47

Yin and Yang of Haskell

LambdaWorld Cádiz 2019

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Welcome!

The quest for being a Haskeller

Learn more and more abstractions?

The quest for being a Haskeller

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- The simple abstractions get you a long way!

The quest for being a Haskeller

Learn more and more abstractions?

- The simple abstractions get you a long way!

You need to know more about the *run-time* system.

- When and how is my program executed?
- When and how is my memory allocated?
- How do I communicate with other resources?

Yin and Yang of Haskell

Each side influences the other:

- Laziness is possible because of purity;
- Laziness forces us to write purer programs.

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- Our aim to track finer-grained effects leads to richer types.

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- Laziness is possible because of purity;
- Laziness forces us to write purer programs.

- We can track effects because of the rich type system;
- Our aim to track finer-grained effects leads to richer types.

We need to know about the two sides.

Practicalities

The workshop is organized in blocks:

- Some time of me talking and **you asking questions**.
- Followed by some time of you coding.

Drinks and food will be served here:

- With a longer break for lunch around 13.00.

`github.com/47deg/yin-yang-haskell-workshop`

Yin: Pure modelling with ADTs

Our domain: Pen-and-paper role-playing game

Pathfinder is a fork of Dungeons & Dragons 3.5.

- *Character Sheet*: Quite complex.
  - Absolute *scores* lead to *modifiers*.
  - These modifiers are used when throwing dice.
  - And may be supplemented by skills or ranks.
- *Combat*: A lot of possibilities.
  - Move, attack, use spell...
  - They take different amounts of time.

Modelling characters

Within the game we have different kinds of **characters**:

- Players, which have the most detailed stats.
- Non-playing characters (NPCs):
  - Monsters and other figthers, which just need enough information to execute combat.
  - Other characters with only basic stats.

The game and the story is directed by a **(game) master**.

Modelling characters

(Following Wlaschin's terminology)

```
A character is...
      a player  with basic stats AND combat stats AND skills
  OR a fighter with basic stats AND combat stats
  OR a NPC     with basic stats
```

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```

```haskell
data Character
  = Player  BasicStats CombatStats Skills
  | Fighter BasicStats CombatStats
  | NPC     BasicStats
```

Pattern matching

We access the information by using different patterns:

```
basicStats :: Character -> BasicStats
basicStats c = case c of
                 Player  s _ _ -> s
                 Fighter s _   -> s
                 NPC     s     -> s
```

Pattern matching

We access the information by using different patterns:

```
basicStats :: Character -> BasicStats
basicStats c = case c of
                 Player  s _ _ -> s
                 Fighter s _   -> s
                 NPC     s     -> s

-- functions have an implicit top-level case
basicStats (Player  s _ _) = s
basicStats (Fighter s _)   = s
basicStats (NPC     s)     = s
```

Sums / choices / (discriminated, tagged) unions

This is an important difference with OOP:

- Do not think of open, extensible hierarchies;
- But of a closed set of possibilities.

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- But of a closed set of possibilities.

Advantages

- *Modelling*: No fear of forward compatibility.
  - What if somebody overrides this method?
- *Compilation*: Ability to check for exhaustive coverage.

More examples of sums

- States that a program or value may be in.
  - During combat, a character may be taking part, have fainted (0 HP), or be dead (-10 HP).
- Actions or commands that may be taken.
- Events that may arise.
  - Ties very well with CQRS or event sourcing.

More examples of sums

- States that a program or value may be in.
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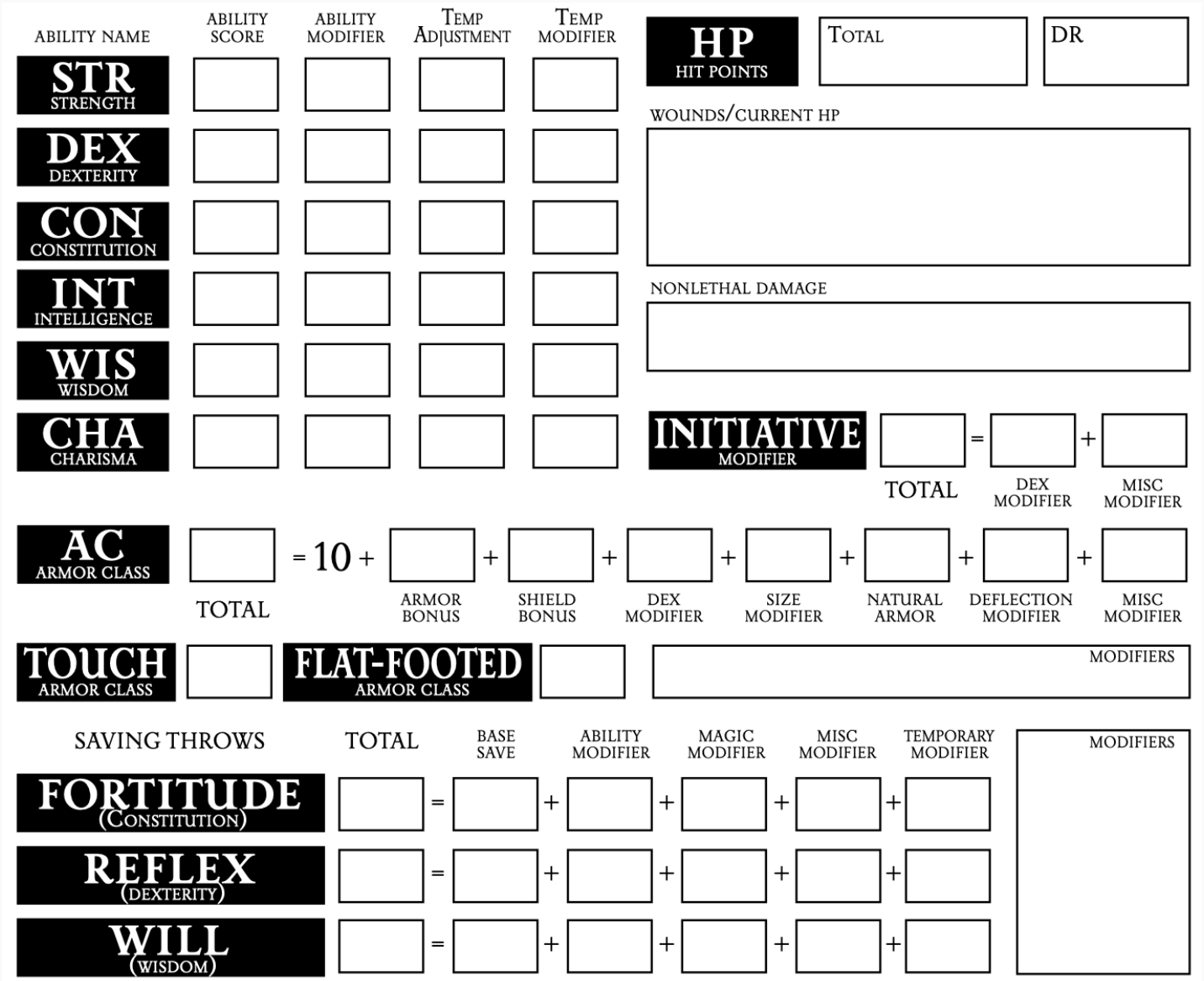
- Actions or commands that may be taken.
- Events that may arise.
  - Ties very well with CQRS or event sourcing.

In short, sum up your data types!

Modelling nightmare



Absolute values versus modifiers

```
data BasicStats
  = BasicStats { str :: Int, dex :: Int, con :: Int
               , int :: Int, wis :: Int, cha :: Int
               , fort :: Int, refl :: Int, will :: Int
               , ... }
```

Absolute values versus modifiers

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data BasicStats
  = BasicStats { str :: Int, dex :: Int, con :: Int
               , int :: Int, wis :: Int, cha :: Int
               , fort :: Int, refl :: Int, will :: Int
               , ... }
```

Record syntax: Stating a name for each field in a constructor.

- Generates accessor functions for free.

```
str :: BasicStats -> Int
dex :: BasicStats -> Int
```

- Gives you extra powers for pattern match.

```
f BasicStats { str = s, dex = d } = ...
```

- Mostly used for single-constructor data types.

Absolute values versus modifiers

```
data BasicStats
  = BasicStats { str :: Int, dex :: Int, con :: Int
               , int :: Int, wis :: Int, cha :: Int
               , fort :: Int, refl :: Int, will :: Int
               , ... }
```

We have used `Int` for everything, yet:

- Absolute values in Pathfinder never go below 0.
- In contrast, modifiers usually do.
- You can apply a modifier to an absolute value, but the combination of absolute values does not make sense.

One type per notion in your domain

In Haskell, you use a `newtype` to wrap an existing type:

```haskell
newtype AbsoluteValue = AbsoluteValue { unAbsoluteValue :: Int }
newtype Modifier      = Modifier { unModifier :: Int }

applyModifier :: AbsoluteValue -> Modifier -> AbsoluteValue
applyModifier (AbsoluteValue v) (Modifier m)
  = AbsoluteValue (v + m)
-- now using field accessors
applyModifier v m
  = AbsoluteValue (unAbsoluteValue v) (unModifier m)
```

Wrapping and unwrapping `newtypes` is memory and time free!

Derived combat statistics

We have given both `Players` and `Fighers` combat statistics, but in players, combat stats are derived from their skills.

```
data Character
  = Player  BasicStats Skills
  | Fighter BasicStats CombatStats
  | NPC     BasicStats
```

How to treat `Player` and `Figher` uniformly during combat?

View patterns

1. A new data type to express exactly what you need:

```haskell
data Combatant  -- cannot reuse Fighter :(
  = Combatant CombatStats
  | NonCombatant
```

2. A function to turn one into the other:

```haskell
asCombatant :: Character -> Combatant
asCombatant (Player stats skills) = Combatant ...
asCombatant (Figher _ cstats)     = Combatant cstats
asCombatant (NPC _)               = NonCombatant
```

View patterns

3. *View patterns* to apply that transformation before matching:

```
punch :: Character -> Character -> ...
punch one (asCombatant -> Combatant cstats) = ...
punch one (asCombatant -> NonCombatant)     = ...
```

Write as many views as you need for your types.

Optics

Another way to view types differently is by means of an *optic*.

- *Lens*: Access and modify a value that is always there.
  - Like the `BasicStats` in a `Character`.
- *Prism*: Access and modify a possibly-missing value.
  - Like `CombatStats` in a `Character`.
- Many others!

Main advantage: optics are composable.

Optics

Another way to view types differently is by means of an *optic*.

- *Lens*: Access and modify a value that is always there.
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- *Prism*: Access and modify a possibly-missing value.
  - Like `CombatStats` in a `Character`.
- Many others!

Main advantage: optics are composable.

But, unfortunately, we do not have the time to cover them.

- Read `lens-tutorial` and then use `optics`.

Equipment is an open notion

`Equipment` does not lend itself to a closed representation:

- Lots of choices:

```
data Equipment = SmallSword  ...
               | MediumSword ...
               | SpellWand   ...
               | ... -- thousands of choices
```

- And they might grow in the future!

OOP says: New derived classes. What about FP?

Categorize and parametrize

```
data Equipment
  = Weapon { hit :: AbsoluteValue, ... }
  | MagicObject { execute :: Character -> Character, ... }
  | ...
```

Functions as data provide a way to model different behavior. But:

- Functions are hard to inspect,
- As a result, functions are hard to serialize.

More on programs-as-data afterwards!

In summary...

Modelling data with Algebraic Data Types:

- Think in terms of *sums*, not of class hierarchies;
- Use *one type per concept* in the domain;
- It is helpful to see the same data from different *views*,
  - View patterns and optics help you with this;
- *Open* data benefits from functional fields.

Time to code!

Exercise 1: *Modelling a Game*

- Speak and discuss with your peers,
- I might listen to the conversation and jump in :P

Exercise 0: *Game using Gloss*

Feel free to ask questions about the pre-workshop exercise.

Yang: Impure execution

FP compilers are magical creatures

GHC has no less than 3 intermediate languages.

Haskell $\rightarrow$ Core $\rightarrow$ STG $\rightarrow$ C– $\rightarrow$ (LLVM) $\rightarrow$ assembly

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STG = Spineless Tagless Graph Reduction Machine

The main difference

- Most languages have a strict order of execution:
  - For each function call, execute the code fully to obtain the arguments, then pass the resulting values to the function body.
  - Predictable, but potentially costly.
- Haskell has a lazy execution model:
  - Code is only executed "when needed."
  - It mostly works well, but when it doesn't...
  - How does it work when you communicate with the outside world?

GHC/Haskell's execution model

Some examples

Consider the function:

```
f []     = "empty"
f (_:_) = "non-empty"
```

Some examples

Consider the function:

```
f []    = "empty"
f (_:_) = "non-empty"
```

To make things more clear, we rewrite this as:

```
f xs = case xs of []    -> "empty"
                  (_:_) -> "non-empty"
```

Some examples

Consider a `takesLong` function that takes a lot of time to execute:

```
takesLong = go 10000000000000000
  where go 0 = []
        go n = go (n-1)
```

The question is, what happens when we do:

```
f takesLong
```

Some examples

Strict evaluation (the usual one):

```
  f takesLong
= -- execute takesLong
  f []
= "empty"
```

Lazy evaluation (Haskell's):

```
  f takesLong
= case takesLong of []    -> "empty"
                    (_:_) -> "non-empty"
= -- execute takesLong
  "empty"
```

Unused arguments

The `const` function forgets about its second argument.

```
const x y = x
```

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The `const` function forgets about its second argument.

```
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```

Strict evaluation:

```
  const 3 takesLong
= -- execute 3 and takesLong
= 3
```

Lazy evaluation:

```
  const 3 takesLong
= 3  -- takesLong is not needed!
```

Making “when needed” precise

Haskell functions are only executed when we need to inspect the value to choose how to continue.

- In other words, when we are in a `case` statement.

Making “when needed” precise

Haskell functions are only executed when we need to inspect the value to choose how to continue.

- In other words, when we are in a `case` statement.

Even better, functions are only executed “as much as needed.”

Takes long in a different way

```
headTakesLong = [ go 10000000000000000, 2 ]
  where go 0 = 0 ; go n = go (n-1)
```

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headTakesLong = [ go 10000000000000000, 2 ]
  where go 0 = 0 ; go n = go (n-1)
```

Strict evaluation:

```
  f headTakesLong
= -- execute headTakesLong fully
  "non-empty"
```

Lazy evaluation:

```
  f headTakesLong = case headTakesLong of ...
= case [ go 10000000000000000, 2 ] of []    -> "empty"
                                      (_:_) -> "non-empty"
= "non-empty"  -- go 10000000000000000 is never executed!
```

Short-circuiting = lazy evaluation

Most C-like languages distinguish between `&` and `&&`.

```
False && _ = False
_     && y = y

x && y = case x of
           False -> False
           _     -> y
```

- `y` is only executed if `x` is `False`.

Build your own control structures

```
if_ True  t e = t
if_ False t e = e
```

In a strict language, `if_` does not work as a real `if`.

- Both arguments are executed, which defeats the purpose.
- We only want *one* of them to be executed.

In Haskell, `if_` is really an `if-then-else`.

Infinite loops can be avoided

```
infiniteLoop :: a -> b
infiniteLoop x = infiniteLoop x

f (infiniteLoop 3) -- does not terminate

  const 3 (infiniteLoop 3)
= 3

  f [ infiniteLoop 3, 2 ]
= case [ infiniteLoop 3, 2 ] of ...
= "non-empty"
```

Infinite structures can be manipulated

```haskell
-- allNumbers = [0, 1, 2, 3, ...]
allNumbers = go 0
  where go n = n : go (n + 1)
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-- allNumbers = [0, 1, 2, 3, ...]
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  take 2 allNumbers
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```

Infinite structures can be manipulated

```haskell
-- allNumbers = [0, 1, 2, 3, ...]
allNumbers = go 0
  where go n = n : go (n + 1)

  take 2 allNumbers
= [0, 1]  -- works!

  take 2 (map (\x -> x * 3) allNumbers)
= [0, 3] -- works!
```

Enough magic!

Show me the trick!

Thunks

Each expression yet-to-be-executed is kept in a *thunk*:

- Includes the code to be executed, and
- References to any other required thunks.

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`case` statements *force* thunks:

- The code inside of it is executed,
- Until a constructor appears on the top of the value,
  - At that point, `case` can take a choice,
- The thunk is updated in case it is needed afterwards.

Sharing thunks

```
let x = takesLong in (f x, null x)
```

- The first time we need to inspect one of the elements of the tuple, `takesLong` is executed.
- After the first execution, this thunk is updated to `[]`.
- Any subsequent uses of `x` return immediately.

Sharing thunks

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let x = takesLong in (f x, null x)
```

- The first time we need to inspect one of the elements of the tuple, `takesLong` is executed.
- After the first execution, this thunk is updated to `[]`.
- Any subsequent uses of `x` return immediately.

Advantage: Haskell does the minimal amount of work.

Disadvantage: Potential thunks in memory which we never use.

- As a result, garbage collection must consider thunks.
  - GC looks at your data and your *code*.

Problems in paradise

Space leak: Your thunks grow bigger, or live longer than expected.

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The #1 performance bug in Haskell:

- (Moderably) easy to spot: Your code is slow, and your memory usage skyrockets.
- Hard to debug: You must consider both the definition of your code, and also every place where it is used.

Fold starting from the head

```
foldl _ v []     = v
foldl f v (x:xs) = foldl f (f v x) xs

foldl (-) 0 [1,2,3] = ((0 - 1) - 2) - 3
foldr (-) 0 [1,2,3] = 1 - (2 - (3 - 0))
```

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foldl (-) 0 [1,2,3] = ((0 - 1) - 2) - 3
foldr (-) 0 [1,2,3] = 1 - (2 - (3 - 0))
```

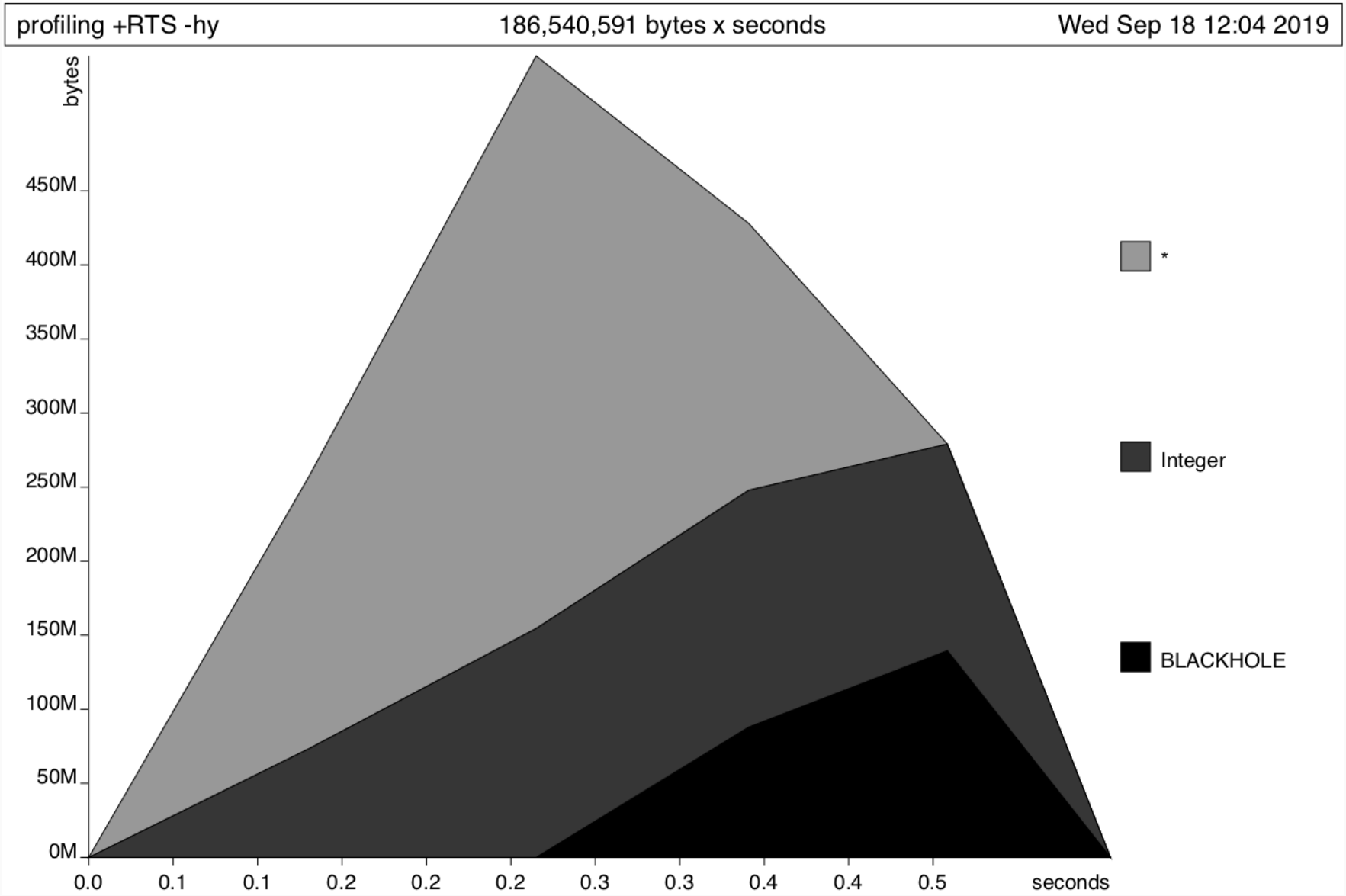
Let's do something simple (for a computer):

```
main = print (foldl (+) 0 [1 .. 10000000])
```

Profiling

1. Create a Cabal project with an executable.
2. Make the previous expression to be the `main`.
3. `stack build --profile`.
4. `long/path/to/your/bin +RTS -hy`.
5. `hp2ps <your-bin>.hp`
6. Open the `<your-bin>.ps` file.

Profiling results



Making sense of the results

`foldl` is creating a huge expression:

```
( ... (((0 + 1) + 2) + 3) + ...)
```

- We can only start evaluating at the end.
- Each subexpression is a new thunk:
  - We have one million thunks in memory!

Forcing additions

Adding two numbers is much faster than thunk (de)constructions!

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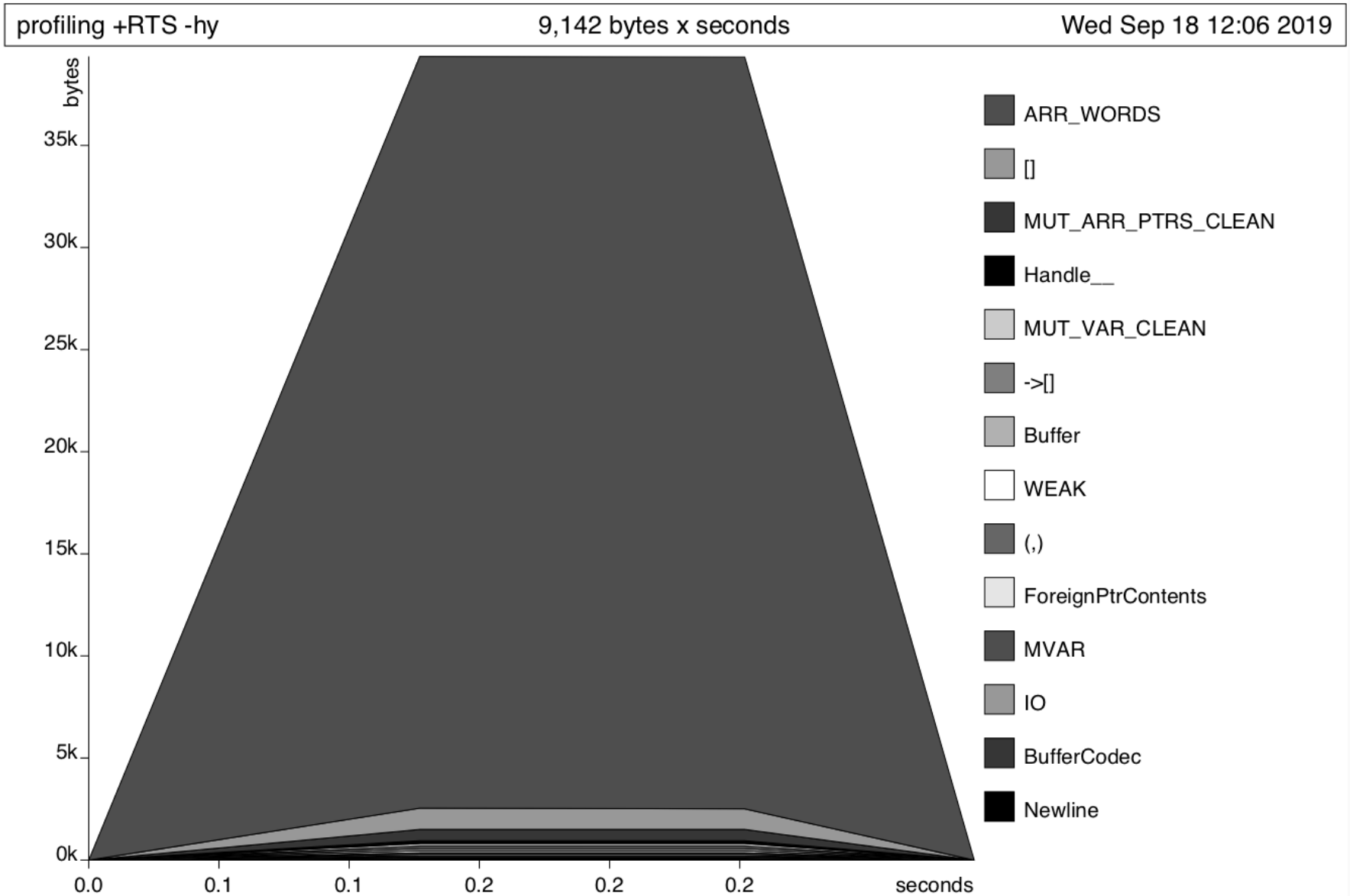
Let us kindly ask GHC to execute a thunk *now* instead of keeping it for *later* by using `seq`:

```
foldl' _ v []     = v
foldl' f v (x:xs) = let acc = f v x
                    in acc `seq` foldl' f acc xs
```

Profiling results



Bang patterns

```haskell
{-# language BangPatterns #-}
foldl' _ v []     = v
foldl' f v (x:xs) = let !acc = f v x
                    in foldl' f acc xs
```

You can also add them to fields to ensure that they are always forced at construction time:

```haskell
data Point = Point !Float !Float
```

Force versus deep force

`seq` only forces as much as a `case` statement:

- Figure out which is the top-most constructor,
  - Is it `Nothing` or `Just`? Is it `[]` or cons?
- But do *not* force any of the contents.

You can get *predictability* at the expense of *potentially useless* execution:

- You can force all the way down with `deepseq`.
- But note that you cannot force through functions.

Strict containers

`containers` is one of the most used and most useful packages in the Haskell ecosystem.

- It provides all sorts of data structures: Dictionaries, sets, graphs, sequences...
- Hash-based containers live in `unordered-containers`.

For each of these structures, you usually have a `Strict` module.

- They force the elements before saving them.

Summary for lazy people

- Haskell expressions are executed "when needed":
  - The evaluation is deferred in form of a *thunk*.
  - Inspecting a value (using `case`) *forces* a thunk to be evaluated "as much as needed"
- Good things we get:
  - Don't need to worry about doing too much work.
  - Manipulation of infinite structures.
- Terrible things that may happen:
  - *Space leak*: Thunks taking more time and space than the actual computation.
  - Use `seq` to manually force evaluation.
  - The profiler can help you find the right spot.

Dealing with the outside world

The “outside world”

Up to now, we have only talked about the *pure* part of Haskell.

- Functions whose only computational content is to obtain an output value based on the value of its arguments.

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Up to now, we have only talked about the *pure* part of Haskell.

- Functions whose only computational content is to obtain an output value based on the value of its arguments.

Most programs need to do other stuff:

- Interact with the user,
  - Hidden from you in the Gloss exercise;
- Communicate over a network,
- Persist information.

All these are *side effects*, and we call function with those *impure*.

Purity as a goal

Pure has almost a *moral* meaning.

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- But here, impure is not strictly bad.

The goal is to separate as much as possible the pure from the impure in your program.

- Later, even different kinds of impurity from each other.
- We want to be *precise* about purity.

Simple console input and output

```
main = do putStrLn "What is your name?"
          name <- getLine
          putStrLn ("Hello, " ++ name ++ "!")
```

Simple console input and output

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          name <- getLine
          putStrLn ("Hello, " ++ name ++ "!")
```

- Input/output blocks are marked with `do`.
- Each line is a *statement*, with some effects, and optionally a return value.
  - We bind the value to a variable with `<-`.
- You can use pure functions freely.

Referential transparency

When does `e == e` return the same as `let x = e in x == x`?

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When does `e == e` return the same as `let x = e in x == x`?

```
take 2 [1,2,3] == take 2 [1,2,3]
let x = take 2 [1,2,3] in x == x

-- Asks the user *twice*
getLine == getLine
-- Asks the user *once*
let x = getLine in x == x
```

We say `getLine` is not *referentially transparent*.

- RT is one of the components of purity.
- Actually, the term *pure* is up for debate.

The IO type

How does Haskell ensure that `getLine` is not used wrong?

```
> getLine == getLine
<interactive>:1:1: error:
    • No instance for (Eq (IO String)) arising from ...
    • In the expression: getLine == getLine

> :t getLine
getLine :: IO String
```

The `IO` type

Functions with side effects are marked with `IO`:

```
putStrLn :: String -> IO ()
getLine  ::           IO String
```

The IO type

Functions with side effects are marked with `IO`:

```
putStrLn :: String -> IO ()
getLine  ::           IO String
```

```
> putStrLn getLine
<interactive>:3:10: error:
    • Couldn't match type ‘IO String’ with ‘String’
```

```
> do n <- getLine ; putStrLn n
Hello
Hello
```

Pure computations in `do`

If we want to have a name for a pure expression, we use `let` without `in`.

```
main = do putStrLn "What is your name?"
          name <- getLine
          let greeting = "Hello, " ++ name ++ "!"
          putStrLn greeting
```

Naïve `IO`

Using `IO` in this way brings two problems:

- Some functions may fail and raise an *exception*.
- Laziness means that order is not guaranteed.

Exceptions

```
readFile :: FilePath -> IO String
```

simply reads the entire contents of a file as a string.

```
> readFile "elquijote.md"
"En un lugar de la Mancha" ...
> readFile "ghostfile.md"
*** Exception: ghostfile.md: openFile: does not exist
    (No such file or directory)
```

Wait! What?

Wasn't Haskell all about being super-precise about the types?

Why not have the following signature?

```
readFile :: FilePath -> IO (Either IOError String)
```

Wait! What?

Wasn't Haskell all about being super-precise about the types?

Why not have the following signature?

```
readFile :: FilePath -> IO (Either IOError String)
```

We have to strike a **balance** between preciseness and ease of use.

`IO` = can do anything *and throw exceptions*

Catching exceptions

Everything related to exceptions lives in `Control.Exception`.

```
catch :: Exception e => IO a -> (e -> IO a) -> IO a
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Everything related to exceptions lives in `Control.Exception`.

```
catch :: Exception e => IO a -> (e -> IO a) -> IO a
```

- `catch` is mostly used infix.
- We have to declare which exceptions we want to handle.

```
{-# language ScopedTypeVariables #-}

main = do txt <- readFile "ghostfile.md"
          putStrLn txt
       `catch` \(e :: IOException) ->
          putStrLn "file not found"
```

Different kinds of exceptions

```
print (1 `div` 0)
`catch` \(e :: ArithException) ->
  putStrLn "computing went wrong"

print (head [])
`catch` \(ErrorCall e) ->
  putStrLn "you should not do that"
```

Different kinds of exceptions

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print (1 `div` 0)
`catch` \(e :: ArithException) ->
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print (head [])
`catch` \(ErrorCall e) ->
  putStrLn "you should not do that"
```

Exceptions may be raised from pure functions:

```
error :: String -> a
throw :: Exception e => e -> a
```

Laziness and IO

IO computations are executed lazily too.

```
-- Read a file as if we were C programmers
main = > do h <- openFile "existing.md" ReadMode
            c <- hGetContents h
            hClose h
            print (length c)
*** Exception: existing.md: hGetContents: illegal operation
    (delayed read on closed handle)
```

Laziness and IO

`IO` computations are executed lazily too.

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*** Exception: existing.md: hGetContents: illegal operation
    (delayed read on closed handle)
```

By the time we force `c`, the handle `h` has already been closed.

Too complicated?

The problem is that our input/output is *too low-level*.

Solution: Use the `bracket` pattern: Functions that take care of resources correctly (even in the case of exceptions).

```
withFile "elquijote.md" ReadMode $ \h ->
  do c <- getContents
     print (length c)
```

Too complicated?

The problem is that our input/output is *too low-level*.

Solution: Use the `bracket` pattern: Functions that take care of resources correctly (even in the case of exceptions).

```
withFile "elquijote.md" ReadMode $ \h ->
  do c <- getContents
     print (length c)
```

This solution has some problems:

1. It leads to deeply nested code,
2. Resources are deallocated in inverse order of allocation,
3. It only takes care of one resource.

Higher-level resource management

Use `managed` to manage your independent resources.

```
runManaged $ do
  h <- managed (withFile "elquijote.md" ReadMode)
  c <- liftIO getContents
  liftIO $ print (length c)
```

Higher-level resource management

Use `managed` to manage your independent resources.

```
runManaged $ do
  h <- managed (withFile "elquijote.md" ReadMode)
  c <- liftIO getContents
  liftIO $ print (length c)
```

Use `resource-pool` to manage pools of resources.

- For example, database connections.

IO Summary

- Haskell distinguishes pure from side effectful computations.
  - The latter is marked with `IO`.
  - `IO` comes with its own `do` notation.
- Functions may throw *exceptions*.
  - Use `Control.Exception` to handle them.
- Lazy `IO` can be very problematic.
  - Especially with (de)allocation of resources.
  - Use `managed` or `resource-pool` for safe higher-level manipulation.

Time to code!

Exercise 2: *A simple TCP server*

- Do some real `IO` stuff!
- Learn about "generics."

Remember: *Pair programming* helps you break the monotomy and helps you share thoughts!

Deep darkness: Variables in Haskell

A single-value TCP server

We want to develop a very stupid TCP server:

- `{ command: "write", value: "hello" }` updates the current value in our (memory-based) store to `"hello"` and sends back the previous one.
- `{ command: "read" }` sends the current value over the wire.

Concurrent connections

From the `network-simple` docs:

> *[...] A single TCP server can sequentially accept many incoming connections, possibly handling each one concurrently.*

What can go wrong?

Concurrent connections

From the `network-simple` docs:

> *[...] A single TCP server can sequentially accept many incoming connections, possibly handling each one concurrently.*

What can go wrong?

What can go wrong????? Concurrent updates, reading dirty values, maybe laziness... And how do we even get variables in a pure language???

Software Transactional Memory

- (Transactional) *variables* are represented by `TVar a`.
- *Transactions* are represented by `STM` computations.
  - Atomic and isolated ("all-or-nothing").
- Use `atomically` to run a transaction.

The server, part 1

```haskell
main :: IO ()
main = do
  v <- newTVarIO "hello"  --- !!1
  serve (Host "127.0.0.1") "8080" $ \(socket, _) -> do
        content <- recv socket 10000
        case content >>= decodeStrict of
           Just (Command "read" _) -> do
             currentValue <- readTVarIO v  -- !!2
             send socket (pack currentValue)
```

1. Create a new transactional variable.
   - They always have a value.
2. Read a transactional variable.
   - This operation happens in `IO`.

The server, part 2

```
case content >>= decodeStrict of
  ...
  Just (Command "write" (Just newValue)) -> do
    oldValue <- atomically $ do
      old <- readTVar v      -- T
      writeTVar v newValue   -- T
      return old             -- T
    send socket (pack oldValue)
```

Everything marked with `T` is a single *transaction*.

- `STM` is a stripped-down version of `IO`.
- `return` gives back something from the block.

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

Other STM structures

- `TMVar`s work like locks or semaphores with a value:
  - They might be empty or full.
  - `readTMVar` on an empty one is blocking.
  - `putTMVar` on a full one makes the transaction fail.
- `TChan` and `TQueue` provide *FIFO queues*.

STM transactions may fail

You may want to check some invariants before proceeding.

```
check :: Bool -> STM a
```

This has two effects:

- The current transaction is *rolled back*.
- The current thread is blocked until any of the `TVars` change.
  - Then the transaction is performed again.

Time to code!

Keep working on Exercise 2: *A simple TCP server*

- Now add some concurrent functionality.

Remember: *Pair programming* helps you break the monotomy and helps you share thoughts!

Lunch time!

Yin: Pure modelling

Polymorphic programs

The Orc strategy

```
orcStrategy :: Character -> World -> IO World
orcStrategy orc w = do
  let p = position orc w
      cs = [c | s <- surroundings p
              , Just (Combatant c) <- combatantInfo s w ]
  case cs of
    [] -> do d <- randomElement [N .. W]
             w' <- move orc d w
             redraw w'
             orcStrategy orc w'
    _  -> do c <- randomElement cs
             w' <- attack orc c w
             redraw w'
             orcStrategy orc w'
```

(So many) problems

- Logic is mixed with calls to `redraw`.
- Random execution is very difficult to test.
  - The calls to `randomElement` tie us to `IO`.
  - Which implies that we cannot use this in a pure environment.

First step: Extract dependencies

```
orcStrategy :: ([a] -> IO a) -> (World -> IO ())
            -> Character -> World -> IO World
orcStrategy rand redraw orc w = do
  let ...
  case cs of
    [] -> do d <- rand [N .. W]
             w' <- move orc d w
             redraw w'
             orcStrategy orc w'
    _  -> do c <- rand cs
             w' <- attack rand orc c w
             redraw w'
             orcStrategy orc w'
```

First step: Extract dependencies

```
orcStrategy :: ([a] -> IO a) -> (World -> IO ())
            -> Character -> World -> IO World
```

- Dependencies are explicit.
  - We can easily swap them for testing purposes.
- However...
  - They require a lot of manual passing (look at `attack`).
  - We are still tied to `IO`.

Reminder: Type classes

Type classes are Haskell version of *interfaces*, *traits*, or *protocols*.

- Define some *methods* to be supported by a type.

```haskell
class Eq a where
  equals :: a -> a -> Bool
```

- A type declares its support for a class by providing an *instance*.

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

Second step: Introduce type classes

```haskell
class Gamble m where
  roll :: [a] -> m a
class DrawWorld m where
  redraw :: World -> m ()
```

Second step: Introduce type classes

```haskell
class Gamble m where
  roll :: [a] -> m a
class DrawWorld m where
  redraw :: World -> m ()

orcStrategy :: (Gamble m, DrawWorld m)
            => Character -> World -> m World
orcStrategy orc w = do
  let ...
  case cs of
    [] -> ...
    _  -> do c <- roll cs
             w' <- attack orc c w
             redraw w'
             orcStrategy orc w'
```

Going one step further

In `orcStrategy` we implicitly assume that `position` is pure.

- What about durable persistence?
- What about dealing with a shared concurrent state?

Using a `Character` to index the position is also an implementation detail, which we can abstract over.

Going one step further

In `orcStrategy` we implicitly assume that `position` is pure.

- What about durable persistence?
- What about dealing with a shared concurrent state?

Using a `Character` to index the position is also an implementation detail, which we can abstract over.

```
-- In this class there is an implicit 'me',
-- which is the combatant the script talks about.
class Combat m where
  myPosition :: m Position
  move       :: Direction -> m ()
  attack     :: Combatant -> m AttackResult
```

Abstracting over effects

Why do we try so hard to abstract over `IO`?

- `IO` means that any side effect may happen.
- We cannot swap an implementation for a mock.

Abstracting over effects

Why do we try so hard to abstract over `IO`?

- `IO` means that any side effect may happen.
- We cannot swap an implementation for a mock.

```haskell
instance Gamble TreeOfPossibilities where
  roll = -- save all possibilities, not only one

instance DrawWorld STM where
  redraw = -- do something concurrent
```

The code above does not compile!!!

```
No instance for (Monad m) arising from a do statement
```

We managed to not speak about *monads* for more than half a day!

The code above does not compile!!!

```
No instance for (Monad m) arising from a do statement
```

We managed to not speak about *monads* for more than half a day!

The key point here is *in a* `do` *statement*.

Simple intro to monads

To specify how computation with effects works, you need to tell:

1. The primitive effects that one may use.
   - `roll`, `redraw`, and so on.
2. How to **stitch** those effects together.

```
diceSum = do x <- roll [1 .. 6]
             y <- roll [1 .. 6]
             return (x + y)
```

   - In other words, how to compose statements.
   - This is the information `Monad` gives us.

Monad as computations

```
class Monad m where
```

- If you have a value, you can create a computation with no effects that just returns that value.

```
return, pure :: a -> m a
```

- If you have a computation, and a way to keep working, you can compose in a sequential manner.

```
(>>=) :: m a -> (a -> m b) -> m b  -- "bind"
```

  - Similar to applying a function to a value:

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

`Maybe` as a monad

`Maybe` models optional values (called `Option` in other languages).

```
data Maybe a = Nothing | Just a

instance Monad Maybe where
```

- If you have a value, you can create a computation with no effects that just returns that value.

  ```
  return x = Just x
  ```

- If you have a computation, and a way to keep working, you can compose in a sequential manner.

  ```
  Nothing >>= _ = Nothing
  Just x  >>= f = f x
  ```

Using `Maybe` as a monad

We used this ability in Exercise 2:

```
do ...
   content <- recv socket 10000
   case content >>= decodeStrict of
     ...
```

```
content       :: Maybe ByteString
decodeStrict :: ByteString -> Maybe Command
-----------------------------------------
content >>= decodeStrict  ::  Maybe Command
```

Fixing our code

- Introduce a `Monad` constraint on each function:

```
orcStrategy :: (Monad m, Gamble m, DrawWorld m) => ...
```

- Make `Monad` a superclass of all of them:

```
class Monad m => Gamble    m where ...
class Monad m => DrawWorld m where ...
class Monad m => Combat    m where ...
```

Monads, applicatives, alternatives

- Monads represent *sequential* execution.

```
(>>=) :: m a -> (a -> m b) -> m b
```

- Applicatives represent *parallel* execution.

```
(&&&) :: m a -> m b -> m (a, b)
```

  - Sequential can simulate parallel, hence any monad is also an applicative.

- Alternatives represent *failure* and *choice*.

```
empty :: m a
(<|>) :: m a -> m a -> m a
```

Two approaches at service abstraction

1. *Extract dependencies* (Wlaschin's approach):
   - Start with a highly-coupled implementation.
   - Turn functions that come from a different bounded countext into arguments.
   - Gather sets of functions into type classes.
2. *Design an algebra* (Ghosh's approach):
   - During the modelling phase, think about the services that your domain provides.
   - Refine the services into a small set of core primitives.
   - Turn this small set into a type class.

A word on terminology

People refer to the idea of having type classes for operations with different names:

- *Tagless Final* (pioneered by Oleg Kiselyov)
- *Polymorphic Programs*
- *Monad Classes* and `mtl`-*style* (mostly in Haskell-land)

There is also some terminology about the elements:

- *Algebra* refers to the type class, which defines the *operations*
- Each instance is an *interpreter* or a *handler*

Restrictive monads

`IO` is the ultimate monad: Anything may happen there.

- There is a type class for monads that support `IO` operations.

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

The trend is to create *subsets* of `IO` as type classes:

- You can still interpret them in `IO`.
- You gain safety because operations are restricted.

Time to code!

Exercise 3: *`GambleMonad`*

- Extract the dependencies of a piece of code into type classes.
- Implement interpreters for those type classes, both impure and pure (a tree of all possibilities).

The `Monad` instances are provided, but you can also learn a lot from inspecting them.

Exercise 4: *Three Monads*

Write `Functor`, `Applicative`, `Alternative`, and `Monad` for lists, optionals, and computations with environments.

Generalized ADTs

You must escape your strings

Why not track the difference between both in the data type?

```
data Stringo = NotYetEscaped String
             | Escaped       String

escape :: Stringo -> Stringo
escape (NotYetEscaped s) = Escaped (... s ...)
escape (Escaped       s) = Escaped s
```

You must escape your strings

Why not track the difference between both in the data type?

```
data Stringo = NotYetEscaped String
             | Escaped       String

escape :: Stringo -> Stringo
escape (NotYetEscaped s) = Escaped (... s ...)
escape (Escaped       s) = Escaped s
```

However, now all functions using `Stringo` need to consider both cases (and eventually call `escape`):

- We pollute other functions with escaping.
- **We cannot guarantee that escaping is always performed.**

Tracking information in the types

1. Introduce two (empty) data types to describe the possible states of the string:

```
data Escaped
data NotEscaped
```

Tracking information in the types

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```haskell
data Escaped
data NotEscaped
```

2. Make `Stringo` use this type as *index*:
   - An *index* is a type argument that specifies some property.

```haskell
-- Stringo is indexed by e(scaping)
newtype Stringo e = Stringo String
```

   - As opposed to *parameter*, which defines the type of some sub-component of the type.

```haskell
data Maybe a = Nothing | Just a
```

Tracking information in the types

3. Provide two different ways to create `Stringo`s:

```
fromString :: String -> Stringo NotEscaped
escape     :: Stringo e -> Stringo Escaped
```

Tracking information in the types

3. Provide two different ways to create `Stringo`s:

```
fromString :: String -> Stringo NotEscaped
escape     :: Stringo e -> Stringo Escaped
```

4. Now functions may require the programmer to escape the string by asking for the proper type:

```
buildHtmlTitle :: Stringo Escaped -> HtmlElement
```

Tracking authentication

Imagine that we want to define *connection*s, which may be in three different states:

- *Closed*: No communication is possible.
- *Open*: Only anonymous communication possible.
- *Auth*: We have gone through an additional step of authentication.

We cannot use the same trick as `Stringo`, because different states have **different data**.

Representing data types by their constructors

```
{-# language GADTSyntax #-}

data Character where
  Player  :: BasicStats -> Skills      -> Character
  Fighter :: BasicStats -> CombatStats -> Character
  NPC     :: BasicStats                -> Character
```

Representing data types by their constructors

```haskell
{-# language GADTSyntax #-}

data Character where
  Player  :: BasicStats -> Skills      -> Character
  Fighter :: BasicStats -> CombatStats -> Character
  NPC     :: BasicStats                -> Character

data Maybe a = Nothing | Just a
-- can be written as
data Maybe a where
  Nothing ::      Maybe a
  Just    :: a -> Maybe a
```

Generalized ADTs

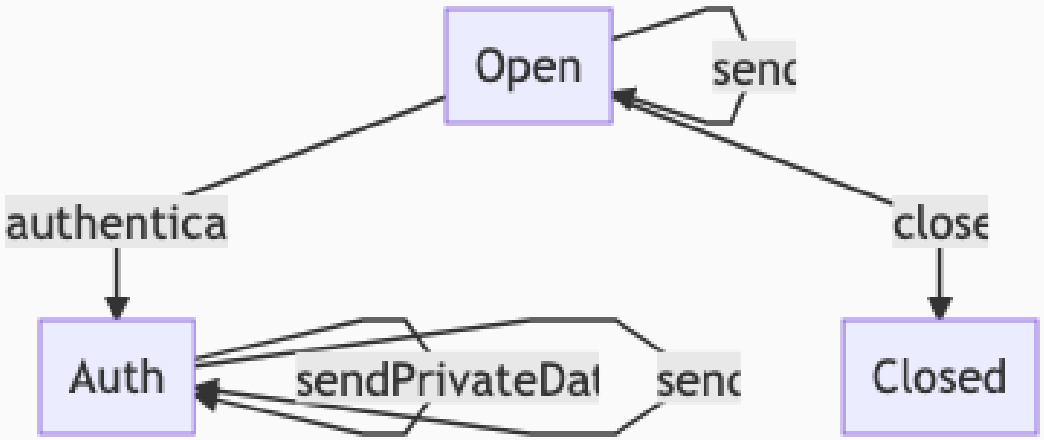
Normal ADTs do not allow us to use different indices for each constructor. **Generalized ADTs** (GADTs) do.

```
data Open
data Closed
data Auth

data Connection s where
  ConnClosed ::                          Connection Closed
  ConnOpen   :: Socket                -> Connection Open
  ConnAuth   :: Socket -> AuthData    -> Connection Auth
```

Connection state machine

```
connect         :: ConnData
                -> IO (Either ConnError (Connection Open))
authenticate    :: AuthData -> Connection Open
                -> IO (Either AuthError (Connection Auth))
sendPrivateData :: Connection Auth -> ByteString -> IO ()
close           :: Connection s -> Connection Closed
```



Sending from `Open` or `Auth`

This type signature is *wrong*: We cannot send if `s` is `Closed`.

```
send :: Connection s -> ByteString -> IO ()
```

Sending from `Open` or `Auth`

This type signature is *wrong*: We cannot send if `s` is `Closed`.

```
send :: Connection s -> ByteString -> IO ()
```

```
class CanSend s where connSocket :: Connection s -> Socket
instance CanSend Open where ...
instance CanSend Auth where ...
```

```
send :: CanSend s => Connection s -> ByteString -> IO ()
```

GADTs are great!

Refine your indices with the *state* of your data.

Then functions work as *transitions* in a state machine.

Yang: Impure concurrent execution

Simple concurrency

Going back to this morning

We have already dealt with concurrency issues in the TCP server.

- Each connection gets its own thread.
- Communication was done using Software Transactional Memory.

Going back to this morning

We have already dealt with concurrency issues in the TCP server.

- Each connection gets its own thread.
- Communication was done using Software Transactional Memory.

How do you create your own threads?

Parallelism for pure code

Haskell code is great for parallelism:

- The input is immutable, so you can reorder the computations as you want.
- Some higher-order functions lean themselves to be parallelize.
  - Think of a `map` or an associative `fold`.

Parallelism for pure code

Haskell code is great for parallelism:

- The input is immutable, so you can reorder the computations as you want.
- Some higher-order functions lean themselves to be parallelize.
  - Think of a `map` or an associative `fold`.

Two main strategies in the Haskell ecosystem:

- `parallel` uses *strategies* to define how to parallelize.
  - "Divide this list in chunks of length 5, and do each one in parallel".
- `monad-par` uses a *promise*-based interface.

Spawn-based parallelism

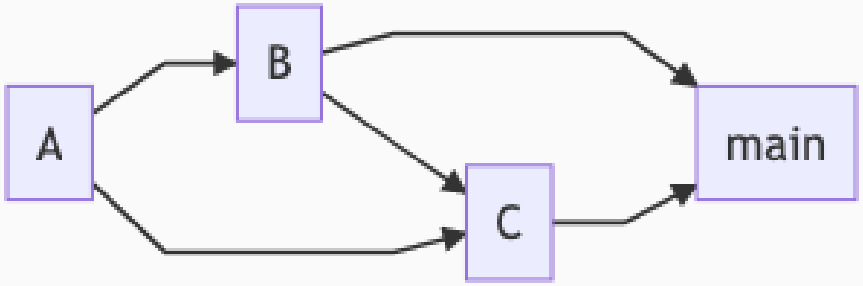
Similar to STM, we have a specialized `Par` monad.

```
-- ask to run computations in parallel
spawn  :: NFData a => Par a -> Par (IVar a)
spawnP :: NFData a =>      a -> Par (IVar a)

-- read the result of a computation
get :: IVar a -> Par a

-- actually execute the computation
runPar :: Par a -> a
```

Data flow parallelism




```
promiseA <- spawn codeA
promiseB <- spawn $ do valA <- read promiseA
                       codeB
promiseC <- spawn $ do valA <- read promiseA
                       valB <- read promiseB
                       codeC
valB <- read promiseB
valC <- read promiseC
mainComputation valB valC
```

Parallelism for `IO`

We usually want to parallelize input/output operations:

- Download two files in parallel.
- Send data to a database and an event store.

Parallelism for `IO`

We usually want to parallelize input/output operations:

- Download two files in parallel.
- Send data to a database and an event store.

Again, we have two library choices:

- `monad-par` provides `ParIO` in addition to `Par`.
  - No need to learn another set of functions.

```
runParIO :: ParIO a -> IO a
```

- `async` also provides a promise-based interface.
  - More control on execution: computations can be cancelled.
  - Exceptions are propagated correctly.

Example of `Async`

`simpleHTTP` comes from the `HTTP` library.

```
withAsync (simpleHTTP (getRequest "http://foo")) $ \req1 ->
withAsync (simpleHTTP (getRequest "http://bar")) $ \req2 ->
do rsp1 <- wait req1
   rsp2 <- wait req2
   case (rsp1, rsp2) of
     (Right res1, Right res2) -> ...
     _ -> putStrLn "error downloading"
```

Useful combinators

Spawning threads and waiting for all of them is quite common.

```
responses <- concurrently (simpleHTTP (getRequest ...))
                          (simpleHTTP (getRequest ...))
case responses of ...
```

Useful combinators

Spawning threads and waiting for all of them is quite common.

```
responses <- concurrently (simpleHTTP (getRequest ...))
                          (simpleHTTP (getRequest ...))
case responses of ...
```

There are more combinators in `async`:

```
   concurrently :: IO a -> IO b -> IO (a, b)
           race :: IO a -> IO b -> IO (Either a b)
mapConcurrently :: Traversable t
                => (a -> IO b) -> t a -> IO (t b)
```

Green threads

By default, Haskell threads are not real OS threads.

- We call them *green threads*.
- Main difference: Threads are managed by the run-time.
- Result: They are extremely cheap to create.

Most I/O operations use non-blocking primitives under the hood.

- The I/O manager takes care of pausing and resuming threads when the work they required has been done.
- There is a lot of work in a parallel I/O manager.

Haskell's `IO` versus ZIO / Cats Effects / ...

Haskell's ecosystem has all the building blocks:

- `IO` marks impure computations,
- `Async` is similar to a fiber,
- `STM` provides variables and queues,
- `Managed` handles resources gracefully,
- `Conduit` gives you streams.

Haskell's `IO` versus ZIO / Cats Effects / ...

Haskell's ecosystem has all the building blocks:

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- `Managed` handles resources gracefully,
- `Conduit` gives you streams.

Missing:

- reified information over exceptions,
- fine-grained control over execution.

Time to code!

Exercise 5: *Tossing coins in different ways*

- Implement a simple function that produces n random Booleans using different styles of parallel and concurrent programming in Haskell.
- Measure the performance of each of them.

Streaming libraries

Manual input/output can be hard

We have already looked at several problems:

- Laziness means consuming at unexpected moments,
  - This may incur in huge memory consumption,
- Resource (de)allocation is hard,
- All of this, combined with correct exception handling.

Streaming libraries

`conduit`, `pipes`, and `streaming` try to solve these problems:

- Keep a constant memory usage,
  - No need to keep all data in memory,
- Handle resources correctly,
  - Close a file when you have arrived to the EOF,
- Common interface for data consumption and generation.

Streaming libraries

`conduit`, `pipes`, and `streaming` try to solve these problems:

- Keep a constant memory usage,
  - No need to keep all data in memory,
- Handle resources correctly,
  - Close a file when you have arrived to the EOF,
- Common interface for data consumption and generation.

`conduit` seems to have the most "adapters" in the ecosystem.

- Be aware of pre-1.3 documentation!

Core concepts

```
data ConduitT input output effects result
```

- Consumes a stream of values of type `input`,
- Produces a stream of values of type `output`,
- May produce effects from monad `effect`,
- At the end, produces a single value of type `result`.

Core concepts

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```

- Consumes a stream of values of type `input`,
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- May produce effects from monad `effect`,
- At the end, produces a single value of type `result`.

The connect/fuse operator joins two of them:

```haskell
(.|) :: Monad m => ConduitM a b m ()
                -> ConduitM b c m r
                -> ConduitM a c m r
```

`ConduitT` is very general

Producers (or sources):

```
sourceFile :: FilePath -> ConduitT i ByteString m ()
```

Consumers (or sinks):

```
-- without interesting result
sinkFile :: FilePath -> ConduitT ByteString o m ()
-- with interesting result
sumC :: Num n => ConduitT n o m n
```

Transformers (or conduits):

```
mapC :: (a -> b) -> ConduitT a b m ()
```

Running a `ConduitT`

You need to "start the engine" by means of:

```
runConduit     :: Monad m
               => ConduitT () Void m r -> m r
runConduitRes  :: MonadUnliftIO m
               => ConduitT () Void (ResourceT m) r -> m r
runConduitPure :: ConduitT () Void Identity r -> r
```

Running a `ConduitT`

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```
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               => ConduitT () Void (ResourceT m) r -> m r
runConduitPure :: ConduitT () Void Identity r -> r
```

- `ResourceT` takes care of resource management.
- `Identity` is the do-nothing monad.
- `Void` is a data type with *no* values.
  - That means that, by the end of your pipeline, all data must have been consumed.

Shout the contents of a file

In other words, print the contents of a file, but all in capitals.

```
sourceFile :: FilePath -> ConduitT i ByteString m ()
decodeUtf8LenientC ::     ConduitT ByteString Text m ()
mapC toUpper ::           ConduitT Text Text m ()
encodeUtf8C ::            ConduitT Text ByteString m ()
stdoutC ::                ConduitT ByteString o m ()
```

Shout the contents of a file

In other words, print the contents of a file, but all in capitals.

```
sourceFile :: FilePath -> ConduitT i ByteString m ()
decodeUtf8LenientC ::     ConduitT ByteString Text m ()
mapC toUpper ::           ConduitT Text Text m ()
encodeUtf8C ::            ConduitT Text ByteString m ()
stdoutC ::                ConduitT ByteString o m ()

shoutFile fp = runConduitRes $
      sourceFile fp .| decodeUtf8LenientC
   .| mapC Data.Text.toUpper
   .| encodeUtf8C .| stdoutC
```

Where to look for conduits?

- `conduit` and `conduit-extra`
  - basic list-like operators (map, fold)
  - filesystem, network, binary serialization...
- `http-conduit`: Simple HTTP requests
- `stm-conduit`: Wraps STM channels
- `ndjson-conduit`: Wraps Aeson for JSON serialization
- `amqp-conduit`: Connects to RabbitMQ
- `hw-kafka-conduit`: Connects to Kafa
- and many more in Stackage and Hackage!

Writing our own conduit

Most of the time you use combinators, but the interface is not very complicated:

- `ConduitT i o m` is a monad.
  - `return` gives the result and marks the stream as finished.
- `await` obtains the next input value,
  - It returns `Nothing` if the stream is finished.
- `yield` and `yieldM` generate an output value.

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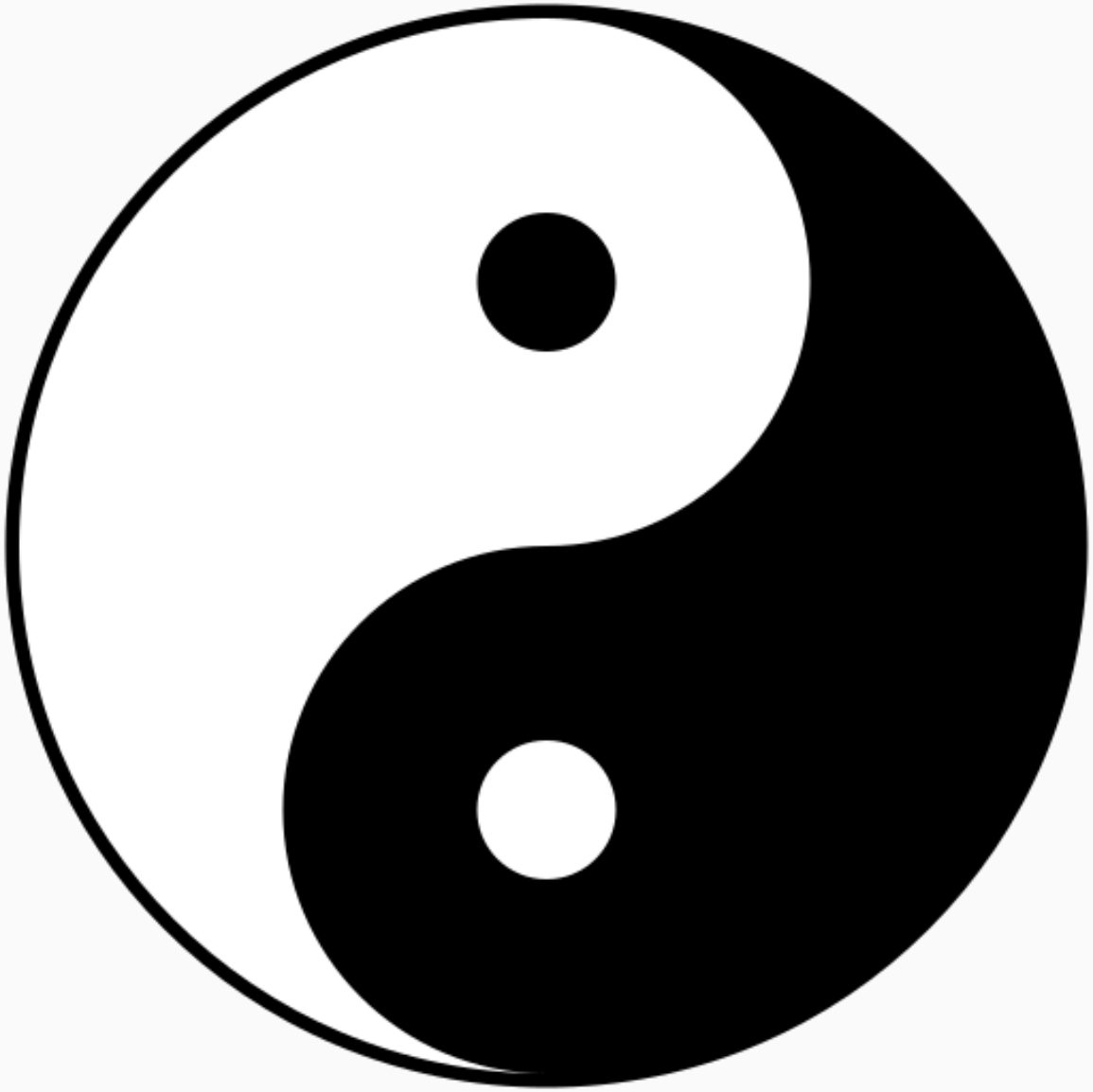
```
duplicate :: Monad m => ConduitT v v m ()
duplicate = do v <- await
               case v of
                 Nothing -> return ()
                 Just w  -> yield w >> yield w >> duplicate
```

Time to code!

Exercise 6: *A chat server using streams*

- Implement a chat server using streams to communicate between clients and to wrap the connections.
- If time allows, implement private messages.



Common architectural patterns

The main question

What should be the types of my bussiness domain?

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The “frontiers” of an application must have some sort of `IO` type.

Answer 1: Hexagonal / onion architecture

Functions use the *polymorphic programs* technique to declare their *dependencies*.

```
orcStrategy :: (Monad m, Gamble m, DrawWorld m) => ...
```

- Each of the type classes works as a *port*.
- Each instance defines an *adapter*.
- The compiler *injects* the dependencies based on the types.

```
instance DrawWorld IO   where ...
instance DrawWorld Html where ...
```

Answer 2: Functional core, imperative shell

Functions are completely pure.

```
orcStrategy :: CombatData -> Character -> NextMove
```

- Pure functions are then composed in larger pipelines that consume the data in the system.
- A somehow dumb shell that moves data around the systems.

This is the same architetcure as in Gloss (or Elm, or even React).

Answer 2': Streaming FC/IS

Defining an application using streams is very close to the previous architecture:

- Pure stream transformers form the functional core.
- Around them you plug side-effectful sources and sinks, which make up the imperative shell.

What does a function represent?

- In FC/IS, functions are pure data manipulation, and type reflect the shape of the data they work with.
- In H/O architecture, types reflect the services from other contexts needed to run the application.

What does a function represent?

- In FC/IS, functions are pure data manipulation, and type reflect the shape of the data they work with.
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Unfortunately, there is no answer to which point of view is best.

Summary

The Yin: Pure modelling

- Modelling data:
  - Make *sum types* part of your designs.
  - Distinguish between different concepts with *different types*.
  - Provide different *views* for the same data.
- Modelling services:
  - Polymorphic programs declare their *dependencies as type classes* (or algebras).
  - Using different instances, we can provide different implementations, including mocks.
  - *Monads* are the basic structure for sequential computation.

The Yang: Impure execution

- Laziness means the run-time evaluates "only when needed" and "as much as needed."
  - Space leaks: We keep too many thunks in memory.
  - Can be solved by selective forcing.
- Input/output is tricky.
  - Exceptions may arise
  - Laziness conflicts with resource management.
  - Streaming offers a good solution.
- Concurrency is simple.
  - GHC uses (lightweight) green threads by default.
  - `monad-par` and `async` provide promise-based interfaces.
  - STM adds transactional behavior to shared variables.

The Duality

Two main architectural patterns:

1. Hexagonal / onion archiecture.
    - Use polymorphic program technique in your domain.
2. Functional core, reactive shell
    - Keep the domain as pure data-manipulation functions.

- Pattern matching and view patterns.
- `do` notation for monads.
- Generics to derive serialization.
- Profiling and benchmarking.
- *Missing*: Applicative notation.

Where to go next?

- Look at property-based testing (QuickCheck and friends).
- Understand parsing (for example, `aeson`):
  - Learn about `(<$>)`, `(<*>)`, and `(<|>)`.
- More type-level programming:
  - Type families, data kinds, singletons.
  - Servant defines REST APIs at type level.
  - Persistent and Esqueleto define type-safe database queries.
- Reify programs as data:
  - Free and operational monads.

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As usual, keep practicing, reading, and learning.

- Mailing list, blogs, Discourse, IRC.

One final warning

Haskell is also widely used as a vehicle for research.

- That you cannot read a research paper about type families, and understand the whole formalization, does not mean that you cannot use them.
- Be wise with the resources that you choose.

Enjoy Lambda World!

(I'll be around. Feel free to ask anything during these days)