COMP3141

Software System Design and Implementation

Effects and State

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Example (IO)

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Example (Non-termination)

```
// infinite loop
while (1) {};
```

Example (Control flow)

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// exception effect
throw new Exception();
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Internal vs. External Effects

External Observability

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Are memory effects *external* or *internal*?

Answer: Depends on the scope of the memory being accessed. Global variable accesses are *external*.

Purity

A function with no external effects is called a *pure* function.

Pure functions

A *pure function* is the mathematical notion of a function. That is, a function of type `a -> b` is *fully* specified by a mapping from all elements of the domain type `a` to the codomain type `b`.

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Question: Are Haskell functions pure?

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Despite the impurity of Haskell functions, we can often reason as though they are pure. Hence we call Haskell a purely functional language.

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We can't, in general, reason equationally about effectful programs!

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Typically, a computation involving some state of type `s` and returning a result of type `a` can be expressed as a function:


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Efficiency?

All that copying might seem expensive, but by using tree data structures, we can usually reduce the cost to an $\mathcal{O}(\log n)$ overhead.

State Passing

Example (Labelling Nodes)

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data Tree a = Branch a (Tree a) (Tree a) | Leaf
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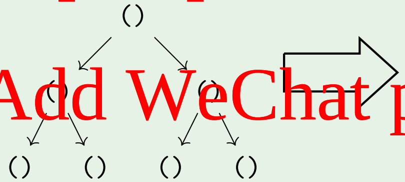
Given a tree, label each node with an ascending number in infix order:

```
label :: Tree () -> Tree Int
```



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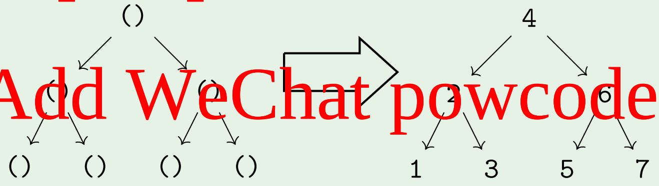

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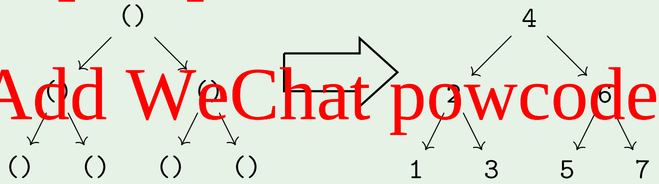

Let's use a data type to simplify this!

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Sequential Composition

Do one state action after another with `do` blocks:

```
do put 42          desugars
   pure True         ==>      put 42 >> put True
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(>>) :: State s a -> State s b -> State s b
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Bind

The 2nd step can depend on the first with bind:

```
do x <- get      desugars
   pure (x+1)       ==>      get >>= \x -> pure (x + 1)
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Example

Implement `modify`:

```
(s -> s) -> State s ()
```

And re-do the tree labelling.

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State Implementation

The `State` type is essentially implemented as the same state passing we did before!

```
newtype State s a = State (s -> (s,a))
```

Example

Let's implement each of the `State` operations for this newtype.

Caution

In the Haskell standard library `mtl`, the `State` type is actually implemented slightly differently, but the implementation essentially works the same way.

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Haskell's approach

Pure by default. Effectful when necessary.

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A procedure that performs some side effects, returning a result of type a is written as `IO a`.

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World interpretation

IO a is an abstract type. But we can think of it as a function:


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```
(>>=) :: IO a -> (a -> IO b) -> IO b
pure  :: a -> IO a

getChar :: IO Char
readLine :: IO String
putStrLn :: String -> IO ()
```

Infectious IO

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The only function that gets an `a` from an `IO a` is `>>=`:

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(>>=) :: IO a -> (a -> IO b) -> IO b
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But it returns an `IO` procedure as well.

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But it returns an IO procedure as well.

Conclusion

The moment you use an IO procedure in a function, IO shows up in the types, and you can't get rid of it!

If a function makes use of IO effects directly or indirectly, it will have IO in its type!

Haskell Design Strategy

We ultimately "run" IO procedures by calling them from main:

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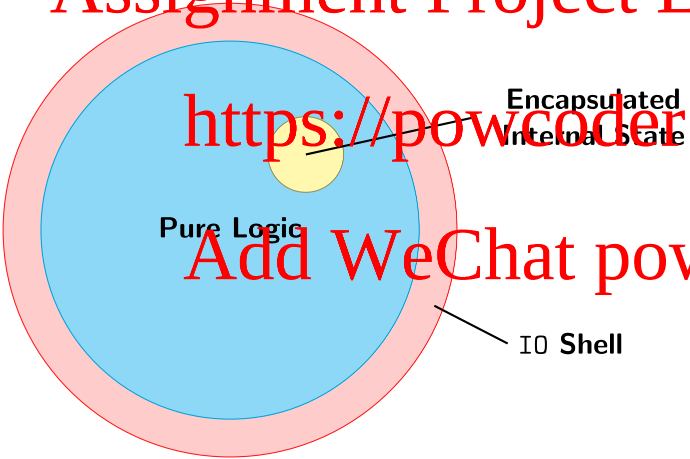

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Given an input number n, print a triangle of $*$ characters of base width n.

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Example (Maze Game)

Design a game that reads in a $n \times n$ maze from a file. The player starts at position $(0, 0)$ and must reach position $(n-1, n-1)$ to win. The game accepts keyboard input to move the player around the maze.

Benefits of an IO Type

- Absence of effects makes type system more informative:
  - A type signatures captures entire interface of the function.
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- It is easier to reason about pure code and it is easier to test:
  - Testing is local, doesn't require complex set-up and tear-down.
  - Reasoning is local, doesn't require state invariants.
  - Type checking leads to strong guarantees.

Mutable Variables

We can have honest-to-goodness mutability in Haskell, if we really need it, using IORef.


```haskell
data IORef a
newIORef :: a -> IO (IORef a)
readIORef :: IORef a -> IO a
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Example (Effectful Average)

Average a list of numbers using `IORefs`.

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Something like averaging a list of numbers doesn't require external effects, even if we use mutation internally.

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data STRef s a
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Note

The ST type is not assessable in this course, but it is useful sometimes in Haskell programming.

QuickChecking Effects

QuickCheck lets us test IO (and ST) using this special property monad interface:


```
monadicIO :: PropertyM IO () -> Property
pre       :: Bool -> PropertyM IO ()
assert    :: Bool -> PropertyM IO ()
run       :: IO a -> PropertyM IO a
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Do notation and similar can be used for PropertyM IO procedures just as with State s and IO procedures.

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Example (Testing gfactor)

Let's test that the GNU factor program works correctly!

Homework

1. New exercise out, due the week after next week.
2. Last week's quiz is due on Friday.
3. This week's quiz is due the Friday after the following Friday.