2 1
```

A library called criterion for Haskell, written by Bryan O'Sullivan, is a great way to do benchmarking; it's a really good library. It's used as follows:

```
import Criterion.Main

...

main :: IO ()
main = defaultMain [
        bench "thread switch test" mybench
       ]
    where mybench = pingpong False 10000

-- -O for optimization
$ ghc -O pingpong.hs
[1 of 1] Compiling Main             ( pingpong.hs, pingpong.o )
Linking pingpong ...
$ ./pingpong
...
benchmarking thread switch test
mean: 3.774590 ms, lb 3.739223 ms, ub 3.808865 ms, ci 0.950
...
```

It turns out that there are two versions of the Haskell runtime: by calling ghc -threaded, one can take advantage of multiprocessing. Specifically, this allows one to create OS threads (as with pthreads). Then, the initial thread is an OS thread, and with forkOS, a new OS thread is created, akin to forkIO.

So you'd think adding -threaded makes things faster, but this means some threads are unbound, and therefore migrate between heavier-weight OS threads. The initial thread was bound, so this was basically a benchmark of Linux threads! Thus, if one can keep communicating threads in the same OS thread, context switches will be more like function calls. There's a library call runInUnboundThread for this, which is implemented somewhat like this:

```
wrap :: IO a -> IO a
wrap action = do
  mv <- newEmptyMVar
  -- Exception transferred to parent from child, by laziness
  _ <- forkIO $ (action >>= putMVar mv) `catch`
              \e@(SomeException _) -> putMVar mv (throw e)
  takeMVar mv
```

But bound threads are useful: if an unbound thread blocks, it could block the whole program, so it's nice to keep that within its own thread. This is also relevant to the Foreign Function Interface for Haskell calls into C code: with `-threaded`, safe C code calls are given their own OS thread. Similarly, there are C libraries where the code expects to be called from the same thread. Finally, one might want to run on a specific CPU (e.g. `forkOn`).

Another useful collection of functions allow one to modify an `MVar` without forgetting to release it:

```
modifyMVar :: MVar a -> (a -> IO (a, b)) -> IO b
modifyMVar_ :: MVar a -> (a -> IO a) -> IO ()
```

For example, to increment an `MVar Int`, one could write `modifyMVar x (\n -> return (n+1, n))`. The underscored version always returns unit; the other one returns the modified value.

Here's what an initial implementation might look like:

```
modifyMVar :: MVar a -> (a -> IO (a,b)) -> IO b
modifyMVar m action = do
  v0 <- takeMVar m
  (v, r) <- action v0 ‘onException‘ putMVar m v0
  putMVar m v
  return r
```

But what if another thread kills this thread using `killThread` in the middle? Then, the `MVar` is stuck. This is where we might want support for masking exceptions:

```
mask :: ((forall a. IO a -> IO a) -> IO b) -> IO b
```

(The `forall` comes from a language extension called `RankNTypes`, and can be ignored for now.) Then, `mask $ \f -> b` runs action `b` with asynchronous exceptions ignored, and the function `f` allows exceptions to be unmasked again. Exceptions are also unmasked while a thread sleeps (e.g. `takeMVar`).

Here's a masked version of the above code:

```
modifyMVar :: MVar a -> (a -> IO (a,b)) -> IO b
modifyMVar m action = mask $ \unmask -> do
  v0 <- takeMVar m -- automatically unmasked while waiting
  -- here, we do want to allow exceptions, but not before or after
  (v, r) <- unmask (action v0) ‘onException‘ putMVar m v0
  putMVar m v
  return r
```

The `wrap` function given above is also not good, and can be fixed as follows:

```
wrap :: IO a -> IO a          -- Fixed version of wrap
wrap action = do
  mv <- newEmptyMVar
  -- first we disable interrupts
  mask $ \unmask -> do
      -- but if we get an exception here, we stick it into the MVar
      tid <- forkIO $ (unmask action >>= putMVar mv) ‘catch‘
                      \e@(SomeException _) -> putMVar mv (throw e)
      -- here, takeMVar re-enables exceptions, and passes them off to the child thread
      -- eventually, takeMVar succeeds, and we return its value.
      let loop = takeMVar mv ‘catch‘ \e@(SomeException _) ->
                 throwTo tid e >> loop
      loop
```

`mask` is powerful but tricky, so let's introduce some higher-level constructs. `bracket` accepts an opening action, a cleanup action, and then a main action:

```
--          Init    Cleanup         Main
bracket :: IO a -> (a -> IO b) -> (a -> IO c) -> IO c

-- Thus, no matter what, we close the file.
bracket (openFile "/etc/mtab" ReadMode) -- first
        hClose                          -- last
        (\h -> hGetContents h >>= doit) -- main
```

Now, we can fix the `parent` function from the time-out example:

```
parent = bracket (forkIO child) killThread $
    \_ -> fmap Just action
```

MVars are fairly versatile: if you need or want a mutex, an MVar will do fine.

```
type Mutex = MVar ThreadId

mutex_create :: IO Mutex
mutex_create = newEmptyMVar

mutex_lock , mutex_unlock :: Mutex -> IO ()

mutex_lock mv = myThreadId >>= putMVar mv

mutex_unlock mv = do mytid <- myThreadId
                     lockTid <- tryTakeMVar mv
                     unless (lockTid == Just mytid) $
                         error "mutex_unlock"
```

As for condition variables, they tend not to work well with asynchronous exceptions, but one could make a condition variable an MVar which is a list of MVar units, each of which belongs to a thread that's waiting. Here's the full implementation:

```
data Cond = Cond (MVar [MVar ()])

cond_create :: IO Cond
cond_create = liftM Cond $ newMVar []
-- liftM is fmap for Monads (i.e., no required Functor instance):
-- liftM f m1 = do x <- m1; return (f m1)

cond_wait :: Mutex -> Cond -> IO ()
cond_wait m (Cond waiters) = do
  -- we wait by adding ourselves to the end of the list
  me <- newEmptyMVar
  modifyMVar_ waiters $ \others -> return $ others ++ [me]
  mutex_unlock m   -- note we don’t care if preempted after this
  takeMVar me ‘finally‘ mutex_lock m -- wake up, and mutex is unlocked
{- In general , it’s bad to not atomically release the mutex and then go
   to sleep, but here, this "inside" MVar is local to a single thread -}

cond_signal , cond_broadcast :: Cond -> IO ()
cond_signal (Cond waiters) = modifyMVar_ waiters wakeone
    where wakeone [] = return []
          wakeone (w:ws) = putMVar w () >> return ws

cond_broadcast (Cond waiters) = modifyMVar_ waiters wakeall
    where wakeall ws = do mapM_ (flip putMVar ()) ws
                          return []
```

The point is that putting MVars inside each other can be very powerful.

Control.Concurrent.Chan provides unbounded channels, also like Go.

```
data Item a = Item a (Stream a)
type Stream a = MVar (Item a)
data Chan a = Chan (MVar (Stream a)) (MVar (Stream a))
```

This can actually be implemented, in a simplified way, with MVars.

```
data Item a = Item a (Stream a)
type Stream a = MVar (Item a)
data Chan a = Chan (MVar (Stream a)) (MVar (Stream a))

newChan :: IO (Chan a)
newChan = do
  empty <- newEmptyMVar
  liftM2 Chan (newMVar empty) (newMVar empty)
-- liftM2 is like liftM for functions of two arguments:
-- liftM2 f m1 m2 = do x1 <- m1; x2 <- m2; return (f x1 x2)

writeChan :: Chan a -> a -> IO ()
writeChan (Chan _ w) a = do
  empty <- newEmptyMVar
  modifyMVar_ w $ \oldEmpty -> do
```

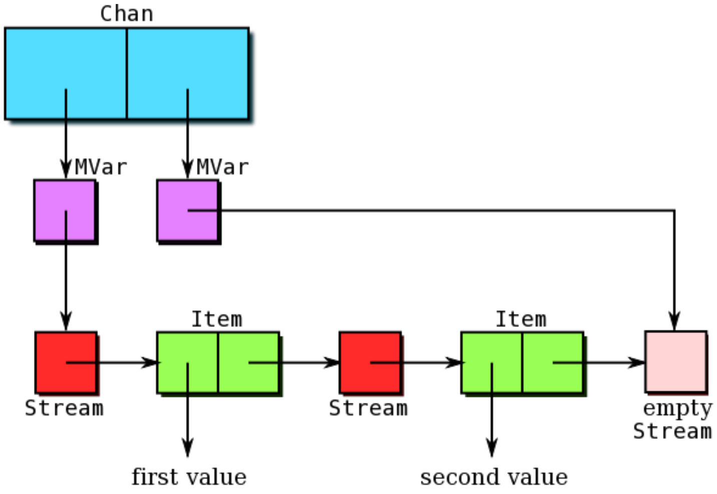


Figure 1. A schematic of how items can be placed into channels in this implementation. Source: `http://www.scs.stanford.edu/14sp-cs240h/slides/concurrency.html`

```
    putMVar oldEmpty (Item a empty)
    return empty

readChan :: Chan a -> IO a
readChan (Chan r _) =
    modifyMVar r $ \full -> do
      (Item a newFull) <- takeMVar full
      return (newFull, a)
```

This threading also allows one to do networking! In the `Network` package, there's support for high-level networking, specifically TCP and Unix-domain sockets.

```
connectTo :: HostName -> PortID -> IO Handle
listenOn :: PortID -> IO Socket
accept :: Socket -> IO (Handle, HostName, PortNumber)
sClose :: Socket -> IO ()
hClose :: Handle -> IO ()
```

For example, one could take last week's rock-paper-scissors program and make it work over a network:

```
import Network

-- accepts a single connection, plays a game, and then exits.

withClient :: PortID -> (Handle -> IO a) -> IO a
withClient listenPort fn =
  bracket (listenOn listenPort) sClose $ \s -> do
    bracket (accept s) (\(h, _, _) -> hClose h) $
      \(h, host, port) -> do
        putStrLn $ "Connection from host " ++ host
                   ++ " port " ++ show port
        fn h
```

Use of `bracket` prevents leaking of file descriptors.

5. API Design: 4/15/14

"Dwarf Fortress... why was I reading about Dwarf Fortress?"

Today we'll talk about API design and phantoms, a nontraditional apprach. Patterns are something we've seen before., albeit implicitly. For example, addition: we have a 0 such that $0 + n = n + 0 = n$, and addition associates. Similarly, we have multiplication: there's a 1 that is the identity, and multiplication associates. Similarly, lists and concatenation have a similar structure, with the empty list functioning as the identity, and concatenation ++ associating. The same is true with booleans and `&&`, with `True` the identity and associativity.

This is something called a monoid, which comes to us via abstract algebra.

Definition. A monoid is a set M with an associative function $\oplus : M \times M \to M$ and an identity element $0 \in M$ such that $0 \oplus m = m \oplus 0 = m$ for all $m \in M$.

In Haskell, these appear in the `Data.Monoid` class: the identity is called `mempty` and the associative operator is called `mappend` (which is bad naming, but such is life). Then, they are required to satisfy these axioms delineated above. But how does Haskell enforce these axioms? It doesn't. Haskell is a programming language, not a theorem prover (e.g. Agda or Coq), so be careful.

Here's an example:

```
instance Monoid [a] where
    mempty           = []
    xs `mappend` ys = xs ++ ys
```

There are several other definitions which are type-correct, syntactically correct, and obey the monoid laws. For example, one could do

```
instance Monoid [a] where
    mempty       = []
    mappend _ _ = []
```

This one is useless, but the former one is the one that is actually useful, and we'll use it. Numbers are interesting becaue they are monoids in two "good" ways, addition and multiplication. There's a lesson here: one should use a typeclass where there's exactly one canonical behavior one would expect for a given type; there's one canonical choice for lists, so this can be done. For numbers, we can hide the machinery:

```
-- This syntax defines the constructor and the unwrapper getProduct at the same time.
newtype Product a = Product { getProduct :: a}
    deriving (Eq, Ord, Read, Show, Bounded)

instance Num a => Monoid (Product a) where
    mempty                          = 1
    Product x `mappend` Product y = Product (x * y)

newtype Sum a = Sum { getSum :: a}
    deriving (Eq, Ord, Read, Show, Bounded)

instance Num a => Monoid (Sum a) where
    mempty                  = 0
    Sum x `mappend` Sum y = Sum (x + y)
```

Now we take advantage of the `Either` type, which is usually used for error handling. For example, one might define `type Result a = Error String a`. One might use it to construct a `Monoid` instance that gives the first success from a chain of `Either` statements.

```
-- please don't try to type-check this!
instance Monoid (Either a b) where
    mempty          = undefined -- oops!
    xs `mappend` ys
        | xs == Right b = b
        | otherwise = ys
```

The issue is, there doesn't seem to be a good canonical value for `mempty`. In Haskell, type variables are quantfied, i.e. the live in some domain. If there's no typeclass mentioned, a type variable is implicitly universally quantified (which can be explicitly specified with a `forall` construction in a language extension), so, for example, `length` must accept a list of any class. But there's no `mempty` for a general type, so this doesn't work! So maybe we should restrict this to `Either String a` (so the left side is always strings). Thus, the following typechecks with the `FexibleInstances` language extension. (Not all language extensions are safe or a good idea, but this one is pretty OK. One bad one is `UndecidableInstances`, which means the compiler doesn't have to terminate![2])

```
{- this is a normal comment -}
{-# this is a special comment, a pragma for the compiler #-}
{-# LANGUAGE FlexibleInstances #-}

instance Monoid Either String a) where
    mempty = Left "fnord"
```

[2] This is useful for two reasons: you might be a researcher, for whom infinite loops lead to papers, or because one might know a program is type-safe but the type-checker can't verify it.

```
    Right a ‘meppend‘ _ = Right a
    _       ‘mappend‘ b = b
```

So this is a valid monoid. But is it canonical? Not really. This is important becase any time one declares an instance of any typeclass, it is automatically available to any module that imports the code, which pollutes your library users' code. The way to get around this is to use a `newtype` to hide the special instance.

```
{-# LANGUAGE FlexibleInstances #-}

import Data.Monoid

newtype FirstRight a b = FirstRight {
    getFirstRight :: Either a b
}

instance Monoid (FirstRight String a) where
    mempty = FirstRight(Left "suxx0rz")

    a@(FirstRight (Right )) ‘mappend‘ _ = a
    _                       ‘mappend‘ b = b
```

. Because monoids have this really predictable behavior, it's now extremely obvious how one ought to use it, which is useful for organizing types an data. Basically, there's a way to glue two of them together and obtain another one.

Let's talk about HTTP POST requests. An ancient form protocol involves posting multipart data, some of which is mandatory, and some of which is optional.

```
data Part = Part {
    name :: String -- mandatory
    pathname :: Maybe FilePath -- optional
    -- et cetera
}
```

We can make an algebraic data type to represent a POST request body. Here are some types.

```
type Param = (String, String)

type ContenType = String

data Payload = NoPayload
    | Raw ContentType String
    | Params [Param]
    | FormData [Part]
      deriving Show
```

Can we make a nice `Monoid` out of them? `NoPayload` is the clear choice for `mempty`, but them after some cases it's not clear how to proceed.

```
instance Monoid (Maybe Payload) where
    mempty = Nothing
    mappend Nothing b = b
    mappend a Nothing = a

    mappend (Just (Params a)) (Just (Params b)) = Just (Params (a ++ b))
    mappend _ _ = Nothing
```

This is technically a monoid, but it's not a very satisfying one. There are plenty of APIs like this in the real world, but you can do better than a bunch of cases and pattern-matching.

But wait! If you feed this to `GHCi`, there's an eight-line error message! This is scary; eight lines is far too long.[3] The isue here is: `FLexibleInstances` allows both instances of `Maybe Payload` and `Maybe a` (the latter in `Data.Monoid`) as `Monoid`s. The language extension means there's a compile-time error, though it only is discovered at a call to `mappend`, which is kind of annoying.

The solution is... another language extension. This is called `OverlappingInstances`, which dictates that conflicts such as this resolve to the most specific type. This is very convenient! And very dangerous. Here's what can happen:

- Overlapping instances are big doors for semantic meaning of a program to escape entirely.
- One can get very confusing error messages.

[3] Let's not talk about C++.

- A new instance can be defined invisibly somewhere else, which can completely change the actions of the program.

On the other hand, this lead to interesting research.

One solution is something called a phantom type:

```haskell
data Payload a = NoPayload
    | Raw ContentType String
    | Params [Param]
    | FormData [Part]
      deriving Show
```

The type a appears exactly once, to prevent this overlapping instance conflict. Now, we can write an API.

```haskell
param :: String -> String -> Payload Param
param name value = Params [(name, value)]

filePart :: String -> FilePath -> IO (Payload [Part])
filePart name path = do
    body <- readFile name
    return (FormData [Part name (Just path) Nothing [body]])
```

These have the same runtime representation, but have different types, so the compiler can't mix them. Now, we can write the following.

```haskell
addParams (Params as) (Params bs) = Params (as ++ bs)

instance Monoid (Payload [Param]) where
  mempty = NoPayload
  mappend = addParams
```

Now, we have the functions `Param`, `filePart`, and `fileString`, but how does one enforce the fact that this is it? This can be done by exporting the name of the type `Part`, but not its constructors (though instances, as mentioned above, alway get exported). For example, the following `(..)` notation exports a type and all of its constructors:

```haskell
module PayloadPhantom
    (
      Part (..)
      -- and so on
    ) where
```

But instead, we can export the `Payload` type, without all of the constructors:

```haskell
module PayloadPhantom
    (
      Part (..)
      Payload, -- meaning no constructors!
      param,
      filePart,
      fileString
    ) where
```

Another cool piece of syntax is that `(<>)` is shorthand for `mappend`. This is used all over the place.

So, why monoids? They tend to work well for APIs, becaue they force one to address important design questions early on. There's also the `semigroups` package on Hackage, which gives monoids without an identity (just an associative operation); these aren't related to monoids in the language, but ought to be.

There's another interesting ata type for concurrent operations called `IORef`, which is non-blocking. This lives in `Data.IORef`, and allows anyone who has access to it to read, write, or modify the contents. But what if one wanted specific permissions? Some people's access should be read-only, and others should have read and write access. Here phantom types come to the rescue again!

```haskell
import Data.IORef

newtype Ref t a = Ref (IORef a)
```

Notice that `Ref` only exists and compile time, and the runtime performance is the same.

```haskell
module Ref
    (
        Ref, -- export type constructor, but not value constructor
        newRef, readOnly,
        readRef, writeRef
    ) where

-- anybody can read a Ref
readRef :: Ref t a -> IO a
readRef (Ref ref) = readIORef ref

-- All of the checking is done at compile time!
-- No cost upon runtime
writeRef :: Ref ReadWrite a -> a -> IO ()
writeRef (Ref ref) v = writeIORef ref v

readOnly :: Ref t a -> Ref ReadOnly a
readOnly (Ref ref) = Ref ref
```

The type system allows for some expressive and surprising applications. For good reads on monoids, check out "Data Analysis with Monoids" and R. Lämmel's paper 'Google's MapReduce Programming Model — Revisited", which flavors MapReduce with all sorts of interesting algebra.

6. STM: 4/17/14

How might one write a program to make a transaction? This entails sending money from Alice to Bob, but in a way that is thread-safe and checks if Alice has enough money to send.

```
import Control.Concurrent
import Control.Monad

type Account = MVar Double

printMV :: (Show a) => MVar a -> IO ()
printMV mv = withMVar mv print

{- This is a bad solution: what if you get an asynchronous exception?
   Needs to do some exception handling.

   It can also deadlock, e.g. transacting Alice -> Bob and Bob -> Alice
transfer account from to =
    modifyMVar_ from $ \bf -> do
        when (bf < amount) $ fail "not enough money"
        modifyMVar_ to $ \bt -> return $! bt + amount
        return $! bf - amount
 -}

transfer :: Double -> Account -> Account -> IO ()
transfer amount from to = do
    let tryTransfer = modifyMVar From $ \ bf -> do
        when (bf < amount) $ fail "not enough money"
        mbt <- tryTakeMVar to
        case mbt of
            Just bt -> do putMVar to $! bt + amount
                          return (bf - amount, True)
            Nothing -> return (bf, False)
    ok <- tryTransfer
    unless ok $ safetransfer (- amount) to from
-- Still needs to be fixed against asynchronous exceptions

main :: IO ()
main = do
  ac1 <- newMVar 10
  ac2 <- newMVar 0
  transfer 1 ac1 ac2
  printMV ac1
  printMV ac2
  return ()
```

This is pretty gross... instead, a model called software transactional memory uses database-like transactions to do things like this (e.g. writing to memory). This involves writing to a long, and then committing everything in the end. Notice that this would be difficult in procedural languages, such as C or Java, as something could write to the file system while this is going on. However, here, the IO type can control side effects.

In Control.Concurrent.TVar, there's a type called TVar which makes this work. Here are some methods.

```
newTVarIO    :: a -> IO (TVar a)
readTVarIO   :: TVar a -> IO a

readTVar     :: TVar a -> STM a
writeTVar    :: TVar a -> a -> STM ()
modifyTVar   :: TVar a -> (a -> a) -> STM ()   -- lazy
modifyTVar'  :: TVar a -> (a -> a) -> STM ()   -- strict

atomically :: STM a -> IO a
```

The last function is very interesting: the STM monad gives one global lock — but it acts otherwise like a more fine-grained lock. This comes at the price of lacking external IO actions. The transaction example from above now looks like this:

```
type Account = TVar Double

transfer :: Double -> Account -> Account -> STM ()
transfer amount from to = do
-- Quirk of Haskell: a - b can't be prefixed, since this conflicts with unary negation
-- so subtract a b = b - a
    modifyTVar' from (subtract amount)
    modifyTVar' to (+ amount)

main :: IO ()
main = do
    ac1 <- newTVarIO 10
    ac2 <- newTVarIO 0
    atomically $ transfer 1 ac1 ac2
```

Two more useful functions are retry :: STM a and orELse :: STM a -> STM a -> STM a. retry aborts a transaction, and then retries. But it's "smart" in that it knows what TVars have been read, and sleeps until at least one of them changes.

```
transfer :: Double -> Account -> Account -> STM ()
transfer amount from to = do
  bf <- readTVar from
  -- when is in Control.Monad. It waits for th Boolean it accepts to be true,
  -- and then executes.
  when (amount > bf) retry
  modifyTVar' from (subtract amount)
  modifyTVar' to (+ amount)
```

orElse takes two transactions, and executes the first; then, if this fails, then it executes the second (if both fail, it sleeps). This is useful for nesting transactions.

```
transfer2 :: Double -> Account -> Account -> Account -> STM ()
transfer2 amount from1 from2 to =
  atomically $ transferSTM amount from1 to
               `orElse` transferSTM amount from2 to
```

Another useful function is alwaysSucceeds :: STM a -> STM (). This adds an invariant to check after every transaction, which either throws the exception, or is ignored. Here's an example in use:

```
newAccount :: Double -> STM Account
newAccount balance = do
  tv <- newTVar balance
  alwaysSucceeds $ do balance <- readTVar tv
                      when (balance < 0) $ fail "negative balance"
  return tv
```

One can absolutely do this with weirder constraints. It's a really nice concurrency abstraction; there's no such thing as idiot-proof concurrent programming, but this makes many things a lot clearer.

Let's switch gears somewhat. How does the compiler represent data in memory? A value has a constructor and arguments, so it seems reasonable that we have a value's constructor at runtime (but not the type, because this is just type-checked at compile time).

```
struct Val {
  unsigned long constrno; /* constructor # */
  struct Val *args[];     /* flexible array */
};
```

There may be more than one constructor, e.g. for list types, which is what `constrno` is useful for (it's different for each constructor). However, this approach has neither room for exceptions nor thunks, which are very important. The garbage collector also can't really follow this, and having lots of pointers for simple types like `Int` makes the whole program less efficient.

Here's another idea; add a level of indirection to describe values.

```
typedef struct Val {
  const struct ValInfo *info;
  struct Val *args[];
} Val;

/* Statically allocated at compile time.  Only one per
 * constructor (or closure-creating expression, etc.) */
struct ValInfo {
  struct GCInfo gcInfo;  /* for garbage collector */
  enum { CONSTRNO, FUNC, THUNK, IND } tag;
  union {
    unsigned int constrno;
    Val *(*func) (const Val *closure, const Val *arg);
    Exception *(*thunk) (Val *closure);
  };
};
```

Here, this struct can contain either a constructor (the tag is `CONSTRNO`, so the code from the previous block can still be used), a function, an exception, or a thunk. Note that the type is not present at runtime, as the program has already been checked at compile-time. Then, `gcInfo` indicates how many `Val*`s are in the `args` array, and where they are, so the garbage collector can do its thing. Notice that if `tag == IND`, then `args[0]` is an indirect pointer to another `Val`. This is useful in case `args` needs to grow in size.

Looking at functions, we can assume that all functions take only one argument (thanks to currying; this is somewhat untrue due to compiler optimization, but is reasonable enough for a first look). To apply `f` to argument `a`, one calls `f->info->func (f, a);` the `closure` argument is useful so that the function can be reused; it holds `f` itself. The closure isn't always necessary (e.g. top-level bindings), but consider the following:

```
add :: Int -> (Int -> Int)
add n = \m -> addn m
    where addn m = n + m
```

It seems that there are *n* different `addn` structures, even though they'll have the same `ValInfo` value. Thus, the closure passed in is the same, and `args[0]` holds the value of `n`.

What about thunks? Then, there's another function pointer, evaluated as `v->info->thunk (v);`. Then, the thunk is updated in-place in memory (and isn't a thunk anymore); `v` is passed in as a closure again, but this time, unlike functions, thunks update themselves, and they can also throw exceptions (functions can too, but then they can just be taken to return a thunk that throws an exception).

Turning a thunk into a non-thunk is known as "forcing." One issue is that if the thunk's return value doesn't fit in its arguments, one has to allocate a new `Val`. This is why `IND` is a possible tag: the former thunk should be made with the `IND` tag, woth a forwarding pointer to the new `Val`. Here's what it might look like.

```
Exception *force (Val **vp)
{
  for (;;) {
    if ((*vp)->info->tag == IND)
      *vp = (*vp)->arg[0];
    else if ((*vp)->info->tag == THUNK) {
      Exception *e = (*vp)->info->thunk (*vp);
      if (e)
        return e;
    }
    else // no exception
      return NULL;
  }
}
```

As an exaple of what this does, here's how it handles currying. Start with the following function.

```
const3 :: a -> b -> c -> a
const3 a b c = a
```

Then, the curried function `const3 a` returns a function `const3_1(const3, a)`, which is a function pointer to `const3_2`, and so on.

```
Val *const3_1 (Val *ignored, Val *a)
{
  v = (Val *) gc_malloc (offsetof (Val, args[1]));
  v->info = &const3_2_info;  /* func = const3_2 */
  v->args[0] = a;
  return v;
}

Val *const3_2 (Val *closure, Val *b)
{
  v = (Val *) gc_malloc (offsetof (Val, args[2]));
  v->info = &const3_3_info;  /* func = const3_3 */
  v->args[0] = b;
  v->args[1] = closure;
  return v;
}

Val *const3_3 (Val *closure, Val *v)
{
  return v->args[1]->args[0];
}
```

This solves some problems elegantly, but introduces lots of overhead, e.g. each `Int` needs a distinct `ValInfo` structure, and we don't know which ones the program will need ahead of time. Thus, there are unboxed types that don't need a `Val` struct to be used. Here's a way of doing it.

```
union Arg {
  struct Val *boxed;      /* most values are boxed */
  unsigned long unboxed; /* "primitive" values */
};

typedef struct Val {
  const struct ValInfo *info;
  union Arg args[];      /* args can be boxed or unboxed */
} Val;
```

Unboxed types have no constructors, and can't be thunks. But this requires updating the garbage collector slightly.

A GHC extension, via the `-XMAgicHash` option, allows one to get unboxed types with the sharp character `#`; for example, we have the type `Int#`, and the operation `+#+` (which is a single machine instruction). See also: `GHC.Prim` or `:browse GHC.Prim` in the interpreter. This looks like a module, but has an awful lot of magic compiler builtins in it. There are also unboxed constants, e.g. `2#`, `2##` (unsigned), `'a'#`, and `2.0##`.

Now we know what `Int` actually is. It's a single-constructor data type with exactly one unboxed argument. This allows it to contain thunks, but avoids all of the pointer traversing (e.g. unboxed `Int#`s can be stored in registers). Thus, while calculating $1 + 1 = 2$ might be as complicated as `case 1 of I# u -> I# (u +# 2#)`, it's extremely useful in inner loops.

However, there are some restrictions on these unboxed types. They're different kinds of types: an `Int` is of type `*` (and we also had `* -> *`, etc.), but unboxed types are of kind `#`, which is different. This is done because they aren't polymorphic in the same way as boxed types. But applying the constructor allows one to box the type and define new datatypes.

```
{-# LANGUAGE MagicHash #-}
import GHC.Prim

-- These unboxed types are a challenge to syntax highlighters
data FastPoint = FastPoint Double# Double#  -- ok
fp = FastPoint 2.0## 2.0##                  -- ok

-- Error: can't pass unboxed type to polymorphic function
fp' = FastPoint 2.0## (id 2.0##)
```

```
-- Error: can't use unboxed type as type parameter
noInt :: Maybe Int#
noInt = Nothing
```

The next thing to look at is seq, which forces its first argument, and then forces the second argument and returns it. This ends up being tricky:

```
infiniteLoop = infiniteLoop :: Char    -- loops forever

seqTest1 = infiniteLoop `seq` "Hello" -- loops forever

seqTest2 = str `seq` length str        -- returns 6
    where str = infiniteLoop:"Hello"
```

seq forces a Val, but not its arguments, so it forces a string's constructor, but not its head or tail. This is a concept known as weak-head normal form (WHNF). Here's an example implementation.

```
const struct ValInfo seq_info = {
  some_gcinfo, THUNK, .thunk = &seq_thunk
};

Val *seq_2 (Val *closure, Val *b)
{ /* assume seq_1 put first arg of (seq a b) in closure */
  c = (Val *) gc_malloc (offsetof (Val, args[2]));
  c->info = &seq_info;
  c->args[0] = closure->args[0];
  c->args[1] = b;
  return c;
}

Exception *seq_thunk (Void *c)
{
  Exception *e = force (&c->args[0]);
  if (!e) {
    c->info = &ind_info;      /* ValInfo with tag = IND */
    c->args[0] = c->args[1]; /* forward to b */
  }
  return e;
}
```

With this behind-the-scenes look at Haskell, it's possible to understand some more of the higher-level magic. For example, one can declare strict wrapper types, e.g. data IntWrapper = IntWrapper !Int. This means that the Val's struct can't have the thunk or indirect types, so accessing a strict Int requires only one cache line.

Strictness is primarily used for optimization, in order to avoid building up long chains of thunks, or save overhead on checking whether a thunk has evaluated. But this comes at a loss of semantic data: a non-strict Int isn't just a number. There's also the value ⊥, corresponding to looping forever or throwing an exception. Types including ⊥ are called lifted. Thus, statements such as Maybe !Int incur an error.

The case statement can also force thunks; with the exception of irrefutable patterns (those that always evaluate, e.g. _ or just a single variable), any non-irrefutable pattern forces evaluation of its argument, in top-to-bottom, then left-to-right order. Even function pattern matching is desugared into case statements, e.g. the following.

```
f ('a':'b':rest) = rest
f _              = "ok"
test1 = f (undefined:[])   -- error
test2 = f ('a':undefined)  -- error
test3 = f ('x':undefined)  -- "ok" (didn't force tail)
```

A minor, but useful syntactic trick is that ~ makes a statement irrefutable. For example, three = (\ ~(h:t) -> 3) undefined evaluates to 3. This is useful for weird fixed-point constructions defined in terms of themselves. Finally, newtype, unlike data, creates an alias for a type (so no runtime code is different). Thus, a case statement on a newtype compiles to nothing.

```
newtype NTInt = NTInt Int deriving (Show)
uNTInt = NTInt undefined
-- fine, because _ is irrefutable
testNT = case uNTInt of NTInt _ -> True    -- returns True
```

However, forcing a value with its constructor leads to something different.

```
data SInt = SInt !Int deriving (Show)
uSInt = SInt undefined
testS = case uSInt of SInt _ -> True        -- undefined
```

Thus, `newtype` is almost always better, when it applies. A pragma called `UNPACK` allows one to unbox all strict fields, via the compiler flag `-funbox-strict-fields`.

7. Language Extensions: 4/22/14

GHC implements many language extensions to Haskell, enabled by placing `{-# LANGUAGE` *extensionName* `#-}` at the top of a file, or compiling with `-X`*extensionName* (or `:set` with the same flag in the interpreter). Some of these are very safe, integrated in Haskell's or GHC's libraries, or are easy to desugar, and others make type-checking nondeterministic or other less safe consequences.

Monad transformers are type constructors that build monads parameterized by other monads.

```
class MonadTrans t where
    lift :: Monad m => m a -> t m a
```

Since monads have kind `* -> *`, transformers have kind `(* -> *) -> * -> *`.

For example, the state transformer monad allows one to keep track of a global state, akin to an imperative program.

```
newtype StateT s m a = StateT { runStateT :: s -> m (a,s) }

instance (Monad m) => Monad (StateT s m) where
    return a = StateT $ \s -> return (a, s)
    m >>= k = StateT $ \s0 -> do      -- in monad m
        -- lazy pattern matching: don't check until we need one of the components
        ~(a, s1) <- runStateT m s0
        runstateT (k a) s1

instance MonadTrans (StateT s) where
    lift ma = StateT $ \s -> do   -- in monad m
                a <- ma
                return (a,s)
```

Then, there are helper functions `get` and `put`:

```
get :: (Monad m) => StateT s m s
put :: (Monad m) => s -> StateT s m ()
```

For example, one can call the equivalent of `x++` using state computations by getting `x` and putting back an incremented variable.

The `monadIO` class is useful if one wants to execute an I/O action regardless of the current monad (however many lifts are necessary to get to the I/O monad).

```
class (Monad m) => MonadIO m where
    liftIO :: IO a -> m a

instance MoadIO IO where
    liftIO . id

instance (MonadIO m) => MonadIO (StateT s m) where
    liftIO = lift. liftIO
```

Now, we can write functions that perform I/O, but work in many monads.

```
myprint :: (Show a, MonadIO m) -> a -> m ()
myprint a = liftIO (print . show) a
```

Another background example is that bindings in Haskell are allowed to be recursive, e.g.

```
oneTwo :: (Int, Int)
oneTwo = (fst y, snd x)
    where x = (1, snd y) -- mutual recursion
          y = (fst x, 2)

-- more reasonable example: memoizes the Fibonacci sequence~
nthFib :: Int -> Integer
nthFib n = fibList !! n
```

```
    -- zipWith combines two lists with the given function.
    -- The thunks all boil down to the right answer.
    where fibList = 1 : 1 : zipWith (+) fibList (tail fiblist)
```

This recursion can be implemented using something called a fixed-point combinator (which is a function that is a solution to a certain fixed-point equation). Instead, here we'll use recursive bindings to implement a fixed-point combinator.

```
-- in standard library
fix :: (a -> a) -> a
fix f = let x = f x in x

-- now, we use it. We define (x, y) to be the fixed point of a carefully constructed function.
oneTwo' :: (Int, Int)
oneTwo' = (fst y, snd x)
    where (x, y) = fix $ \ ~(x0, y0) -> let x1 = (1, snd y0)
                                            y1 = (fst x0, 2)
                                        in (x1, y1)

nthFib' n = fibList !! n
    where fibList = fix $ \l -> 1 : 1 : zipWith (+) l (tail l)
```

What this means is that if one takes a function that isn't recursive, `fix` simulates recursion by computing a fixed point.

However, monadic bindings are *not* recursive: the thing you're binding isn't in scope in the binding.

```
-- This is a parse error!
do fibList <- return (1 : 1 : zipWith (+) fibList (tail fibList))
```

However, monads in the `MonadFix` class have a fixed-point combinator `mfix`. Thus:

```
mfib :: (MonadFIx m) => Int -> m Integer
mfib n = do
    fibList <_ mfix $ \l -> return $ 1: 1 : zipWith (+) l (tail l)
    return (fibList !! n)
```

This is useful for simulating circuits with monads, which is actually pretty elegant, but requires recursion whenever a circuit has a loop.

Hence, the `RecursiveDo` language extension, which allows the new `rec` keyword to be desugared into `mfix`. Thus, it's useful for structuring one's thinking, even if it's easy to fix later. For example, it's easy to create recursive data structures.

```
data Link a = Line !a !(MVar (Link a)) -- note that ! is 0 here

mkCycle :: IO (MVar (Link Int))
mkCycle = do
    rec l1 <- newMVar $ Link 1 l2
        l2 <- newMVar $ Link 2 l1
    return l1
```

It can also be used to call non-strict methods of classes. So, how would one actually implement `mfix`? For a warm-up, here's the `Identity` monad, which doesn't actually do much.

```
newType Identity a = Identity { runIdentity :: a }
instance Monad Identity where
    return = Identity
    m >>= k = k (runIdentity m)
```

Then, `mfix` is essentially `fix`.

For a less trivial example, lazy I/O is accomplished using a magic `unsafeInterleaveIO :: IO a -> IO A`, which looks like an `IO` identity function, but defers the I/O until the output is forced. But don't use this at home, as it's not Haskell-like or even functional.

For `IO`, `mfix` is just `fixIO`:

```
fixIO :: (a -> IO a) -> IO a
fixIO k = do
    ref <- newIORef (throw NonTermination)
    ans <- unsafeInterleaveIO (readIORef ref)
    result <- k ans
    writeIORef ref result
    return result
```

This is surprisingly similar to how the compiler implements the ordinary `fix`. In particular, by the time the thunk is forced, it contains the correct value.

One might want to generalie `mfix` to all monads, using something like `mfix' f = fix (>>= f)` (turns it into a pure value), or `mfix' f = mfix' f >>= f`. But this doesn't work, because >>= is strict in the first argument for many monads, so it recurses infinitely and causes a stack overflow. Thus, `mfix` needs to take the fixed point over a value, not a monadic action, which ends up being monad-specific and doesn't work for all of them (e.g. not `ContT` or `ListT`).

One way to make this more concrete is to look at the `mfix` syntax for `StateT`.

```
instance MonadFix m => MonadFix (StateT s m) where
    mfix f = StateT $ \s20 -> do
        rec ~(a, s1) <- runStateT (f a) s0
        return (a, s1)

-- Can be implemented without language extensions
instance MonadFix m => MonadFix (StateT s m) where
    mfix f = StateT $ \s -> mfix (\ ~(a,_) -> runStateT (f, a) s)
```

Another way to think of this is `fix f` is a fixed-point of `f`, i.e. `fix f = f (fix f)`, but it's better to think of it as `let x = f x in x`. This latter definition is preferred because it won't cause a stack overflow. This is because a `let` statement corresponds to allocating a thunk, but the first definition doesn't allocate a thunk, so it keeps calling `fix` recursively, allocating memory for each iteration. This is a good rule to remember.

FOr a quick review of type classes, a Haskell 2010 type class declaration is of the form

```
class ClassName var where
    methodName :: Typ {- and so on -}
```

Here, `var` need not have kind `*`. Then, one may have superclasses, etc, but the type of each menthod must mention `var`, and ths `Classname var` is implicitly carried around.

Right now, each typeclass can take only a single parameter, but a language extension works around this.

```
{-# LANGUAGE MultiParamTypeClasses #-}
class Convert a b where convert :: a -> b
instance Convert Int Bool where convert = (/= 0)
instance Convert Int Integer where convert = toInteger
instance (Convert a b) => Convert [a] [b] where
    convert = map convert
```

This extension is relatively safe in itself, but is a gateway drug to all sorts of depravity. It encourages other extensions, because each method's type must mention every parameter: we can't just write `myDefault :: a`. Also, all types must be fully detrmined, so we can't just call `convert 0 :: Bool`, since 0 has type `(Num a) => a`.

Okay, so let's emable flexible instances.

```
{-# LANGUAGE FLexibleInstances #-}

instanc Convert Int [Char] where
    convert = show
instance Convert a a where convert a = a
```

This works sometimes, and then throws an overlapping instances error for converting a list of `Int`s to itself. So we need another language extension! Clearly. `OverlappingInstances` is used, but widely frowned upon; it chooses the more specific instance, but *doesn't consider the context*. Import this where the overlapping extensions are defined, not where those instances are used. An instance I_1 is more specific than I_2 when an instance for I_1 can be created by substuting the values for I_2, but not vice versa.

```
-- requires OverlappingInstances, but works fine.
class MyShow a where MyShow :: a -> String
instance MyShow Char where myShow = show
instance MyShow Int where myShow = show
instance MyShow [Char] where myShow = id
instane (MyShow a) => myShow a = "[" ++ (join (myShow a)) ++ "]"
```

But this doesn't solve our problem with `Convert`! For `Convert [Int] [Int]`, one now has to add a third instance `Convert [a] [a]` to break the tie, as it's more specific than both.

```
module Help where
    class MyShow a where
        myShow :: a -> String
    instance myShow a => MyShow [a] where
```

```
        myShow xs = concatMap myShow xs

    showHelp :: MyShow a => [a] -> String
    showHelp xs = myshow xs -- doesn't see ovrlapping instance

module Main where
    import Help

    data T = MkT
    instance MyShow T where
        myShow x = "Used generic instance"
    instance MyShow [T] where
        myShow xs = "Used more specific isntance"

    main = do
        myShow [MkT] -- generic
        showHelp [MkT] -- specific...? Oops.
```

One can add an extra helper metod `showList` to handle this tie, but it's still a good argument against the `OverlappingInstances` extension. But `FlexibleContexts` is a relatively safe: `MultiParamTypeClasses` leads to imexpressible types, with some otherwise ilegal contexts. Basically, we can define functions, but not write down their types without the extension.

The upshot is that we can make `StateT` work from lots of methods.

```
{-# LANGUAGE MultiParamTypeClasses #-}
{-# LANGUAGE FlexibleContexts #-}

class (Monad m) => MonadState s m where
    get :: m s -- these have the same implementations as before.
    put :: s -> m ()
```

But this causes problems to the following code.

```
xplusplus = do n <- get; put (n+1); return n
```

We can't infer that `get` has the type we need, which means it has to be explicitly specified (which is ugly, both in print and from a programming perspective) — what if there's some similar function out there for `StateT` with a `Double`?

Hence the `FunctionalDependencies` extension, which is widely used, but somewhat frowned upon. This lets a class define some parameters as functions of others, e.g.:

```
class (Monad m) => MonadState s m | m -> s
    -- and then get and put, and so on
```

Each of these steps seemed pretty reasonable, but can create instances where the type-checker can do arbitrary computation (!), and in particular might not terminate. In order to avoid this, there are two conditions. Write an instance as `instance [`*context* `=>]` *head* `[where` *body*`]`. Here, the context is zero or more comma-separated assertions (e.g. it's numeric).

There are two conditions, called the Paterson and Coverage conditions, imposed by the compiler, which reduce things to decidability.

```
crash = f5 ()
    where f0 x = (x,x)
    f1 x = f0 (f0 x)
    f2 x = f1 (f1 x)
    f3 x = f3 (f3 x)
    f4 x = f4 (f4 x)
    f5 x = f4 (f4 x)
```

This is perfectly legal and deciable, but the type size of f_n grows exponentially, and causes the compiler to crash!

So now (gasp) we have the `UndecidableInstances` extension, which lifts the conditions and instead just imposes a maximum stack size on `ghc` (which can be increased or decreased with pragmas and/or compiler flags). This allows one instance to cover all monadic transformers! Somehow, this is less frowned upon than `OverlappingInstances`.

This allows one to do some pretty gnarly stuff.

```
data HFalse = HFalse deriving Show
data HTrue = HTRue eriving Show

-- then, functions such as hNot and hAnd hOr, by casework.
```

Can we compute when two typs are equal?

```
class TypeEq a b c | a b -> c where typeEq :: a -> b -> c
instance TypeEq a a HTrue where typeEq _ _ = HTrue
instance TypeEq a b HFalse where typeEq _ _ = HFalse
```

But this is defeated by the overlapping instances: neither is more specific than the other. With a little bit of trickery, this can be elided... and used to program recursively at the type level by distinguishing base and recursive cases. This relies fundamentally on `OverlappingInstances`, though. For one example, this can be used to make `MonadState` to recursively lift (base case, if this type is equal to that type, do the base case; otherwise, recurse). This can save you a lot of typing[4] when designing general things.

8. Generic Programming: 4/24/14

> *"The bottom is a singular value that inhabits every type. When evaluated the semantics of Haskell longer yield a meaningful value. It's usually written as the symbol $\perp$ (i.e. the compiler flipping you off)."*
> *– Stephen Diehl*

The origin of this is that typing can be annoying in some contexts. For example, it's easy to convert pairs (tuples) to lists of `String`s, but it's not possible to generalize, because `show` is a method (a collection of functions), rather than a function itself. One solution is to use language extensions to allow methods to be passed as arguments to functions.

```
{-# LANGUAGE MultiParamTypeClasses #-}
{-# LANGUAGE FunctionalDependencies #-}
{-# LANGUAGE FlexibleInstances #-}

class Function f a b | f a -> b where
    funcall :: f -> a -> b
instance Function (a -> b) a b where
    funcall = id

pairToList :: (Function f a c, Function f b c) =>
              f -> (a, b) -> [c]
pairToList f (a, b) = [funcall f a, funcall f b]
```

Now, we need placeholder singleton types to represent methods.

```
data ShowF = ShowF -- some unit type
instnce (Show a) => Function ShowF a a [Char] where
    funcall _ = show

data FromEnumF = FromEnumF
instance (Enum a) => Function FromEnumF a Int where
    funcall _ = fromEnum
```

Now we can implement `pairToList` as intended to convert pairs of tuples to lists of tuples. But can it be generalized to arbitrary n-tuples? There's a way to auto-expand these definitions, e.g.

```
class TupleFoldr f z t r | f z t -> r where
    tupleFoldr :: f -> z -> t -> r
```

This causes the compiler to run out of memory at about $n = 10$, and this is sort of it for compile-time tricks. More insights will come later.

DeriveDataTypeable. Haskell allows six classes to be automatically derived: `Show`, `Read`, `Eq`, `Ord`, `Bounded`, and `Enum`. But the `DeriveDataTypeable` adds two more, `Typeable` and `Data`.

`Typeable`, which lives in `Data.Typeable`, allows one to compare types for equality.

```
class Typeable a where
    typeOf :: a -> TypeRep -- never evaluates argument

data TypeRep -- not exposed to user, but instance of Eq, Ord, Show, and Typeable
```

Now, we can do things like checking the type at runtime.

```
rtTypeEq :: (Typeable a, Typeable b) => a -> b -> Bool
rtTypeEq a b = typeOf a == typeOf b
```

[4] Pun intended?

Last time, we did this at compile time, but this required additional language extensions. And this is generally different anyways.

This also has an ineresting application: GHC has a function called unsafeCoerce, which can coerce any type into any other type... and can do lots of other scary things, such as segfault (e.g. converting () into a string). But using Typeable, one can make a safe case function.

```
cast :: (Typeable a, Typeable b) => a -> Maybe b
cast a = fix $ \ ~(Just b) if typeOf a == typeOf b
                           then Just unsafeCoerce a b
                           else Nothing
```

This can be generalized to monadic computations using gcast.

```
import Data.Maybe (fromJust)
-- fromJust :: Maybe a -> a
-- sends Just a to a, and is an exception on Nothing.

-- here, c is anything of kind * -> *
-- which is figured out automatically discovered by the compiler.
gcast :: (Typeable a, Typeable b) => c a -> Maybe (c b)
gcast c a = mcr
    where mcr = if typeOf (unc ca) == typeOf (unc $ fromJust mcr)
                then Just $ unsafeCoerce ca
                else Nothing
          unc :: c x -> x
          unc = undefined
```

Notice in this routine the undefined function unc. This is a perfectly fine idiom, and uses the fact that typeOf is not strict. One way to think about this is that Typeable b => is like an implicit argument, bringing in the dictionary of functions for a method.

One way to do this (which is a little bit of boilerplate) is a function called mkT, which behaves like id except on one type:

```
mkT :: (Typeable a, Typeable b) => (b -> b) -> a -> a

-- Example
newtype Salary = Salary Double deriving (Show, Data, Typeable)

raiseSalary :: (Typeable a) => a -> a
raiseSalary = mkT $ \(Salary s) -> Salary (s * 1.04)
-- Goal: raiseSalary () --> (), but raiseSalary 7 --> 7.28

-- Example implementation of mkT: uses that (->) is Typeable!
mkT f a = case cast f of Just g     -> g a
                         Nothing    -> a
```

Notice the Haskell type magic: g is applied to a and then returned, so g has type a -> a, so cast f has type Maybe (a -> a), and thus the compiler must know to use the Typeable dictionary of (b 0> b) for the argument, and (a -> a) for the return type of cast. Here's an alternate implementation.

```
-- Standard function: default value, conversion, possible value (to be converted)
maybe :: b -> (a -> b) -> Maybe a -> b
maybe b _ Nothing = b
maybe  _ f (Just a) = f a

-- super duper succinct: if we get nothing, just do nothing (id).
mkT f  = maybe id id $ cast f
```

Relatedly, there's a function called mkQ which computes over one type or returns a default value.

```
-- Example
salaryVal :: Typeable a => a -> Double
salaryVal = mkQ 0 $ \(Salary s) -> s -- 0 is the default value.

mkQ :: (Typeable a, Typeable b) => r -> (b -> r) -> a -> r
mkQ defaultVal fn a = case cast fn of Just g  -> g a
                                      Nothing -> defaultVal

-- Example: salavyVal () --> 0.0, salaryVal (Salary 7) --> 7.0
```

Awesome. But what if one wants to do something for a few types, and something else for another type? They can be chained.

```
extQ :: (Typeable a, Typeable b) =>
        (a -> r) -> (b -> r) -> a -> r
extQ q f a = case cast a of
                Just b -> f b
                Nothing -> q a
```

Now, these can be chained, e.g. to create customized Show functions that operate on several types.

Though it feels like playing Calvinball with new rules, there's yet another useful language extension, called ExistentialQuantification. This allows one to add type variables on the right side of a data declaration.

```
{-# LANGUAGE ExistentialQuantification #-}
data Step s a = Done | Skip !s | Yield !a !s
data Stream a = forall s. Stream (s -> Step s a) !s
```

This says that, given a value Stream a, there exists a tye s such that (and so on). Awkwardly, the same forall keyword is used to avoid adding a new keyword, so don't mix it with the forall from Rank2Types. This is a very safe language extension; Control.Exception relies on it.

One application is Dynamic, an opaque type living in Data.Dynamic that can hold anything typeable. Then, we also have these functions.

```
toDyn :: Typeable a => a -> Dynamic
fromDynamic :: Typeable a => Dynamic -> Maybe a
```

The implementation is pretty ugly (e.g. using unsafeCoerce), but can be implemented with existential quantification.

Another example is how GHC uses primitive, unsafe extensions, raise# and catch# (in GHC.Prim). This causes an unsafe coercion when b isn't always the same type. This is problematic, so SomeException is used to implement safe, hierarchical exceptions, which all derive from Typeable.

```
class (Typeable e, SHow e) => Exception e where
    toException :: e -> SomeException
    toException = SomeException -- default, from SomeException
    fromException :: SomeException -> Maybe e

throw :: Exception e => e -> a
throw e = raise# (toException e)

-- catch is a little more complicated (invokes the IO constructor, which is pretty deep)
catchX :: IO a -> (b -> IO a) -> IO a
catchX (IO a) handler = IO (catch# a (unIO. handler))

catch :: (Exception e) => IO a -> (e -> IO a) -> IO a
catch action handler = catchX action handler'
    where handler' se = -- does the cast that we need, avoiding the low-level stuff
```

It's now easy to create one's own exception types, by making it an instance of Exception (getting the default methods for free). But types can also be created in a hierarchy, making it straightforward to catch some exceptions but not others.

DerivedDataTypeable also allows one to derive the Data class.

```
data T a b = C1 a b | C2 deriving (Typeable, Data)

gfoldl k s (C1 a b) = z C1 `k` a `k` b
gfoldl k z C2       = z C2

toConstr (C1 _ _) = ... --encodes constructor number
toConstr C_2      = ...
gunfold k z c = case constrIndex x of
                        1 -> k (k (z C1))
                        2 -> z C2
```

This is convenient and builds impressively on a small amount of unsafe code, but runtime type checking is slow. Thus, one might wish to push generic programming to compile time. One interesting application of this is as follows.

```
{-# LANGUAGE MultiParamTypeClasses, FunctionalDependencies,
    FlexibleInstances, TypeOperators, DefaultSignatures #-}
-- DefaultSignatures allows default signatures to not work for
-- all instances. It works wherever it works, which is pretty nice
```

```haskell
-- for generic programming.

data Data tag contents = Data contents
data Cons tag contents = Cons contents

class Tag tag where showTag :: m tag c -> String

instance (Tag tag, Show c) => Show (Data tag c) where
    showsPrec d m@(Data c) = showParen (d > 10) $ \rest ->
      "Data[" ++ showTag m ++ "] " ++ showsPrec 11 c rest

instance (Tag tag, Show c) => Show (Cons tag c) where
    showsPrec d m@(Cons c) = showParen (d > 10) $ \rest ->
      "Cons[" ++ showTag m ++ "] " ++ showsPrec 11 c rest

-- Representing types like () with no constructor arguments
data Unit = Unit deriving Show

-- Representing constructor arguments
-- Requires TypeOperators language extension
-- makes a type that acts like ->, i.e. is an infix operator
-- basically, glues together two different types.
newtype Arg t = Arg t deriving Show
data (:*:) a b = a :*: b deriving Show
infixr 6 :*:

-- This isn't exactly what GHC does. The idea is that the compiler can generate
-- an instance for it.
class MetaData d m | d -> m, m -> d where
  fromData :: d -> m
  toData :: m -> d

data T1 = C1 deriving Show

data T1_tag
instance Tag T1_tag where showTag _ = "T1"

data C1_tag
instance Tag C1_tag where showTag _ = "C1"

type T1_meta = Data T1_tag (Cons C1_tag Unit)

instance MetaData T1 T1_meta where
  fromData ~C1 = Data (Cons Unit)
  toData _ = C1

data T2 = C2 String Bool deriving Show

data T2_tag = T2_tag
instance Tag T2_tag where showTag _ = "T2"

data C2_tag = C2_tag deriving (Show, Bounded)
instance Tag C2_tag where showTag _ = "C2"

type T2_meta = Data T2_tag (Cons C1_tag (Arg String :*: Arg Bool))
instance MetaData T2 T2_meta where
-- going from data <-> metadata
  fromData ~(C2 s b) = Data (Cons (Arg s :*: Arg b))
  toData ~(Data (Cons (Arg s :*: Arg b))) = C2 s b

-- We want to automatically derive instances of a Show-like class.
-- Or rather, we want the compiler to do this for us.
class MyShow a where
  myShow :: a -> String
  default myShow :: (MetaData a m, MetaMyShow m) => a -> String
  myShow = genericMyShow

instance MyShow String where myShow = show
instance MyShow Int where myShow = show
instance MyShow Bool where myShow = show

class MetaMyShow a where
  metaMyShow :: a -> String
instance (MetaMyShow c) => MetaMyShow (Data tag c) where
  metaMyShow (Data c) = metaMyShow c
instance (Tag tag, MetaMyShow c) => MetaMyShow (Cons tag c) where
  metaMyShow m@(Cons c) = "(" ++ showTag m ++ metaMyShow c ++ ")"

instance MetaMyShow Unit where metaMyShow _ = ""

instance (MetaMyShow a, MetaMyShow b) => MetaMyShow (a :*: b) where
  metaMyShow (a :*: b) = metaMyShow a ++ metaMyShow b
instance (MyShow a) => MetaMyShow (Arg a) where
  metaMyShow (Arg a) = ' ' : myShow a

genericMyShow :: (MetaData d m, MetaMyShow m) => d -> String
genericMyShow = metaMyShow . fromData

instance MyShow T1 -- simplified by DefaultSignatures
instance MyShow T2
```

Though this looks extremely intimidating, it allows instances of classes and types to work, which has all sorts of applications.

A `DeriveGeneric` extension allows the compiler to support a single `Geneic` class that converts any datatype to a `Rep` class that can be computed over generically.

```
{-# LANGUAGE TypeFamilies #-}

class Generic a where
    type Rep a :: * -> *
--  from and to methods for a <-> Rep a
```

A lot of this lives in a module called `GHC.Generics`, which offers generic types `U1` for units (constructors without arguments), `M1` for meta-information (constructor names, etc.), and `D`, `C`, and `S`, for datatypes, constructors, and selectors, respectively, Selectors allow one to pick out record names from types. This module also uses `:*:` to glue multiple constructor arguments together, with the same fixity. Then, there are `L1` and `R1` for types with multiple constructors and `K1` for concrete types. This means one needs `OverlappingInstances`, which is somewhat unfortunate.

9. Functors, Monads, and Whatnot: 4/29/14

> *"This might be some sort of emoji that looks like a TIE fighter. In fact, it's probably Darth Vader's TIE fighter."*

Today, we'll try to develop some more intuition about abstract things in Haskell. Some of it is easy, e.g. `fmap (+1) [1,2,3]` returns `[2,3,4]`. But what is this actually doing to the list? Its length doesn't change, so the function affects the elements, but not the container.

```
-- Exercise: write a Functor instance for Maybe.
-- Since this has already been done, we need to avoid a name clash
class MyFunctor f where
    myfmap :: (a -> b) -> f a -> f b

instance MyFunctor Maybe a where
    myfmap f (Just x) = Just (f x)
    myfmap _ Nothing  = Nothing
```

This is the same idea as for lists as functors: (`my`)`fmap` applies the function within the container. One could certainly make it return `Nothing` in both cases, but this would be naughty. As for efficiency, this is desugared into the same thing in Haskell's intermediate representation (a language called Core) as the equivalent case statements.

```
newtype Identity a = Identity a -- actually exists in Data.Functor.Identity

instance MyFunctor Identity a where
    myfmap f (Identity a) = Identity (f a)
```

newtype isn't really a container; it exists only at compile time. Thus, Functor can be used on things that aren't just containers. For example, we have the "tupling operator" (,) :: a -> b -> (a,b). But this is actually an operator, so one can do things like

```
ghci> :type (,) 'X'
(,) 'X' :: b -> (Char, b)
```

Thus, the type signatures (,) Char b is identical to (Char, b), e.g. binky b = (,) 'X' b. But this means we can write a MyFunctor instance for them.

```
instance MyFunctor ((,), a) where
    myfmap f (a, b) = (a, f b)
```

The idea is that we could pick eother argument, but not both, and the reason we pick the second and not the first is purely a matter of convention. This is clearly a container, but newtype isn't strictly a container, but behaves enough like one at compile time, which is pretty interesting.

Well, it turhs out that -> is a type constructor: (->) a b is equivalent to a -> b, so we ought to be able to make functions instances of MyFunctor (or regular Functors), which is where the notion of functors acting on containers starts to go awry.

```
instance MyFunctor ((-> a) where
    myfmap f g = f . g -- i.e. \ x = f (g x))
```

These are definitely not containers, so what makes a Functor a Functor? There are two laws that a "good" functor should implement (though this isn't checked by the compiler or runtime): that fmap id == id, and (fmap f) . (fmap g) == fmap (f . g). But since types are curried, the type of fmap is (a -> b) -> (f a -> f b), so it takes a function and lifts it into the new context of the functor, e.g. a list, a Maybe, or a function.

But why functors? You'll come across the damn things everywhere in Haskell, and they're relatively simple (next to Monoid), and the fact that (->) a is a Functor, but not a container, then we are forced to think at this higher level of abstraction of what a Functor actually "is." In some sense, the container is a metaphor, but isn't useful any more. Instead, we'll call the f in instance Functor f a *context*. Maybe it's a state, but in any case, it's information we can use when doing our regular computation. For example, in lists, the context is a list, and for functions with the first argument supplied, the context is the function, and for I/O, the context is stuff that can have side effects.

A step up in power is applicative functors, defined in Control.Applicative.

```
class (Functor f) => Applicative f where
    pure :: a -> f a
    (<*>) :: f (a -> b) -> f a -> f b -- "Darth Vader's TIE Fighter"
```

Notice how similar (<*>) is to fmap and $; they're all just ways of doing function application. There four laws which applicative functors need to follow; the rules can be found at the Typeclassopedia. For a good example of Applicative, here's Maybe:

```
-- already provided in Conttrol.Applicative
instance Applicative Maybe where
    pure = Just
    Just f <*> Just x = Just (f x)
    -- at least one is Nothing, so return Nothing
    _      <*> _      = Nothing
```

Exercise 9.1. If you want to gain a greater understanding of Applicative, write instances of it for lists, Identity, and (->) a. If newtype MyConst a b MyConst a, then write Functor and Applicative instances for it.

Now, we know enough to write a parser (!), using a well-known library for parsing, Parsec.

```
import Control.Applicative
import Data.Char (chr)
import Numeric (readHex)
import Text.Parsec (char, hexDigit)
import Text.Parsec.String (Parser)

hexChar :: Parser Char
-- *> is defined in the Applicative module
hexChar = char '%' *> (combo <$> hexDigit <*> hexDigit) -- <$> is infix for fmap
    where combo a b = case readHex [a,b] -- and so on
```

Now, we can parse an entire URL-encoded string, but this uses a thingy called `Alternative`. This is a subclass of `Applicative`, through the lens of monoids.

```haskell
class Applicative f -> Alternative f where
    empty :: f a                    -- akin to mempty
    (<|>) :: f a -> f a -> f a      -- akin to mappend
```

`empty` is useful for a fail state, and `<|>` makes for "try something, and if that fails, try something else instead." This is useful for making combinators to separate a string by a separator.

```haskell
pair :: Parser (String, Maybe String)
pair = (,) <$> many1 urlChar
           <*> optional (char '=' *> many urlChar

-- Try a regular character, then a hex character, then a space character. Very concice!
urlChar = oneOf urlBaseChar
        <|> hexChar
        <|> ' '<$ char '+'
```

Every `Monad` is an `Applicative`: `return` is `pure`, but what happens for `>>=`? There's a reverse bind funcion too.

```haskell
(>>=) :: Monad m => m a -> (a -> m b) -> m b
(<<=) :: Monad m => (a -> m b) -> m a -> m b
```

...which means that `<<=` does the same thing as `fmap` and its friends: it injects a function into a context. But how does it differ?

`Functor` and `Applicative` are only able to look at the elements of a container (or context, or whatever): they are oblivious to the enclosing structure; both `fmap` and `<*>` cannot affect the context. Notice that with monads, we can; the function type is `a -> m b`. It is possible to see the context, to pattern-match on it, and so on, and return based on that. This is the crucial difference between monads and applicative functors — monads are more powerful, but harder to think about.

However, in the Haskell implementation, `Monad` is independent of these, so it's not yet explicitly an instance of `Applicative`. This will be fixed in GHC 7.10, which ought to be out later this year.

Now, there are lots of subtly different things to use, so which should you use when? Here are some principles; in general. these boil down to simplicity.

- Use `Applicative` in preference to `Monad`, if possible.
- Similary, the principle of least surprise means one should prefer `Functor` to `Applicative` whenever possible.

This also makes it harder for your own users to perform foot-shooting.

Perhaps it will be a surprise that these show up in practice in Facebook. One generic pattern is some database and server, with a service API. Specifically in the context of spam detection, a PHP request is sent to a server that detects whether something is spam or not. But since spam is always innovating, then there's a whole team looking for emergent threats in the spam landscape. People write rules that tell these machine-learning algorithms what to do.

Of course, Facebook's databases are distributed all over the place: there's MySQL, memcache, and so on; and one request can cause others to propagate along the way. For example, querying about spam from a newly registered user could check the number of friends (Since many spammers don't have friends on average), or even a series of fetches to get sophisticated data (age of friends' accounts), and so forth. But we want to make this code sane, modular, abstract, and so forth.

It's possible to use a monad for this, but this gets blocked at the first data fetch:

```haskell
numCommonFriends x y = do
    fx <- friendsOf x -- blocked
    fy <- friendsOf y
    return $ length $ intersect fx fy
```

The monad is notationally convenient, but since the context of `>>=` includes the result of the previous computation, it gets blocked, so an applicative functor is better.

```haskell
    numCommonFriends x y = length <$> (intersect <$> friendsOf x <*> friendsOf y)
```

Since they don't depend on each other, these two requests can be performed in parallel.

This system is called Haxl. A common thread to these kinds of applications of applicative functors and monads is that you get concise code that can be written quickly, and don't depend on hacks in the way other languages' parsing libraries sometimes do. For example, there's a very good command-line parsing library called `OptParse`.

10. Pipes: 5/1/14

Today's lecture was a guest lecture by Gabriel Gonzalez.

There are several functions that are akin to mapping over modads, e.g. `mapM`, `sequence`, and `replicateM`. These do all of their computation before returning the result, which is rather inefficient, both time-wise and memory-wise, and this doesn't work on infinite lists. One solution, specified to the `IO` monad, is lazy I/O, but only works well for sources of information, not sinks or transformations, and makes it a lot harder to reason about programs: specifically, it invalidates the equational reasoning of a Haskell program. Finally, it seems like admitting defeat to the monadic paradigm.

Hence, pipes, which, like generators, are based on coroutines. The idea is to separate the generation of and the consumption of values, making things modular and easier to test and use.

```
import Pipes
import System.IO (isEOF)

stdinLn :: Producer String IO () -- Producer is a generator
stdinLn = do
    eof <- lift isEOF
    if eof -- asks, are we at the end of the input?
        then return ()
        else do
            str <- lift getLine
-- This yield is what makes it a generator; it passes off the value to some unknown
-- handler. yield blocks until its value is used.
            yield str
            stdinLn

useString :: String -> Effect IO ()
useString str = lift (putStrLn str)

-- What happens: until EOF, print the lines that the user enters
echo :: Effect IO ()
echo = for stdinLn useString
```

Cool. So how would we build this? The `Producer` type can be thought of as a list with effects inside, but also as a syntax tree of `Yield` values and a nil value:

```
import Control.Monad.Trans.Class (MonadTrans(lift))

data Producer a m r
    = Yield a (Producer a m r)
    | M    (m (Producer a m r))
    | Return r

yield :: a -> Producer a m ()
yield a = Yield a (Return ())

instance Monad m => Monad (Producer a m) where
--  return :: Monad m => r -> PRoducer a m r
    return r = Return r

    (Yield a p) >>= return’ = Yield a ( p >>= return’)
    (M       m) >>= return’ = M (m >>= \p -> return (p >>= return’))
    -- similarly for Return

-- then, make it an instance of MonadTransformer with liftM
```

`for` connects two syntax trees together to create anew syntax tree.

```
for :: Monad m
    => Producer a m ()
    -> (a -> Producer b m ())
    -> Producer b m ()
for (Yield a p) yield’ = yield’ a >> for p yield’
for (M       m) yield’ = M (m >>= \p return (for p yield))
-- and so on for return
```

Another useful functon is `runEffect`, which is a `Producer` that has no yield constructors (since they're defined to return `Void`, a type without constructors). The idea is that it compiles down to Haskell code tat you could write if you really needed to, and ought to have similar semantics to lazy I/O, but invoking pipes makes writing the code a lot easier. The `Pipes` library also works well for exceptions, but that's a bit beyond the scope of the talk.

Behind this lies the theory of the library, which could be a useful model for how one should write good Haskell code, and even why Haskell is so well-liked in general. Haskell is unique in the ways it applies category theory to programming to reduce complexity.

In general, a piece of software might have lots and lots of components that get connected together in some ways. But typically, the more components, the more complex the system. Thus, we want a way to append things together such that we still get the same type in the end. This is exactly what a monoid does!

```haskell
class Monoid m where
    mappend :: m -> m -> m
    mempty :: m

    (<>) :: Monoid m => m -> m -> m
    (<>) = mappend
```

This is familiar, and we also want <> to satisfy associativity, and with `mempty` its identity element.

So this works nicely with `Yield`: returning unit is akin to returning zero things, and yielding several things (e.g. with do or >>) is akin to adding things. This is an aspect of the fact that (>>) and `return ()` form a monoid within any monad, and satisfy the associativity and identity laws.

But monoids are somewhat of a simpler interface; we can generalize!

```haskell
class Category cat where
    (.) :: cat b c -> cat a b -> cat a c -- akin to mappend
    id :: cat a a                        -- akin to mempty

(>>>) :: Category cat => cat a b -> cat b c -> cat a c
(>>>) = flip (.) -- so we can read types left to right

instance Category (->) where
    (g . f) x = g (f x)
    id x = x
```

We require `(.)` to be associative, and `id` to be the identity with regards to `(.)`.

It turns out that the "fish" operator >=> and `return` form a cateogry (the former is defined as `(f >=> g) x = f x >>= g`), with the latter the identity.

Let's define `(f ~> g) x = for (f x g)` ("into"), so that `(~>)` and `yield` form a category, and obeys the laws. This simplifies the notation, and makes it more powerful.

Associativity in this category is a bit harder. We want the following to hold.

```haskell
for (for p g) h = for p (\x -> for (g x) h)
```

You could convince yourself with examples, or just thinking about what gets printed where.

The goal of the `Pipes` library is to use this to simplify the coroutines into one final syntax tree, so tht it stays about as simple for all sizes.

Here's some information about the API. A `Consumer` is a sink that can change over time, e.g. prefixing a line with an increasing number (e.g. for echoing line numbers).

```haskell
import Pipes
import Pipes.Prelude (stdinLn)

numbered :: Int -> Consumer String IO r
numbered n = do
    str <- await -- we don't know where it'll come from just yet
    let str' = show n ++ ": " ++ str
    lift (putStrLn str')
    numbered (n + 1)

giveString :: Effect IO String
giveString = lift getLine

nl :: Efect IO ()
-- >~ is also called the feed operator.
nl = giveString >~ numbered 0
```

The Consumer type is much like the producer type, but instead of emitting the elements, it accepts them, so there's a Await primitive rather than a Yield. In much the same way as a Producer, these can be connected with do, and have some structure. We have a feed operator again:

```
(>~) :: Monad m => Consumer a m b -> Consumer b m c -> Consumer a m c
```

This is, once again, exactly the same as (>>>) in a category. Then, await is the identity, because await >~ f = f and f >~ await = f.

Now, it's helpful to connect Producers and Consumers, using the pipe operator >->. This connects the await of one to the yield of another.

```
(>->) :: Producer a IO r
      -> Consumer a IO r
      -> Effect     IO r

main :: IO ()
main = runEffect (stdinLn >-> numbered)
```

The above program reads lines in and then prints them out with their line number. Thus, we have a Pipe type which can yield and await! For example, one could create a pipe which accepts two inputs and then terminates on the third (which is really hard to do in lazy I/O), so one could call it take n, and pipe runEffect (stdinLn >-> take 2 >-> numbered) and so on. Because pipes are monads, we can change them over time using take and so on.

Notice that the types have been unclear or somewhat overloaded. This is because there are multiple such operators with the same name, e.g. >-> can go between producers, consumers, and pipes. This is because a producer is just a pipe with the input sealed off (at least in theory; the implementation uses a better trick), so type Consumer a = Pipe a Void. This is parametric polymorphism (top-down, implemented from a big superclass).

Thus, (>->) and cat (exactly the same as the Unix command) form another cateogry! The API is category-inspired, with (>=>) and return, (~>) and yield, (>~) and await, and (>->) and cat. But this is just the beginning: (>=>) and (~>) distribute, in the sense of multiplication and addition, and return >~ h = return (akin to $0 \cdot a = 0$)...

Another advantage of this is that the category laws provide unit tests, in some sense, for the library. This framework keeps complexity simple, and though it seems intimidating, a small amount of theory goes a long way.

Exercise 10.1. Implement takeWhile, which passes lines on until a predicate is satisfied, and then terminates.

Solution.

```
import Pipes
import Pipes.Prelude (stdinLn, stdoutLn)
import Prelude hiding (takeWhile)

takeWhile :: Monad m => (a -> Bool) -> Pipe a a m ()
takeWhile keep = do
    input <- await
    if keep input
        then do
            yield input
            takeWhile keep
        else return ()

main = runEffect $ stdinLn >-> takeWhile (/= "quit") >-> stdoutLn
```

Exercise 10.2. Implement map, which accepts a function and applies that function on everything piped through it.

Solution.

```
import Pipes
import Pipes.Prelude (stdinLn, stdoutLn)
import Prelude hiding (map)

map :: Monad m => (a -> b) -> Pipe a b m ()
map f = do
    input <- await
    yield $ f input
    map f

-- Alternate impementation
map f = for cat (yield . f)
```

```
main = runEffect $ stdinLn >-> map (++ "!") >-> stdoutLn
```

Exercise 10.3. What does the following function do?

```
import Control.Monad (replicateM_)
import Pipes

mystery :: Monad m => Int -> Pipe a a m r
mystery n = do
    replicateM_ n await
    cat
```

Solution. This is akin to the `drop` function from the standard library: it ignores the first `n` inputs and then passes on all of the rest.

Exercise 10.4. What about this one?

```
import Pipes

yes :: Monad m => producer String m r
yes = return "y" >~ cat
```

Solution. This is the Unix `yes` utility, equivalent to `forever $ yield y`.

Finally, here's a simplified `grep` utility, which only passes on strings thaat contain a given string somewhere in them.

```
import Pipes
import qualified Pipes.Prelude as Pipes

grep :: Monad m => String -> Pipe String String m r
grep str = Pipes.filter (isInfixOf str)

main = runEffect $ Pipes.stdinLn >-> grep "import" >-> Pipes.stdoutLn
```

11. Parsing and Continuations: 5/6/14

"Parking here is not my favorite activity."

Today we're going to talk about parsing, which will be a vehicle for talking about API and program design.

In times of yore, peope wrote all of their parsers by hand. There's lots of ugly C++ pointer arithmetic or Java boilerplate. These are extremely hard to debug, and it's not clear from the code what they're supposed to be doing. These do tend to be very fast, though. Alternatively, one can use a domain-specific language (e.g. Ragel), which makes a parser easier to understand and much more compact, but learning a new language (not to mention gluing it to other code) is difficult, and the generated code is hard to follow. But these make debugging much easier.

Let's use Haskell! The simplest parser we can think of accepts a string to match against, then another string as input, and returns whether they're equal. This ought to have type `String -> String -> Bool`. The problem is, this is not how parsers work: they return the result of input conversion (e.g. an integer parser returns the integer parsed), along with the rest of the input, so that parsers can be chained. Thus, a better type signature is `Type Parser s a = s -> (a, s)`. But parsers can fail, so it better is `Parser s a = s -> Maube (a, s)`. Here's a less crappy API for the equality tester `string`.

```
import Data.Char
import Data.List
import Data.Maybe

type Parser a s = s -> Maybe a s

string :: String -> Parser String String
string pat input =
    case stripPrefix pat input of
        Nothing   -> Nothing
        Just rest -> Just (pat, rest)

number :: Parser String Int
number input = let (h, t) = span isDigit input
               in case reads h of
```

```
                    [(n, "")] -> Just (n,t)
                    _         -> Nothing
```

Now, one can chain these together: the following function parsees HTTP version headers.

```
-- version "HTTP/1.1/\r\n" == Just ((1,1), "\r\n")
-- version "HTTP/wibblesticks" == Nothing
version :: Parser String (Int, Int)
version input = do
% hmmm maybe this doesn't work
    (_, input') <- string "HTTP/" input
    (a, input'') <- number input'
    (_, input3) <- string "."
    (b, rest) <- number input4
    return ((a, b), rest)
```

One naïve way to write this is to make a big staircase of case expressions. This boilerplate can be simplified with a function that encapsulates the case statement and returns the result (or nothing). But then, need to return the minimum and maximum, which involves calling the function `\input -> Just (a, input)`. This is type-correct, but unintuitive, and hard to read.

But ther's a better solution, involving some magic trickery: the function used to hide the case statements has the same type as the monadic bind operator, and the returning operator looks like monadic `return`. But this isn't quite a monad. it would be bad for `Parser a s` to be a monad, because then every function `a -> (a, s)` is infected with this instance. Instead, use `newtype`, calling Peter Parker "Spiderman," so to speak. Then, some constructors have to be passed around, but this isn't hard.

```
-- Here, "oldParser" is the non-monadic type and wrapper function we used before
andThen :: OldParser s a -> (a -> OldParser s b) -> OldParser s b
bind    ::    Parser s a -> (a ->    Parser s b) ->    Parser s b
```

Then, one can make this an instance of `Monad` and `Functor` without too mcuh code or fuss. Now, monadic notation makes parsing much easer. But then, since it's a functor, it can be turned into `Applicative`, making the parser much smaller.

```
import Control.Applicative
import Control.Monad (ap)

instance Applicative (Parser s) where
    pure = return
    (<*>) = ap
```

Using various combinators, it can be reduced to just a few lines of code.

Another interesting option is to use `Alternative` to make a parser that can choose another parse if the first one fails.

```
-- can be done since Parser s is already Applicative
instance Alternative (Parser s) where
    -- empty :: f a
    empty = P \input -> Nothing
    -- (<|>) :: f a -> f a -> f a
    f <|> g = -- some case statements follow
```

Parsing was one of the major reasons applicative functors were first introduced, even though they have found many more applications.[5]

The best-known parser for Haskell is called Parsec, but Bryan O'Sullivan has written a much faster version called Attoparsec. It's more specialized, e.g. to `ByteString` and `Text`, but not `String`. Attoparsec also doesn't give readable error messages (assumes it's parsing something automated such as network packets). Use either depending on these constraints.

Here's one thing people should be careful about. Suppose one receives a fragmented or incomplete TCP segment off of the network. The packet doesn't hold its message information (also true of JSON blobs), so how can we tell whether the object contain enough data. Also, can this be elegantly incorporated into a parser?

One solution is monad transformers, which allows one to stack things on top of other things. The composition of two monads is not in general a monad, but monad transformers alow one to stack "transformers" on top of a monad such that the result is still a monad. These are easy to work with, but not to implement. Parsec does this by stacking a transformer type `ParsecT` on top of `IO`. A function called `Partial` can handle partial application/parsing.

[5] Pun intended?

Another way this works is with continuations. It's not a great idea for your mental state to do this for too long. The idea is, if a parse succeeds or fails, one calls a function.

```
{-# LANGUAGE RankNTypes #-}

type ErrMSg = String

newtype ContP a = ContP {
    runP :: forall r.
            String
         -> (ErrMsg -> Either ErrMsg r)
         -> (String -> a -> Either ErrMsg r)
         -> Either ErrMsg r
}
```

But what is this language extension? For polymorphic functions such as `id`, there's an impplict type quantifier not written, i.e. `id :: forall a. a -> a`. This universal quantifier, which is unwritten, is a type-level lambda, akin to the anonymous function declarer (one sometimes sees $\Lambda a \to a$). In some sense, the function asks for a type, and applies it everywhere it sees it. This is a rank-1 type because the universal quantifier is present at the outermost rank. However, in the listing above, the `forall` is hidden. Thus, the type parameter `r` is controled by the calle (the library); the caller (the user) cannot access it. This is a rank-2 type, and higher nesting exists (but is rare). Working with continuations is tough! If you want to be convinced, try writing a `Functor` instance for them.

Let's define types to track input that we've seen and what's left to see, `Input` to `Accept`. Then, one can use these to allow the parser to backtrack if one branckh parses unsuccessfully. Then, there are types

```
-- parse fails: error message, stack of context information
type Failure t r = Input t -> Added t -> More -> [String] -> IResult t r
type Success t a r = Input t -> Added t -> More -> a -> IResult t r

-- partial result: could succeed or fail.
data IResult t r = Fail t [String] String
                 | Parttial (t -> Iresult r)
                 | Success t String r
```

As is usually the case with monads, the user-visible commands are relatively simple.

```
parse :: Monoid t => parser t a -> t - > IResult t a
parse m s = runParser m (I s) (A mempty) Incomplete failK successK
```

The last functions are "terminal continuations," i.e. functions that don't chain up another continuation, but return to normal computation:

```
failK :: Failure t a
failK i0 _a0 _m0 stack msg = Fail (unI i0) stack msg

successK :: Success t a a
successK i- _a0 _m0 a = Done (unI i0) a
```

One interesting resource for information is `#haskell` on `irc.freenode.net`; there are lots of people willing to help with difficult Haskell questions. This has been true for years and years. For example, it's hard to cajole the above kind of parser to rewind and recover thrown away information, so Bryan asked about this, and one well-known user suggested passing around integers as state instead. This is vastly easier, and allows one to write a function that takes a parser of any type to the number of bytes it's read.

Nontheless, most of these don't work when the grammar is ambiguous. For example, `string "foo" <|> string "foobar"` will not do what one expects on input on `"foobarbaz"`. But these can be detected by analyzing the abstract syntax tree form of the parser, which is a great use of applicative functors (not monads; they mess stuff up)!

12. Untrusted Code and Information Flow Control: 5/8/14

These subjects are what got Professor Mazières into Haskell in the first place.

Suppose one wants to incorporate untrusted code into a Haskell application, e.g. one wants to translate a webpage into Pig Latin. On Hackage, there might be some code with the function `toPigLatin :: L.ByteString -> L.BuyteString`. This sounds good, but what if it contains `unsafePerformIO` calls that can do whatever they want?

Starting with GHC 7.2, the `-Xsafe` flag enables Safe Haskell, which disallows the import of any unsafe modules (e.g. `System.IO.Unsafe`, so there's no `unsafePerformIO`); this is courtesy of the course TA, David Terei! There are also safe imports, via `import safe PigLatin (toPigLatin)`, which is enabled by `-XUnsafe`, and should guarantee that toPigLatin doesn't contain unsafe functions. But it's turtles all the way down, so to speak: toPigLatin uses ByteString, which deep down in the call chain uses unsafePerformIO and other unsafe functions.

There's another notion of safety: -XSafe means the compiler promises that it is safe, but -XTrustworthy is a flag that means that the author asserts that the module is safe (even if it contains unsafe code) — then, a module such as Data.ByteString, compiled with this flag, puts its unsafe operations in an inner module Data.ByteString.Unsafe. This bounces back to whether we trust the author of the package, but one can specify trustworthiness on a per-package basis, e.g. with -fpackage-trust, -trust, -distrust, and -distrust-all-packages. But if you don't trust the author and the compiler verifies it, then that's fine.

But what if the untrusted ode needs to do actual IO? For example, actual translation needs to at least read files and (for example) also query Google Translate. The idea here is to use a restricted IO monad, the RIO monad. This creates type signatures such as googleTranslate :: Language -> L.ByteString -> RIO L.ByteString; then, we can make RIO functions with the same names as the IO monad which make this work. Here's a hypothetical example.

```
{-# LANGUAGE Trustworthy #-}
module RIO (RIO(), runRIO, RIO.readFile) where

-- Notice that UnsafeRIO isn't exported from the module.
-- Moreover, this is a compile-time construct -- there is no
-- incurred runtime cost!
newtype RIO a = UnsafeRIO (IO a)
runRIO :: RIO a -> IO a
runRIO (unsafeRIO io) = io

-- Exposing RunRIO is also pretty bad, as you might imagine

-- this is really just IO, but with the right constructors.
-- unsafeRIO is the lift IO a -> RIO a
instance Monad RIO where
    return = UnsafeRIO . return
    m >>= k = UnsafeRIO $ runRIO m >>= runRIO k
    fail = unsafeIO . fail

-- Returns true iff access is allowed to the file ame
pathOK :: FilePath -> IO Bool
-- e.g. only allow files in /tmp

readFile :: FilePath -> RIO String
readFile file = UnsafeRIO $ do
    ok <- pathOK File
    if ok then Prelude.readFile file else return ""
```

Using this sort of monad, one can force a program to only read and write files in some sandbox subdirectory, forbid execution of other programs, only allow connections to certain ports or servers, disallow access to devices, etc. There are similar policies enforced in java and JavaScript, albeit less clearly.

But this isn't quite enough: one could make a googleTranslate function that is allowed to talk to Google Translate to translate email, and thus can store the logged email data in a temp file — and then email that temp file to an attacker. Thus, it's important to keep track of which information is sensitive and where it goes.

The solution is something called Decentralized Information Flow Control (DIFC). Information Flow Control originated with military applications and classified data: every piece of data and thread (or process) has a label, and there's a partial order $\sqsubseteq$ ("can flow to") where $L_E \sqsubseteq L_F$ if L_F can access L_E. But $\sqsubseteq$ is transitive, so to prevent a file from being released to the Internet, one could set its label $L_E \not\sqsubseteq L_{\text{net}}$, and buggy software that can access the file can't push it to the Internet, because that would violate the transitivity. Sometimes, $L_\emptyset$ denotes public data, and if L_A and L_B are the things accessible by two users A and B, then $L_{AB} = L \sqcup L_B$ is the least upper bound in the lattice given by $\sqsubseteq$: the things accessible by both users A and B.

$$\begin{tikzcd}
 & L_{AB} & \\
L_A \arrow[ur, "\sqsubseteq"] & & L_B \arrow[ul, "\sqsupseteq"'] \\
 & L_\emptyset \arrow[ul, "\sqsupseteq"'] \arrow[ur, "\sqsubseteq"] &
\end{tikzcd}$$

The decentralization means that every process has a set p of privileges, and exervising privilege p changes the label requirements. There's a more permissive partial ordering $\sqsubseteq_p$. Thus, one can collapse the lattice above for two users A and B by reasoning about their combined privileges.

One way to do this in Haskell (not the only way) is to encode a lattice in Haskell's type system. There will be a type H for secret data and L for public data.

```
-- define types H and L, and MkSec to wrap things in them

class Flows sl sh where
Flows H H
FLows H L
FLows L H
-- but not Flows H L!
```

Then, e introduce a Sec monad for each data type, where anyone can label a value, but privilege is needed to unlabel.

```
newtype Sec s a = MSec a

instance Monad (Sec s) where
    return x = MkSec x
    MkSec a >>= k = k a

label :: a -> Sec s a
label x = MkSec x

unlabel :: Sec s a -> s -> a
unlabel (MkSec a) s = s ‘seq‘ a -- (s is either H or L, and acts as a key)

-- can define relabel similarly
```

Now, untrusted code gets access to senstiive data only within Sec monads. For example, one might allow Sec H to only be sent to Google, but Sec L be sent over the network in general. Then, the implementation is provided by spexfic functions, using privilege and unlabel. But this is a bit too overpowered: the data itself shouldn't be necessary to make a decision about its security.

Thus, one combines this with RIO to create a SecIO monad that has resticted access and the privilege system. First, we need some utility functions:

```
-- allows a Sec value to be accessed within the Sec monad
value :: Sec s a -> SecIO s a
value sa = MkSecIO (return sa)

-- can return high values from SecIO L by wrapping in Sec
plug :: Less sl sh => SecIO sh a -> SecIO sl (Sec sh a)

-- includes security type
type File s = SecFilePath String

-- checks that the reading and writing is OK
readFileSecIO :: File s -> SecIO s' (Sec s String)
writeFileSecIO :: File s -> String -> SecIO String
```

This is good, and now the untrusted function has type untrustedTranslate :: Sec H L.ByteString -> SecIO H L.ByteString, which has the correct restrictions. But this is static: we might want to update the lattice dynamically each time a user is added, but since it doesn't exist at runtime, this needs to be done differently.

Thus, let's do it dynamically, at runtime, using a LIO monad. This associates a LIOState to every thread, and also tracks the maximum label (clearance).

```
{-# LANGUAGE Unsafe #-}

data LIOState l = LIOState { lioLabel, lioCLearance :: !l}
newtype LIO l a = LIOTCB (IORef (LioState l) -> IO a)

instance Monad (LIO l) where
    -- usual implementation

-- Now, we want some functions that execute trustworthy code.
-- akin to liftIO, but safer
ioTCB :: IO a -> LIO l a
ioTCB = LIOTCB . const

-- also some functions for getting and setting state
```

```
getLIOStateTCB :: LIO l (LIOState l)
getLIOStateTCB = LIOTCB readIORef -- and so on
```

Now, implementing labels is not hard:

```
Module LIO.Label

clas (Eq l, Show l, Read l, Typeable l) => Label l where
    lub :: l -> l -> l
    glb :: l -> l -> l
    infixl 5 `lub` `glb`
    canFlowTo :: l -> l -> Bool
    infix 4 `canFlowTo`
```

For priveleges, we want to know if one subsumes another.

```
class (Typeable p, Show p) => SpeaksFor p where
    speaksFor :: p -> p -> Bool
```

Then, we can implement CanFlowTo and so on. For example, suppose we have a lattice with the following definitions and priveleges.

```
data Level = Public | Secret | TopSecret -- it turns out this is deriving Ord
data Compartment = Nuclear | Crypto
data MilLabel = MilLabel { level :: Level
                         , compartments :: Set Compartment
                         }

instance Label MilLabel where
    lub a b = MilLabel (max (level a) (level b))
                       (Set.union (compartments a) (compartments b))
    glb a b = MilLabel (min (level a) (level b))
                       (Set.intersection (compartments a) (compartments b))
    canFlowTo a b = level a <= level b
                  && compartments a `Set.isSubsetOf` compartments b
```

Now, before reading and writing, one should check and possibly adjust the LIOState, checking if the data can flow to the user in question (and also vice versa for writing).

Though this isn't super easy, it's much, much easier than the corresponding code on the OS level.

For priveleges, we want to be able to talk about them in any context, so we'll use them by wrapping them in a newtype.

```
class (Label l, SpeaksFor p) => PrivDesc l p where -- ... can downgrade data if has the right
    clearance, etc.

newtype Priv a = PrivTCB a deriving (Show, Eq, Typeable)

instance Monoid p => Monoid (Priv p) where
    mempty = PrivTCB mempty
    mappend (ProvTCB m1) (ProvTCB m2) = PrivTCB (m1 `mappend` m2)

privDesc :: priv a -> a
privDesc (PRivTCB a) = a
-- we can go from a privelege to a privDesc, but not vice versa.
```

But how should they be created in the first place? main runs unrestricted IO, so it can initialize priveleges.

Most LIO functions have variants requiring privelege that take a P suffix, which then call internal privelege-checking functions. But privileges can also be delegated, etc.:

```
delegate :: SpeaksFor p => Priv p -> p -> Priv p

newtype Gate p a = GateTCB (p -> a) deriving Typeable

gate :: (p -> a) -> Gate p a
gate = GateTCB -- not exported

callGate :: Gate p a -> Priv p -> a
callGate (GateTCB g) = g . privDesc
```

Here, a gate is a wrapper around a function that allows things to work even in the case of mutual distrust.

Now, there are lots of functions we might want to use that need to be rewritten just slightly, which can be simplified via a `blessTCB` helper, through the magic of functional dependencies.

```
data LObj label object = LObjTCB !label !object deriving Typeable
-- actually in LIO.TCB.LObj
```

Ine of the main applications is a web framework called `Hails`, which works via multiple applications that might distrust each other. Communications are via policy models that make this security work. Another example is `GitStar`, which can host potentially private git repositories, and then, for example, call functions like a syntax-highlighting library without giving it access to copy the sources.

13. Zippers and Lenses: 5/13/14

"Sounding very clever is obviously one of the most important parts of learning Haskell."

Today we will talk about Haskell programs that don't go wrong for a bit: no infinite loops and crashes, there are exactly two values of type `Bool`, and three different values of type `Ordering`, `LT`, `EQ`, and `GT`. In Haskell 2010, there are even types with no constructors (for phantom types or type-level programming).

Consider the type `data NextType = A Bool | B Ordering`. This can have five possible values, and `Either a b` does the same thing (the sum of the number of values for `a` and `b`); thus, types such as this, with an `|`, are called sum types. Similarly, tuples are called product types, becaue one obtains the product of the individual numbers of values of the types. These are called algebraic data types, in that they are really doing algebra.

But they're also useful for applications; for example, the `criterion` package for profiling has many nested types upon nested types, and then the record accession types interact nicely with function composition to make data access easy. But updating is ugly, since each explicit nest must be dealt with. Thus, we want to access fields within records, both for accessing and editing, such that both accesses and updates are composable. Haskell's record syntax already handles $2\frac{1}{2}$ of them, but that's not enough.

Let's start from fairly simple building blocks, the tuple `(a,b)`. To edit its second or first elements, one can write functions like these.

```
editSnd :: (b -> c) -> (a,b) -> (a,c)
editSnd f (a,b) = (a, f b)

--editFst is the same
editFst :: (a -> c) -> (a,b) -> (c,b)
editFst f (a,b) = (f a, b)
```

In this idea, we *focus* on either the first or the second element.

We can count the number of possible values, representing dropping a field from a product type:

```
data Hole3 a b c = AHole b c
                 | BHole a c
                 | CHole a b
```

Substitute in `(x,x,x)`, which has x^3 possible values; then, the type `Hole3 x x x` has $3x^2$ different values... which is a derivative. This is not a coincidence; it also happens with other parameterized types.

Returning to 2-tuples, here's a hole type.

```
data PairHole a b = HoleFst b
                  | HoleSnd a

-- c is one of a or b
data PairZipper a b c = PZ c (PairHole a b)

-- Now, we have shinier implementations of focusFst and focusSnd
-- given the types, these are the only implementations that could possibly work.
focusFst :: (a,b) -> PairZipper a b a
focusFst (a,b) = PZ a (HoleFst b)

focusSnd :: (a,b) -> PairZipper a b b
focusSnd (a,b) = PZ a (HoleSnd a)
```

These types of functions are called zippers. The fact that the polymorphism forces there to be only one implementation is really nice.

Obviously, we need to be able to go the other way.

```
unfocusFst :: PairZipper a b a -> (a,b)
unFocusFst PZ a (HoleFst b) = (a,b)

-- now, getting the value we focused on
view :: PairZipper a b c -> c
view PZ c _ = c

-- this is the more fun part!
over :: (c -> c) -> PairZipper a b c -> PairZipper a b c
over f (PZ c l) = PZ (f c) l
```

Now, editing a record is as natural as `unfocusSnd . over (+1) . focusSnd`. This is pretty cool, but right now it only works on functions that return the same type as their arguments. This can be remedied by fiddling with the type signatures, but this quickly becomes ugly.

Let's instead wrap everything up in one type:

```
data Focused t a b = Focused {
    focused :: a
  , rebuild :: b -> t
}\end{lstlisitng}
This is a pair consisting of a focused element and a function that knows how to reconstitute the
    original value.
\begin{lstlisting}
type Focuser s t a b = s -> Focused t a b
```

Typically, the author of a library writes the function, and its user only needs to understand its type signature. Here, `s` and `t` might be the same, as might `a` and `b`, depending on whether editing changes the type. A `Focuser` is a function that takes a value and returns a `Focused`.

Now, some more machinery for working with these types.

```
unfocus :: Focused s a a -> s
unfocus (Focused focused rebuild) = rebuild focused

view :: Focuser s t a b -> s -> a
view l s - focused (l s)

over :: Focuser s t a b -> (a -> b) -> s -> t
over l f s = let Focused focused rebuild = l s
             in rebuild (f focused)

-- how we recast focusFst and focusSnd, with simpler names
_1 :: Focuser (a,b) (c,b) a c
_1 (a,b) = Focused a (\c -> (c,b))

_2 :: Focuser (a,b) (a,c) b c
_2 (a,b) = Focused b (\c -> (a,c))
```

Notice that if `a` and `b` are the same, then so are `s` and `t`.

Now, one can implement a relatively concrete example.

```
focusHead :: Focuser [a] [a] a a
focusHead (a:as) = Focused a (:as)
```

The `(:as)` syntax defines a function `\c -> (c:as)`, which is nice.

`over` and `view` have very similar types and implementations. One could abstract they via types.

```
wat :: Focuser s t a b -> (a -> f b) -> s -> f t
```

This assumes the function `f` is a type-level function; if the type-level identity function is passed in, then the type of `over` appears; if one uses `const a` instead, the type of `view` is obtained.

It turns out the type-level identity function does exist, and is defined in `Data.Functor.Identity`. There's also a type-level constant function in `Control.Applicative`.

```
newtype Identity a = Identity { runIdentity :: a }

instance Functor Identity a where -- and so on

newtype Const a b = Const { getConst :: a }
```

```haskell
instance Functor Const a b where
    fmap _ (Const v) = Const v
```

Now we can introduce the abstracted type, called the `lens` type.

```haskell
{-# LANGUAGE RankNTypes #-}

type Lens s t a b = forall f. Functor f =>
                    (a -> f b) -> s -> f t

over :: lens s t a b -> (a -> b) -> s -> t
over l f s = runIdentity (l (Identity . f) s)

view :: lens s t a b -> s -> a
view l s = getConst (l Const s)
```

This says that, given an `s`, this will focus on elements of type `a`. Using `over` to edit changes these types to `b`, and once editing is done, one gets back `t`, which might just be `s`.

Notice how powerful the type-checker is: it doesn't just prevent errors, but defines how the program ought to work. And since `newtype` is only a compile-time construct, then there's no incurred cost.

A language extension called `{-# LANGUAGE TupleSections #-}` makes the function `(a,)` equivalent to `\b -> (a,b)`, which is notationally convenient, as in the following examples.

```haskell
{-# LANGUAGE TupleSections #-}

_1 :: Lens (a,b) (c,b) a c
_1 f (a,b) = (,b) <$> f a

_2 :: Lens (a,b) (a,c) b c
_2 f (a,b) = (a,) <$> f b

-- Same idea works with _head, for the head of a list.
```

The applicative syntax means that we're using a functor, but we don't know which it is (the identity or the const functor).

A lens takes an action on a part of a structure into an action on the whole structure. Thus, it's much easier to compose them together, and `view` and `over` correspond to getters and setters. Thus, this is somewhat like function composition, but very different than naïve getter and setter code.

Lenses are the first and most useful approach to composing editing of deeply nested structures (also first-class labels, semantic editor combinators, etc., which are subsumed by lenses). Thus, they show up more and more in real-world code, to make the API easy to work with and easy to use. It looks and is abstract, but is very useful.

There are a few different packages: `lens-family-core` is simpler and easier to use, and `lens` is incredibly comprehensive, abstract, powerful, and confusing. It contains anything you might ever want to use, and many, many things you won't. `lens` is a bit controversial because it's so big and hard to understand.

These libraries use some operators with different notation (specifically, they remind me of Perl). The getter or `view` is called `^.`, and `over`, the editor, is `%~`, called "wiggly fish thing." Then, `.~`, another fish, is a setter: it acepts a value instead of a function. Finally, `&` is just `$` with the arguments flipped.[6] Thus, things can be composed with `foo & someField %~ ('a':) & otherField .~ 'b'`. These take some getting used to, but after that it's all fine.

14. Web Programming: 5/15/14

"The methodology for this is: I found the graphic that made my point the best."

Today's lecture was given by Amit Levy, a Stanford CS Ph.D. student. The goal is to think about web development and how and why one would do it in Haskell.

Web programming is obviously pretty useful these days, and even if one starts out by building something that doesn't seem like a web-based application, it often might end up on the web anyways. And even discounting this, HTTP is becoming a general-purpose protocol for APIs, available in most languages and good server-side support (frameworks, SSL, virtual domains, ease of convincing the boss or whatever that it should be used).

There are lots and lots of frameworks for web applications. It used to be that Java was king, and Sun indeed pioneered the idea of web apps. But a lot of people didn't like it; it was in many ways a bad language. It's still in use, but not as trendy, falling out of favor towards Ruby on Rails (or Sinatra), Django with Python, server-side Javascript, PHP, etc.; in fact, PHP is be far the most common language in use today.

These newer languages are all dynamic. Why is this? First, they tend to be less verbose (e.g. this Ruby code):

[6] There is a bitwise and operator, but it's surrounded by dots.

```
x = 123

def incr(y)
    y + 1
end
```

Compare to the equivalent (and much longer) Java code:

```
protected static int x = 123;

public static int incr(int y) {
    return y + 1;
}
```

There are often other nice features such as closures (though Java 8 has them now!), or fast development and prototyping, and so on. People also believe that dynamic languages are really good for dynamic content (whereas something such as Scala is better for the more static backend). This is... pretty handwavy, but the idea is that typechecking lots of dynamic content is a pain.

A lot of these arguments, are just arguments against Java. For example, Haskell has strong types but optional type declarations (in many cases), and has closures.

In general, a web application does three things:

(1) parses a request from the client,
(2) performs some side-effect actions (e.g. reading from a database), and
(3) gnerates a response for the client.

For example, given a request (which in Haskell is modeled as some struct type) and a response type, then an application is just of type `type Application = Request -> IO Response`. This is the essence of the WAI (Web Application Interface) package. This is a common interface between servers and applications, with the goal of being able to mix and match, such as the several Haskell-based servers and frameworks (e.g. Yesod, Hails, Scotty).

The actual base types are a little but complicated. They just correspond to all of the fields in an HTTP request or an HTTP response.

```
data Request = Request {
     requestMethod      :: Method
  ,  httpVersion        :: HttpVersion
  ,  rawPathInfo        :: ByteString
  ,  rawQueryString     :: ByteString
  ,  requestHeaders     :: RequestHeaders
  ,  isSecure           :: Bool
  ,  remoteHost         :: SockAddr
-- the server pre-parses the path information and the query into directories
  ,  pathInfo           :: [Text]
  ,  queryString        :: Query -- list of tuples: foo = bar => (foo, bar)
  ,  requestBody        :: Source IO ByteString
  ,  vault              :: Vault
  ,  requestBodyLength  :: RequestBodyLength
  ,  requestHeaderHost  :: Maybe B.ByteString
  ,  requestHeaderRange :: Maybe B.ByteString
  }

-- status is the HTTP status, akin to the return value of a Unix process.
data Response
    = ResponseFile Status ResponseHeaders FilePath (Maybe FilePart) -- sends a static file
    | ResponseBuilder Status ResponseHeaders Builder                -- builds a dynamic file
    | ResponseSource Status ResponseHeaders (forall b. WithSource IO (C.Flush Builder) b)
    | ResponseRaw (forall b. WithRawApp b) Response

type Application = Request -> IO Response
```

For example, here's a very basic app.

```
-- Note: need to call 'cabal install wai warp' to make this work

module Main where

-- Can be simplified by using the OverloadedStrings language extension... but same end result.
import qualified Data.ByteString.Lazy.Char8 as L8
import Network.HTTP.Types
import Network.Wai
import Network.Wai.Handler.Warp (run)

app :: Application
--                 responseLBS uses the response constructor to make a byte string
--                 arguments: status, any arguments, data
app req = return $ responseLBS status200 [] $ L8.pack "Hello, World"

main :: IO ()
main = run 3000 app
```

This is pretty concic compared to other web apps. Even Rails requires lots and lots of files to make things work.

Simple is a web framework with a single `Controller` type, which looks like the `Application` type from above. In fact, it's a small wrapper.

```
newtype Controller s a = Controller {
  -- the Either means to either return and send the response to the client, or continue running
  -- similar to monad transformers StateT and ReaderT
  runController :: s -> Request -> IO (Either Response a, s)
  }

-- These mean it's easier to refer to the controller in different contexts
instance Monad Controller
instance Applicative Controller
instance MonadIO Controller
```

Then, there are a bunch of combinators to make life easier.

```
-- Stop computing and respond to a request.
respond :: Response -> Controller s a
okHtml :: ByteString -> Response
notFound :: Response

-- e.g. respond (okHtml "Hello world")

-- Get the request state and app state
request :: Controller s Request
controllerState :: Controller s s

-- Parse query and form parameters. Return strings or stringlike things (e.g. ByteString)
queryParam' :: Parseable p => Controller s p
parseForm :: Controller s ([Param], (ByteString, FileInfo ByteString))
```

Then, there are also a bunch of routing combinators, which make it easier to do common tasks. Routing is how different types of functions or pieces of code respond to different kinds of code. Thus, there are a bunch of functions to match on patterns and then respond accordingly. Each takes a sub-controller as an argument, which is what gets run if the match succeeds; thus, it's possible to nest these combinators to make more complicated routers.

```
-- Match on next dir in path
routeName :: Text -> Controller s () -> Controller s ()
routeName "articles" $ ...

-- Treat first dir in path as query param
routeVar :: Text -> Controller s () -> Controller s ()
routeName "articles" $ routeVar "name" $ ...

-- Match whole pattern of path
routePattern :: Text -> Controller s () -> Controller s ()
routePattern "/articles/:name" $ ...

-- Match if no path left
routeTop :: Controller s () -> Controller s ()

-- Match on request method
routeMethod :: Method -> Controller s () -> Controller s ()
-- example of nesting.
routeMethod GET (routePattern "/articles/:name")
```

```
-- Match hostname
routeHost :: ByteString -> Controller s () -> Controller s ()
```

And of course, there are things built on top of those.

```
get :: Text -> Controller s () -> Controller s ()
get ptrn ctrl = routeMethod GET $ routePattern ptrn ctrl

post :: Text -> Controller s () -> Controller s ()
post ptrn ctrl = routeMethod POST $ routePattern ptrn ctrl

-- Example of small application.
--  base directory responds with "Hello World"
--  /foo responds with "bar"
myapp :: Controller s ()
myapp = do
  get "/" $ respond $ okHtml "Hello World"
  get "/foo" $ respond $ okHtml "bar"
```

The next thing one might want to use is an object relational mapper (ORM). There's a PostgreSQL ORM (for a specific open-source variety of SQL), which correspond to types with some kind of key, a DBKey type and some data. For example:

```
data Article = Article
  { articleId :: DBKey
  , articleTitle :: Text
  , articleBody :: Text
  , articleShortName :: Text }

class Model a where
  modelInfo :: ModelInfo a
  modelRead :: RowParser a
  modelWrite :: a -> [Action]

data DBKey = DBKey !Int64 | NullKey

data ModelInfo a = ModelInfo {
    modelTable :: ByteString
  , modelColumns :: [ByteString]
  , modelPrimaryColumn :: Int
  , modelGetPrimaryKey :: a -> DBKey }
```

One way to reduce the amount of boilerplate is to make a model derive from Generic.

```
{-# LANGUAGE DeriveGeneric #-}
import GHC.Generics

data Article = Article
  { articleId :: DBKey
  , articleTitle :: Text
  , articleBody :: Text
  , articleShortName :: Text } deriving (Show, Generic)

instance Model Article
```

This provides access to three functions, which save, search, and retrieve entries in the database.

```
-- save a row to the database
save :: Model a => Connection -> a -> IO ()
-- find all rows matching the constraint
-- not lazy! There is a lazy findAll function in the library, though
findAll :: Model a => Connection -> IO [a]
-- retrieve the values for a given key
findRow :: Model a => Connection -> DBRef a -> IO (Maybe a)
```

Because Haskell is strongly typed, some commone dge cases are already irrelevant: fields can't be null, unless they have a Maybe, and fields have their known, strict types. This makes a lot of validation redundant.

One can initialize an app via the command-line command `smpl create --templates --postgresql my_cms` (which initializes a database, etc.). Then, the main function is in one file, and the run function for the application lives in another.

A content management system (CMS) is a method of, for example, generating pages with a form, and having a central homepage which lists all of the other pages. This can be done by initializing a database within Haskell with the `create_table` call. This all looks pretty cool, but involves installing software that doesn't work on many kinds of computers (e.g. my own, running Mac OS 10.6.8), so some amount of confusion has to be overcome before any of this can happen. So, uh, here's some more code, I guess.

```
{-# LANGUAGE OverloadedStrings #-}
module Application where

import Control.Monad.IO.Class -- for liftIO
import MyCms.Common
import Web.Simple
import Web.Simple.Templates

-- for putting articles in a database
data Article = Article {
    articleID :: DBKey
  , articleTitle :: String
  , articleBody :: String
  } deriving (Generic)

instance Model Article where
    -- separates words by underscores to get some string for it.
    -- some complications for backwards compatibility
    modelInfo - underscoreModelInfo "article"

app :: (Application -> IO ()) -> IO ()
app runner = do
    setitngs <- neeAppSettings

    runner $ controllerApp settings $ do
        routeTop $ do
            articles <- withConnection $ \conn -> liftIO (findAll conn :: IO [Article])
            render "index.html" ()
        -- Then: routes go here.
```

15. Performance: 5/20/14

"When I got started in Haskell a while ago, it was a miracle when a program worked at all."

Nowadays, though, we can make our code go very fast, and it feels sad when it can't. There are two perennial questions: why does my program take so long, and why does it take up so much memory? This is particularly tricky in Haskell because of lazy evaluation.

The standard benchmarking library for Haskell is `criterion`, written by Bryan O'Sullivan, as follows.

```
import Criterion.Main -- via 'cabal install criterion'

len :: [a] -> Int
len (x:xs) = 1 + len xs
len _      = 0

main = defaultMain [bench "len" (whnf len [1..100000]) ]
```

The naming might be nonintuitive, but the idea is that the benchmark is named `"len"`, and is of function `len` of the input `[1..100000]`.

The thing being benchmarked is the `whnf`, which indicates the time taken to reduce the function and argument to weak head normal form (WHNF) (there's also `nf`, which reduces it to the related normal form). The idea here is that, since Haskell is lazily evaluated, a function such as `len` can return a thunk rather than the result, so the normal form is a way of specifying that it should be strictly evaluated. For example, the internal representation after using `seq` forces evaluation. This is what allows things like infinite lists to work: the representation never fully evaluates (or else...). Importing `Control.Deepseq` allows for full evaluation (don't do this on infinite lists), and this corresponds to normal form (rather than weak-head normal form). One can look into the internal representation and see "black holes" which forward things to the final object, and are cleaned up by the garbage collector. Try installing `ghc-heap-view` to see this (which requires some magic). Here, we use weak-head normal form, because there's only one constructor for `Int`. Note that weak-head normal form won't go into infinite loops, but `nf` can.

Anyways, the criterion libeary provides both kinds of forms, and provides lots of nice information. In addition to the times tkane to run the function, it also estimates the clock resolution, error, and time cost of a clock call in order to estimate the variance and the number of times it needs to run a benchmark in order to get a reasonable answer. It also estimates variance due to noise (which can come from a huge number of sources, from background programs to Dwarf Fortress to strange decisions made on Macs, such as the desktop updating live previews every time an item is changed). Thus, the library reports how much of the standard deviation and variance are due to noise. This can be reduced, but not eliminated.

Another interesting way to do this is to dump a report as an HTML file, with lots of sleek pictures and Javascript!

There are two other ways to run a benchmark, whnfIO and nfIO, which accept an IO action, run it, and then return the result.

Now, let's talk about space complexity. This requires using the ghc flag -rtsopts, which is off by default because it can cause security leaks. This allows criterion to provide information about space complexity (total memory used, peak used, stats about the garbage collector).

One interesting fact about Haskell's garbage collector is that many of the objects on the heap die really quickly, and others last a long time (which is true of many programming languages), so things are by default placed in one sector of the heap, called Gen 0 or the nursery, because they're expected to die soon (which is a really morbid extended metaphor!); then, as it persists (so if it's not collected), it is moved to Gen 1, which is scanned less often. Once again, it's possible to get more interesting heap data and pretty-print it to postscript files.

Of course, if you try to benchmark len with twenty million elements, it runs out of stack space quickly, which I guess is a crude form of profiling. It indicates something is horribly wrong with a length program... in the very least, it should be possible to run it in not very much space.

Thanks to lazy evaluation, this apears in memory as a giant sum $1 + 1 + \cdots$, and is evaluated by the stack. Ouch. Notice that this isn't lazy evalaution: the same code written in ML or Python or C would have the same problem. Thus, maybe the following code is better.

```
len2 xs = go 0 xs
    where go n (x:xs) = go (n+1) xs
          go n []     = n
```

This seems a bit faster than len, and uses no stack allocation, which is another improvement. Can we do better? It's possible that the strictness analyzer, which lives in ghc-land, tries to discover whether a recursive function's result is only used for the last result, and optimize accordingly. When this is turned off (-O0), there's a much more interesting profile: there are lots of thunks, and a reasonable amount of stack allocation. But then, using seq, it's possible to make the program take less space (but still a lot). However, looking into the GHC summary statistics, 80% of the time is spent garbage collecting unless seq is used. That isn't good.

One good way to understand the code that is being benchmarked is to look at the intermediate representation, a language called Core. Think of this as Haskell without the syntactic sugar. One can access the IR by calling ghc -c -ddump-simpl Length.hs. This is harder to read, of course, but is lower-level and corresponds much more to what the program actually does. For example, + becomes GHC.Num.+ # GHC.Types.Int (i.e. instantiated to the Int type), and so on. But relatively little needs to be understood, and it's also true that relatively little of it is actually hard to understand. Another name for Core is System FC (which comes up in papers and the GHC wiki). Core is then transformed into another intermediate language, to which several optimizations are applied.

In System FC, all evaluation is controlled via the case expression, which demands things to be evaluated to WHNF.

```
--Haskell
foo (Bar a b) = {- ... -}
-- Core
foo wa = case wa of _ { Bar a b -> {- ... -} }
```

It's a very common mode of failure fore new Haskell programmers to ignore this simplified code and instead use strictness (bang patterns, seq, and DeepSeq) everywhere, which is not necessarily all that useful. Instead, it's better to think about what is actually going on.

One common theme is that linked-lists are not all that efficient space-wise (and time-wise), but it's the default for lists. This is an artifact of early Haskell, when people were surprised at all that it was possible to get a lazy program to run efficiently. Thus, for text applications it may be nicer to use Data.ByteString: often, there's a 10- to 50-times speedup. However, this is bad for internationalization, so there's a PackedText type for Unicode code points, and a Vector type up on Hackage which supports packed types (and is good for mathematical work). These aren't the final word either, because huge files don't work well for strict types... thus, each of these comes with a lazy variant. But provided that the cost of dealing with an item in a list is more than the cost of traversing the list, Haskell lists are better — the answer in general is "it depends."

16. A Haskell Compiler: 5/22/14

Today's lecture was given by David Terei, the TA.

Today's class will provide a way of understanding of how the higher-level constructs in Haskell boil down to actual machine code. The basic pipeline is Haskell → GHC Haskell (i.e. raw Integers, unsafePerformIO, and so on) → an internediate representation called Core (a small functional language), to another small functional language called STG, through an imperative language called Cmm or C-- (which is basically a pretty-printer for assembly, sort of like LLVM but less popular), to assembly.

One of the first things GHC does is support Haskell on top of an unsafe variant called GHC Haskell, which has primitive types such as Int#, Array#, TVar#, states, exceptions, and such. These live in GHC.Prim, and offer higher performance but are unsafe. This is a nice way to implement Haskell. All variants of Int are represented internally by an Int#.

```haskell
data Int32 = I32# Int# deriving (Eq, Ord, Typeable)

instance Num Int32 where -- ...
```

Thus, using Int8 to save space isn't actually saving space, at least right now.

For I/O, it's a state-passing monad.

```haskell
newtype IO a = IO (State# RealWorld -> (# State# RealWorld, a #))

returnIO :: a -> IO a
returnIO x = IO $ \s -> (# s, x #)

bindIO :: IO a -> (a -> IO b) -> IO b
bindIO (IO m) k = IO $ \ s -> case m s of (# new_s, a #) -> unIO (k a)
```

The RealWorld token is passed throughout to ensure that the actions are ordered in the way one would want for I/O. In some sense, I/O is really a bunch of transformations on the world! The RealWorld token is only a compile-time construct, and goes away in the assembly code.

To write commands such as unsafePerformIO, one simply throws away the RealWorld token, and then can more or les do what it wants.

The next step in the pipeline is Core, a small functional, lazy language. It has only variables, literals, let, case, lambdas, and one other idea, and it has a very small grammar. Everything else in Haskell boils down to this. Then, the majority of the optimizations are performed on core.

```haskell
-- Haskell
id :: a -> a
id x = x

idChar :: Char -> Char
idChar = id

-- Core
id :: forall a. a -> a
id = \ (@ a) (x :: a) -> x

idChar :: GHC.Types.Char -> GHC.Typs.Char
idChar = id @ GHC.Types.Char
```

Then, where statements become let statements, pattern matching becomes case statements, and typeclasses become data structures, akin to dictionaries.

```haskell
-- Haskell
typeclass MyEnum a where
    toId :: a -> Int
    fromId :: Int -> a

-- Core
data MyEnum a = DMyEnum (a -> Int) (Int -> a)

-- basically, we're passing around the MyEnum dictionary
toId :: forall a. MyEnum a => a -> GhC.Types.Int
toId = \ (@ a) (d :: MyEnum a) (x :: a) ->
    case d of _
        DMyEnum f1 _ -> f1 x
```

```
-- and then fromId
```

Sometimes, one has to life one dictionary to another, e.g. if one wants to use `Maybe`. The code that gets generated takes in the type parameter `@ a` and a dictionary `MyEnum a`.

The `{-#UNPACK#-}` pragma makes Core store the raw types, which leads to better performance, because then data structures operate on diect integers, rather than pointers to them. For example, consider an unpacked `Point` type with two coordinates. Then:

```
-- Haskell
addP :: P -> Int
addP (P x y) = x + y

-- Core: more efficient than if the points weren't unboxed
addP :: P -> Int
addP = \ (p :: P) ->
    case p of _ {
        P x y -> case +# x y of z {
            __DEFAULT -> I# z
        }
    }
```

However, this is only usually a good idea. Sometimes it isn't, so it's necessary to be mindful of the places where it will be a performance loss. For example, if the function is inherited from some polymorphic type, bad stuff happens.

```
module M where

{-# NOINLINE add #-}
add x y = x + y

module P where

addP P x y = add x y
```

In Core, this forces the code to unbox the points, then box them again. Core is a great tool to see how fast one's code performs; all evaluation is via `case` statements.

Now, many of Haskell's optimizations are done as Core-to-Core transformations. For example, functional languages gain a huge boost from inlining (perhaps about twice as much as imperative languages). A naïve implementation of the factorial function leads to lots of thunk allocating and dereferencing pointers and such, but the compiler can reason that the machine-level operations will be ok (unless it's `undefined`, which throws an exception). Thus, it's possible to unbox the `Int`s in the function, which makes the Core code look much more imperative and efficient. However, the original function is still kept so as to preserve the same interface.

Another big optimization is something known as SpecConstr. The idea here is to increase the amount of strictness in functions. For example, the following function isn't strict in its first argument.

```
drop :: Int -> [a] -> [a]
drop n []        = []
drop 0 xs        = xs
drop n (x:xs)    = drop (n-1) xs
```

Thus, `drop` ⊥ `[] = []`, but `drop` ⊥ `(x:xs) =` ⊥.

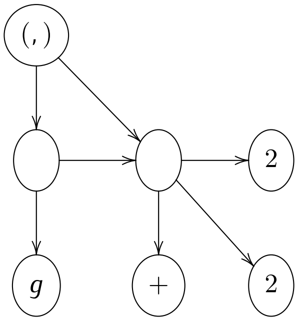
Thus, it compiles into the following code.

```
drop n xs = case xs of
    []     -> []
    (y:ys) -> case n of
        I# n# -> case n# of
            0 -> []
            -- without this optimization, more boxing and unboxing.
            _ -> drop' (n# -# 1#) xs

-- works faster with unboxed n
drop' n# xs = case xs of
    []       -> []
    (y:ys)   -> case n# of
        0#   -> []
        _    -> drop' (n# -# 1#) xs
```

This can cause an explosion in the code size, so GHC sets limits on what can be done.

After Core, GHC compiles to another languaged called STG. It's similar to Core, but laziness and allocation of thunks is very explicit. `case` is the only place evaluation occurs (like Core) but `let` is the only place allocation occurs. There's an idea called graph reduction, which is an interesting way to think and reason about how Haskell code is evaluated.



This is true for functional languages in general. The idea is that the leaves are evaluated, then the nodes that depend on them, and so on.

Haskell represents a lot of data as closures: a header and a payload, with a pointer to the code and metadata for the closure (largely used for the garbage collector). These are used for everything: even the value 10 is represented with a closure. For example, a `data` declaration has a header, then some pointers, then some non-pointers, depending on the structure of the type. Function closures have entry code equal to the function code. Closures also provide a nice framework for partial function application (one can store information about the arguments and the function they should be applied to). Finally, thunks are closures, which represents the data already computed (so that multiple users of the thunk don't have to recompute data).

The calling convention is to pass some arguments in registers (in 64-bit mode; in 32-bit mode, all arguments are passed on the stack) and then others on the stack. The register `R1` often stores the current closure in X86.

Thunks should update their node in a graph to be the computed value once they're evaluated; GHC uses a self-evaluationg model, where a thunk updates itself in the graph.

```
-- very simple thunk
mk :: Int -> Int
mk x = x + 1
```

Here's the code GHC generates for this.

```
// thunk entry - set up stack, evaluate x
mk_entry()
    entry:
        if (Sp - 24 < SpLim) goto gc; // need more space; ask the garbage collector

        I64[Sp - 16] = stg_upd_frame_info; // sets thunk to be updated
        i64[Sp - 8] = R1;

        I64[Sp - 24] = mk_exit // set up continuation

        Sp = Sp - 24;
        R1 = I64[R1 + 8]; // so that x is the only data in the closure
        jump I64[R1] (); // evaluate R1. Since it's a closure, everything can be evaluated.
        // maybe it's a thunk.

        gc: jump std_gc_enter_1 ();
}
// something analgous happens in the exit case
mk_exit()
    entry:
        Hp = Hp + 16;
        if (Hp > HpLim) goto gc;

        v::I64 = I64[R1] + 1;

        I64[Hp - 8] = GHC_TYpes_I_con_info; // set up an Int closure
        I64[Hp + 0] = v::I64;

        R1 = Hp;
        Sp = Sp + 8;
        // and so on: evaluate, and then the garbage collector.
```

The function `stg_upd_info` takes a thunk and replaces pointers to it with pointers to its value once it's been evaluated. This seems like quite a nice synchronization issue, and it seems like thunks should evaluate atomically, but in this case race conditions are OK, because all this does is cause duplication of work. Thunks evaluate deterministically, so this is OK, and the chance of a race occurring is pretty small anyways.

The thunk closure has a result slot, which is empty when it isn't yet evaluated. Then, the update code fills in the result slot, and then changes the pointer in an information table. This is safe in many, many architectures, because word-aligned writes are atomic, so there may be work duplicated, but there won't be any corruption.

In particular, since pointers have to be word-aligned, the last two (three on 64-bit architectures) must be zero, so they can be used to store extra information. Thus, GHC uses these bits at the end of a pointer to store information about what the pointer points to: if it's a constructur that has been evaluated, the tag contains the constructor number, and for a function, it provides the arity of the function. For unevaluated thunks, these are unaligned. The constructors are per type, so this is actually more efficient than one might imagine. This makes the C code above a little more complicated, but not terribly so.

Pointer tagging makes one's own data types more efficient: if the closure is a constructor, then a parameterized type `data MyBool a = MTrue a | MFalse a` is as efficient as using an `Int#` (that is, unboxed!) to represent `True` and `False`.

17. The GHC Runtime System: 5/27/14

Today's lecture was given by Edward Z. Yang!

Last time, we saw the chain from Haskell to Core to STG to C-- to assembly, but this doesn't actually create executable code; instead, there's a bunch of code compiled from C, called the runtime system, linked with every Haskell program. This is important for performance, allowing one to more easily answer questions such as the ones at `http://stackoverflow.com/questions/23462004/code-becomes-slower-as-more-boxed-arrays-are-allocated` and `http://www.quora.com/Computer-Programming/Why-are-Haskell-green-threads-more-efficient-performant-than-native-threads`.

Finally, there are many different runtime systems, most famously the JVM. These have a lot in common with those of Haskell, so learning about one leads to more information about the rest. But of course, runtime systems can be interesting in their own right.

There is a lot contained in Haskell's runtime system: a storage manager (garbage collector and block manager), a scheduler, a dynamic linker (so that object files can be loaded at runtime in GHCi), the STM implementation, profiling (both heap profiling and time profiling), and more. One could spend many hours talking about these; this lecture will focus on only the first two.

Garbage Collection. Recall that garbage collection allows programmers to allocate indefinitely and reclaim memory that is no longer in scope. One standard scheme is reference counting, which keeps track a number of pointers to each point in memory and deallocates something when its pointer count hits 0. However, this is time-intensive, and doesn't handle loops well. Nonetheless, this or variants of it are used by PHP, Perl, and Python. An alternative (more involved) is mark-and-sweep, which marks out objects that are accessible from objects in scope, and then sweeps the entire heap for unmarked memory and deallocates it. This is also pretty simple, and is used by Golang and Ruby. However, this algorithm causes fragmentation (swiss cheese memory, so to speak), which makes allocation more complicated. This can be mitigated by compacting the heap after sweeping, but there's another issue, which is that sweeping the entire heap takes quite some time.

This leads to a generational copying collector, used by GHC and the JVM. The generational hypothesis claims that most objects die young, which is reasonable in general and even more so in functional languages! This leads to a nicer algorithm.

First, consider the stop-and-copy algorithm, used by a copying garbage collection. There are two phases, called evacuation and scavenging. The heap is divided into a "from space" and a "to space," and allocated memory only can live in the from space. For evacuation, allocated memory (in order from a root pointer) is copied into the "to space," but the pointers aren't adjusted. Instead, they're kept as forwarding pointers, which makes this act like a queue, where objects pointed to aren't yet moved over: if $A \to B$ and A is live, then so is B, so during scavenging, the new copy of A has its pointer moved to the new copy of B, and the old copy of B is updated to point to the new copy (so other references can forward their pointers). Once scavenging is done, the only objects alive in the "to space" are the live objects from before, so the "to space" and "from space" can be switched. This is nice in that the newly allocated memory is contiguous, so there's no need to play with a free list.

But GHC uses a modified version of this, called generational copy collection. In this algorithm, there are multiple "to spaces." A generational garbage collector works by partitioning the heap into several generations, and garbage-collecting them at different times. Thus, the generational copy collector has two (or more) "to spaces," one called a nursery and one called generation 1. The idea is that over two minor garbage collections, some objects might not persist, so they stay in the nursery, which is garbage-collected more frequently.

Since Haskell is functional, then it's usually the case that newly allocated objects only point to older ones, which makes life nicer sometimes. But another interesting fact is that the more garbage there is, the faster this runs, because there's less to copy. This is unlike other algorithms, and makes it faster (though still not as fast as manual deallocation of memory in C, of course).

The above algorithm is bog-standard, but difficult to implement: it's beautiful, but used in very few languages. A common problem is that accurate garbage collection requires knowing what the pointers are (e.g. via an object's info table; in particular, which fields in an object are or aren't pointers). This is annoying to code, generate, or maintain, making this less appealing.

But this isn't even the most important issue: the assumption before (that older objects can't point to newer ones) isn't true. For example, `IORefs` make this difficult. For example, one might get a pointer from Generation 1 to the nursery — but a minor garbage collection will only look at the nursery, miss this pointer, and be incorrect. The standard solution is to add mutated objects to a set called the mutable set (also called the remembered set), which is examined in minor garbage collections (and cleared in a major garbage collection). This is sufficient to preserve correctness, but isn't the whole story.

This is hard to implement: every time a pointer is mutated, another object needs to be added to the mutable set. This is bad in languages such as Java, where there can be a lot of pointer mutation; thus, this leads to a factor of two performance hit, and thus other ideas are implemented (such as marking specific portions of memory to also look at) — but this is much more of a problem in Java than in Haskell. Mutation is rare in pure languages like Haskell, and if you are mutating a lot of `IORefs`, then perhaps there are other issues with your program.

... which is to say, `IORefs` are almost always used for long-distance communication, rather than computations. Furthermore, mutations in general are quite rare. Laziness, though, is also a kind of mutation (thunks can be updated, causing pointers to be where one might not expected). One solution is to promote the result of a thunk to Generation 1, so that there's less fussiness with mutable sets. This could work for `IORefs`, as in correctness, but this leads to lots of things being copied into Generation 1 really quickly, and then dying and being missed in minor collections.

The standard caveat is that copy collectors require twice as much memory, for the two sections, but there are various tricks which make this less of an issue (e.g. reusing memory in the copy phase, so that the factor of two is an upper limit, but unlikely in practice).

GHC also uses a neat idea called the parallel garbage collector.[7] This is a garbage collector which parallelizes the scavenging process. However, the garbage collector itself isn't concurrent with the runtime: all Haskell threads stop when the garbage collector runs.

Of course, concurrency comes with its own problems. What happens when two GC threads try to scavenge the same object? They might make two copies of the same object, and the naïve fix is to add a lock to every object, which is really expensive. Purity once again comes to the rescue: if the raced object isn't an `IORef` (which can be detected), then it's immutable, so it's OK if two objects get made, and the slight bump in memory is all right, much like the optimization where the same thunk is copied in some cases. This is the difference between `unsafePerformIO` and `unsafeDupableIO`, the latter of which can be collected in this way, and therefore might get duplicated!

The lesson which keeps coming back is that purity implies flexibility, at least in garbage collection. This answers the StackOverflow question mentioned above: a type called `MutableAraray` has to be placed in the mutable set by default, so allocating lots of them isn't so good of an idea. (This doesn't apply to `MutableByteArrays`, since they don't have pointers.) There's work to be done at making Haskell better at mutable GC.

Scheduling. The scheduler is the heart of the runtime system; in some sense, it uses a function called `StgRun` to run Haskell code, and this calls `StgReturn` to return to the scheduler.

A thread is represented by a TSO object, which lives on the heap. This contains a stack object pointer, which points to a stack object (careful! This is also heap allocated). This contains information about the closure in question, the current stack pointer, and so on. The stack is segmented: there's the thread object, and some stack objects, and that's it. This means making threads is cheap: it doesn't cost much to make threads, and since the stack is segmented, threads can start with a small stack.

The scheduler itself has a thread queue pointing to a bunch of thread objects. It repeatedly picks a thread, runs it, checks for heap overflows (and then collects garbage), and so on. This is considered part of the root set for garbage collection. In multi-core systems (and with the right compiler flags), there's a separate scheduler loop (called a Haskell execution context, or HEC) for each core. These can be thought of as locks, which the OS threads take out. For example, if two OS threads are running Haskell code and a third is idle, so if one of the other threads goes and does something

[7] "Java has something similar, but I understand how GHC's works."

else (like an FFI call), then the third thread jumps in and begins scheduling. Then, the garbage collector takes all of the locks, preventing code from running which garbage is collected.

How does the scheduler balance work amongst the threads? When a thread is out of work, it releases a lock on its run queue; then, a thread which has work may acquire the lock, split its work between them, and then release the lock, giving the other thread more work to do. This is a throughput model, which eliminates the need to fancy inter-thread communication.

Bound threads also fit into this scheme: they are required to run on a specific core; if a bound thread is acquired by the wrong OS thread, then that thread pings the correct one and tells it to acquire the lock, runs it, and then passes the scheduler back to the initial thread (so that it can handle other bound threads, should the need arise). Ideally, one would have all of the bound threads living in one core or one HEC, but in cases where there aren't very many bound threads, it would be inefficient to lock one core up with only a few pieces of work.

`MVars` are very important for the Haskell user, so it's worth peering behind the curtain for these too. An `MVar` contains a queue of threads blocked on it, so when a thread blocks on an `MVar` the scheduler moves it onto the `MVar` queue. This is hard with proper OS threads, so it's really nice to link threads to the data structure they run on (which is also true for other concurrency primitives in GHC). Interestingly, if an `MVar` falls out of scope, all of the threads blocking on it are garbage-collected.

In summary, the scheduler makes everything live on the heap: stacks, thread objects, concurrency primitives, etc. This is nice. One fun aside is that Rust and Go, hip new programming languages, are discovering that contiguous stacks are a bit messier, are looking to similar systems. GHC's approach is not without problems, e.g. a "hot swapping" problem where stacks are continually allocated and deallocated in certain kinds of code. This leads to cheap threads, which are nice, and purity means an awful lot of code is already threadsafe by default. Thus, it's not necessary to be as careful as in Java, because shared memory gives no insulation against races and such. But pure code can't leak across threads.

These are two of the many aspects of the runtime system: there's more to each, of course. There's lots and lots of code and many papers involved in this.

18. Library-Level Optimization: 5/29/14

"Sometimes [the inliner] hits the pub and doesn't get up in the morning, and then your code isn't inlined."

One good strategy is inlining: in GHC-land, inlining is very important for performance. Function application is cheap, but not applying a function at all is cheaper.

```
all :: (a -> Bool) -> [a] -> Bool
all p = and . map p

and :: [Bool] -> Bool
and = foldr && True
-- in some sense, foldr replaces every cons cell with the function one specifies.
```

The above definition, from the Prelude, isn't quite optimal: it generates a list by mapping `p`, and then applying `and`. This is fine with respect to composability, but allocating the intermediate list isn't strictly necessary. Of course, lazy evaluation means that we'll just get a thunk, and the extra cells are generated, but not up front. Here's a more efficient implementation:

```
all' p = go
    where go (x:xs)
            | p x       = go xs
            | otherwise = False
          go _          = True
```

This eliminates the call to `map`, turning 2 traversals of a list into 1 traversal. This does actually make a difference in performance.

If the inliner can see the body of `all'` and `p`, then this would be even more efficient. This doesn't always work; the inliner can be somewhat finicky.

There's a terrible name for a good thing: deforestation is the business of getting rid of intermediate or unnecessary data structures. There's some cognitive dissonnce here: out of context, this sounds bad. But deforestation makes our code more efficient.

GHC has used something called `foldr-build`-fusion to deforest many kinds of function compositions. It relies on the following somewhat strange definition.

```
build :: (forall b. (a -> b -> b) -> b -> b) -> [a]
build g = g (:) []
```

This is called a list producer; it's not meaningful for code, but it acts as a hint to the inliner.

A special pragma `{-# INLINE [1] build #-}` tells GHC to inline things. In C-like languages, it's somewhat coarse: there's an `inline` keyword and an always-inline pragma, but in Haskell, the simplifier (which is a sequence of Core-to-Core transformations which desugar the syntax, but preserve semantics). Each pass of the simplifer has a phase number, decreasing to zero; using the flag `-dverbose-core2core`, one can see the sequence of phase numbers. Then, the syntax `INLINE[k]` indicates to not inline a function until phase `k`, after which it really really should be inlined. This is a full AST transformation scheme: when someone else uses your library, the same inline hints apply, and can greatly improve the performance thereof.

For example, `foldr` is told to inline at phase zero. This relates to the fact that the inliner really can do a lot more: we can specify transformation rules, as follows. This is pretty magical.

```
{-# RULES "map/map"
    forall f g xs.  map f (map g xs) = map (f.g) xs
#-}
```

The name `"map/map"` is unnecessary, but is spit out by compiler debug dumps, so it's nice to have around. This rule says that maps agree with function composition, and thus can be used to eliminate an intermediate list. However, this works only for this one isolated case; there are lots of others (e.g. `map` after or before `filter`). Rather than writing n^2 rules, here's the actual rule used for GHC.

```
{-# RULES "map" [~1]
    forall f xs.
    map f xs = build (\c n -> fold (mapFB c f) n xs)
#-}
```

This ~ notation is new; it means to want to inline something `until` phase `k`, and then not.

This leads to a simple equivalence called η-equivalence: `\x -> f x` is completely equivalent to `f`. Rewriting from the left to the right is called η-contraction, and the reverse process is called η-expansion. Now we can talk about what `mapFB` does: it's just η-expansion.

```
mapFB :: (elt -> lst -> list)
      -> (a -> elt)
      -> a -> lst -> lst
mapFB c f = \x ys -> c (f x) ys
{-# INLINE [0] mapFB #-}
```

Now, we can fuse repeated `mapFB` instances together with a rewrite rule, and then a reverse rule:

```
{-# RULES "maplist" [1]
    forall f.
    foldr (mapFB (:) f) [] = map f
#-}
```

This seems all a bit Rube-Goldbergesque, but it does all make sense. This rule undoes some of the others. But there's one more yet that collapses a `foldr` and a `build`. These make life really confusing, but also all happens to work out right.

This is all very helpful, but it's the very first instance of deforestation in Haskell, twenty years old. It's pretty fragile, and doesn't work on `foldl`-style loops (it makes everything else worse). However, strict left folds are pretty common, e.g. `length`, `sum`, `mean`, and so on.

Yet there is still some progress to be made. Lists are inductively defined, given an empty list `[]` and the inductive case `(:)`. But it's possible to use *co*induction to consume data, as in the `Stream` class.

```
{-# LANGUAGE Rank2Types #-} -- used existentially.

data Stream a =
    forall s. Stream
    (s -> Step s a)   -- observer fuction
    !s                -- current state

data Step s a = Done
              | Skip !s -- skip over stuff, which is useful for stuff like filter
              | Yield !a !s
```

That is, induction is used to produce stuff, and coinduction is used to consume stuff.[8] This `Stream` class maintains a function for retrieving the stream data and a state (hidden from the user, requiring the rank-2 type).

[8] If you've taken enough abstract algebra classes, you're used to ideas and coideas, authors and coauthors, pants and copants, and so on.

One can convert between lists and streams.

```
streamList :: [a] -> Stream a
streamList s = Stream next s
    where next []     = Done
          next (x:xs) = Yield x xs

{-# INLINE [0] streamList #-}

unstreamList :: Stream a -> [a]
unstreamList (Stream next s0) = unfold s0
    where unfold !s = case next s of
        Done    -> []
        Skip s' -> unfold s'
        Yield x s' -> (x:unfold s')
{-# INLINE [0] unstreamList #-}
```

Now, it's easy to write left and right folds, albeit somewhat mechanically from the constructors. All of these functions are inlined at phase 0.

This stream representation is used in several well-used Haskell packages, particularly in packed data types such as `vector` and `text`. `ByteString`, however, doesn't; it predates string/build fusion.

But these interact nicely with stream fusion, as in the following.

```
{-# RULE "STREAM stream/unstrwam fusion"
    forall s.
    stream (unstream s) = s
#-}
```

Well, that wasn't so interesting. But let's throw in a `map`:

```
import qualified Data.Text.Fusion as S

map :: (Char -> Char) -> Text -> Text
map f t = unstream (S.map f (stream t))
-- etc.
```

Then, it's possible to eliminate an intermeiate map in composition.

One significant issue is unrolling recursive functions. GHC doesn't mess with recursive functions (which is a good idea, since it would cause an infinite loop), so these stream transformations have to be nonrecursive. But when this happens, then many streams can be reworked into a pipeline where all of the needed transformations are placed into a stream, avoiding intermediate allocations. This is useful for library writers, but not users (except that they should use pipelining styles). Stream fusion, like `foldr` optimization, is still a bit finicky.

Stream fusion can be unpleasant to code.

```
data I s = I1 !s
         | I2 !s {-# UNPACK #-} !Char
         | I3 !s

intersperse :: Char -> Stream Char -> Stream Char
intersperse c (Stream next0 s0) = Stream next (I1 s0)
    where
        -- ten lines of boilerplate...
```

However, sometimes it's even necessary to write rather imperative code, with hand-rolled loops, to reduce heap allocation. Adding rules is a great way to make sure the fusion-based and the array-based versions of a function are paired with similar pieces of code to get better performance. The library writer has to write about twice as much code, but the result is considerably faster code.

The `vector` library has a more sophisticated version, because it came along later. To wit, there are monadic streams, so that one can do stream fusion over mutable arrays.

There's actually still lots of recent research on streaming and related optimizations. This can be discovered on Reddit's Haskell subforum (of all places; more useful than one might think!), e.g. `http://www.reddit.com/r/haskell/comments/26j20h/nomeata_does_list_fusion_work/`.

19. The Swift Programming Language: 6/3/14

"[Swift] brings mobile computing from the stone age to the mid-1990s, so instead of grunting and hitting each other with the sticks of Objective-C, we can now listen to Nirvana when we code."

Swift is a new programming language released yesterday (!) by Apple for mobile computing. Chris Lattner (behind LLVM) and other luminaries are behind it, and the language seems promising. Yesterday at Facebook, for example, there was a lot of discussion about this new mobile language, since Facebook is probably the most complicated iOS app in existence. Apple has a cap of 60 MB for apps, which sets reasonable limits on the iOS's runtime system, but Facebook has been skirting this for about a year, and has only been able to work with it due to increasingly clever fixes.[9]

```
// main.swift
// wibble

import Foundation

println("Hello, World!")
```

This language is relatively strongly typed, and this allows for static analysis — which is quite useful in the real world. Objective-C is very dynamic, but this dynamicity has a huge cost: every method adds a few dozen bits in descriptors and such, which is actually quite high compared to that in C++. The lack of safety in Objective-C also means that diffs to the Facebook iOS app sometimes crash on startup (though these are detected before being released); Swift has by default no null pointer, and a very hidden `Maybe`-like type: one can write `var i: Int`, but `var i: Int?` to indicate that it could be nullable.

Swift also doesn't implicitly coerce anything, so `NULL` doesn't evaluate to false, and nor does 0. But one can test `if j {...}` for nullity, within which `j` is unwrapped. This isn't as awesome as Haskell, but is pretty good. Using generics, one can actually implement this (e.g. `Maybe<T>`, with `Just<T>` or `Nothing`) and do pattern-matching.

However, long experience with programming languages breeds cynicism. Some of the shinier aspects of Haskell are lost in translation to the real world, e.g. pattern matching can only be done one level deep, and types cannot be recursively defined (as with trees in Haskell). This is probably because information propagates in interesting ways (in this case, probably across Twitter). But there are closures, and there's garbage collection (though it's reference counting, which is a bit of a mixed blessing). People disagree, often zealously, as to which of these methods are best, but these aren't the kinds of folks you want at your dinner parties.

Swift makes a distinction between reference types (called `classes`), passed by pointer, and value types, called `structs`, which are passed by value. Unfortunately, there's no good way to convert one to the other, and many core types (e.g. the String type) are value types, which leads to extra memory calls. However, a lot of this is behind a barrier accessible to the language implementer but not the programmer, which is bad mojo and leads to anger. Go is particularly bad at this.

Swift also claims that its arrays are immutable, which they define strangely: the size of an array can't be modified, but its contents can be changed! This means that the bounds are statically known, which is fine, but immutable is the wrong word to use there.

It's likely that these will be fixed in upcoming years, as the language gets thought about more, and it certainly does a *lot* of things better than Objective-C. However, it doesn't improve on its module system, nor its slow compilation (Go really is the only language that gets this really well; GHC, for all of its wonderful aspects, is slower than almost anything except Scala).

```
// map across stuff. With Bash-like syntax!
// though at least it's $0 and not $1.
import Foundation

println([1,2,3].map({$0+1}))
```

Swift is built on LLVM, so it can interoperate with Objective-C. Methods designed to work with both are tagged with an annotation, so that the compiler generates code for both versions.

The Jackknife. The Jackknife is a method of statistical analysis. Suppose one has a sample $[0,0,1,0]$ from some population about which we don't really know much. The mean of the sample is, unsurprisingy, 0.25, but this isn't a very interesting property. One might instead ask how much it's affected by the data within it, e.g. by computing its variance.

A package caled `Statistics.Sample` is good for this, along with `Data.Vector.Unboxed` (often imported as `U`). The language extension `OverloadedLists` allows one to treat lists much like vectors. It turns out versioning issues put the code into Cabal hell, so let's open up a Python script and calculate the variance, which is 0.25.

This is where the Jackknife enters into the play: it's an advanced tool, but it's pretty easy to understand. First, do a leave-one-out subsample process, where each entry is deleted once: $[0,0,1]$, $[0,0,0]$, and so on. Three of these have variance $1/3$, and the fourth has variance 0, so the mean of these four variances is $(3/4)(1/3) = 1/4$. What would it look like if the overall variance and that of the jackknifed sample were different?

[9] "Objective-C is really a shit programming language from any way you look at it. it takes the worst aspects of C and the worst aspects of Smalltalk, and looks like a turd that was shit out of several animals at once."

Well, laziness is king, so let's write a QuickCheck test to discover a good counterexample for us.

```
import Statistics.Resampling
import Statistics.Types
import qualified Data.Vector.Unboxed as U
import Test.QuickCheck

t_est est x y z xs = estimate estv === -- this operator means "print the value if they're not equal
    ," and otherwise is ==
                     estimate Mean (jackknife est v)
    here v = Ufromlist . map (fromIntegral) ( (x:y:z:xs))
```

This quickly fails with a useful counterexample. The point is, QuickCheck isn't just about testing code; it can do a bunch of checking things.

The jackknife is an $O(n^2)$ algorithm, which is bad for larger samples, and was a bottleneck in the `criterion` benchmarking library for a while. But a function called `scanl` uses a technique called prefix sums, which was a faster way to speed up this sort of statistical algorithm. In other words, thinking about functional programming is useful for solving interesting problems too!