Software System Design and Implementation

Controlling Effects

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Examples of effects

```
printf ("Hello World!");
```

I/O effect

```
char c = getchar ();
```

I/O effect

```
int *p;

 :
*p = *p + 2;
```

write effect

read effect

```
class MyException
extends Exception {}

 :
throw new MyException();
```

exception effect (non-local control flow)

```
pthread_t mythread;

pthread_create (&mythread, NULL, thread_function,
                NULL);
```

thread-creation effect

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Internal versus external effects

- External effects can be observed outside of the function where they occur
    - I/O is an external effect
    - Accessing a global variable may be an external effect
- Internal effects cannot be observed on the outside
    - Allocating, using, and deallocating memory
- We can often treat a function with only internal effects as a pure function
    - Purity is about what is observable!

A definition of pure functions

- A pure function is fully specified by a mapping of argument to result values
- Consequences include the following:
  - Two invocations with the same arguments result in the same result
  - A pure function leaves no observable trace beyond its result
- Caveat:
  - Purity pertains to a particular level of abstraction
  - After all, the assembly instructions of a pure Haskell function are not pure

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A definition of impure or effectful functions

- An impure or effectful function is one that is not pure:
  - it makes use of information beyond its arguments or
  - produces an observable effect beyond its result (or both)
- They are not functions in the mathematical sense; they are sometimes called procedures

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Why are effects harmful?

- They introduce (often subtle) requirements on the execution order
- They are not readily apparent from a function prototype or signature
- They introduce non-local dependencies
- They interfere badly with strong typing; for example:
    - Subtyping and mutable arrays in Java (even worse with generics)
    - Polymorphism and mutable references in ML

Effects and execution order

- Execution order can be surprising
- Execution order can be indeterminate:
  - Global object initialisation
  - Concurrency

```c
#include <stdio.h>

int main (int argc, char *argv[])
{
    if (getchar () < getchar ()) printf ("yes\n"); else printf ("no\n");
    return 0;
}
```

```c
#include <stdio.h>

void compare_chars (char x, char y)
{
    if (x < y) printf ("yes\n"); else printf ("no\n");
}

int main (int argc, char *argv[])
{
    compare_chars (getchar (), getchar ());
    return 0;
}
```

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Avoiding effects

- Without effects, all functions are pure
  - Can you program like that?
  - Experience suggest, yes — actually, very well!
  - Need to get used to the programming style, though
- It impacts the program structure (often positively)
- It may require the use of different algorithms
- Leads to purely functional programming

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Sometimes we need effects

- Most notably: I/O is usually effectful
- Interoperating with impure languages requires effects
- Sometimes effectful algorithms are more efficient
    - Internal effects are usually sufficient

Haskell's approach:
Pure by default, effectful when necessary!

Haskell functions are pure by default

```
f :: a -> b
```

- Maps a value of type `a` to a value of type `b` without any effects
- Effectful functions require specialised types

Haskell functions are pure by default

```
f :: a -> b
```

- Maps a value of type **`a`** to a value of type **`b`** without any effects

- Effectful functions require specialised types

perform external effects and then return a value of type b

```
g :: a -> IO b
```

Effects need to be carefully contained

- Effects have to be reflected in the type:

```
g :: a -> World -> (b, World)
```

```
printStr ::  String -> World -> ((), World)
```

```
getChar ::  World -> (Char, World)
```

- Why is this problematic?

Effects need to be carefully contained

- Effects have to be reflected in the type:

```
g :: a -> World -> (b, World)
```

```
newtype IO b = IO (World -> (b, World))
```

conceptually, the `World` is hidden inside the abstract data type `IO`

```
g :: a -> IO b
```

```
main      :: IO ()
```

```
getChar   :: IO Char
```

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

What can we do with `IO` operations?

- Combine them to form more complex IO-operations using the do notation:

```
do {
  putStrLn “Hi, ”;               :: IO()
  putStrLn “how are you?”;       :: IO()
}
```

Braces and semicolon optional

- This is a kind a function composition, as the world is passed from the first to the second operation, and so on

- All operations in the do have to be of type `IO`

The do notation and types

```
getChar :: IO Char
putChar :: Char -> IO ()
```

Type mismatch:
`IO Char != Char`

```
putChar getChar
```

Type error!

`IO Char`

`Char`

```
do {
  c <- getChar;
  putChar c;
}
```

Strips the `IO`

What can we do with IO operations?

```
do {
    ch1 <- getChar;                    :: IO Char
    ch2 <- getChar;                    :: IO Char
    if (ord ch1 < ord ch2)
      then putStrLn “yes”              :: IO ()
      else putStrLn “no”               :: IO ()
  }
```

What can we do with `IO` operations?

- Call pure functions and bind their return value to a variable:

```
do {
  ch <- getChar;                  :: IO Char
  let chUp = toUpper ch           :: IO Char
  return (ord chUp)               :: IO Int
 }
```

```
return :: a -> IO a
```

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What can't we do with `IO` operations?

- We cannot write a function of type:

```
IO a -> a
```

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Effects need to be carefully contained

```
f x = ...g...

g :: a -> IO b
g y = ...
```

contaminated by effects

- If a pure function `f` calls an impure function `g`, `f` becomes impure
- We have the following rule:
  - Only impure functions can call impure functions
  - Unless the inner function contains only internal effects that we encapsulate

Haskell uses the type system, to enforce this rule

Local state

- Sometimes, local state is sufficient

```
g :: a -> s -> (b, s)
```

state can be different things

```
State s b
```

```
runState :: State s a -> s -> (a, s)
```

- Let's say we want a global counter:

```
type Counter = State Int

getCnt :: Counter Int
incCnt :: Counter ()
setCnt :: Int -> Counter ()
```

```
incCounterMax :: Int -> Counter Bool
incCounterMax max = do
  curr <- getCnt
  if curr < max
    then do {incCnt; return False}
    else do {setCnt 0; return True}
```

Which on type constructors can we use the ‘do’ notation?

- The type constructor `m` has to be a ***monad***

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

called “bind”

- The do-notation is just syntactic sugar to make using bind more convenient
- Following properties have to be met:

```
• return a >>= k                =    k a
• ma >>= return                 =    ma
• ma >>= (\x -> k x >>= h)      =   (ma >>= k) >>= h
```

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Monads don't necessarily encapsulate state

- `Maybe` type constructor is another example of a monad

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

```
return :: a -> Maybe a
return x = Just x

(>>=) :: Maybe a -> (a -> Maybe b) -> Maybe b
(>>=) Nothing _   = Nothing
(>>=) (Just x) f = f x
```

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Monads don’t necessarily encapsulate state

- `[ ]` type constructor is another example of a monad

```
return :: a -> [a]
return x = [x]

(>>=) :: [a] -> (a -> [b]) -> [b]
(>>=) as f  = concat (map f as)
```

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Generators in QuickCheck are monads

```
searchTrees :: Gen BinaryIntTree
searchTrees = sized searchTrees'
  where
   searchTrees' 0 = return Leaf
   searchTrees' n = do
      v <- (arbitrary :: Gen Int)
      fmap (insert v) (searchTrees' $ n - 1)
```

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

The benefits of controlling effects

- Absence of effects makes strong typing in pure functions more powerful
  - A type signature captures the entire interface of a function
  - All dependencies are explicit in the form of data dependencies
  - All dependencies are typed
- It is easier to reason about pure code & and it is easier to test pure code
  - Testing and reasoning (formal & informal) is local, independent of context
  - Type checking leads to stronger guarantees

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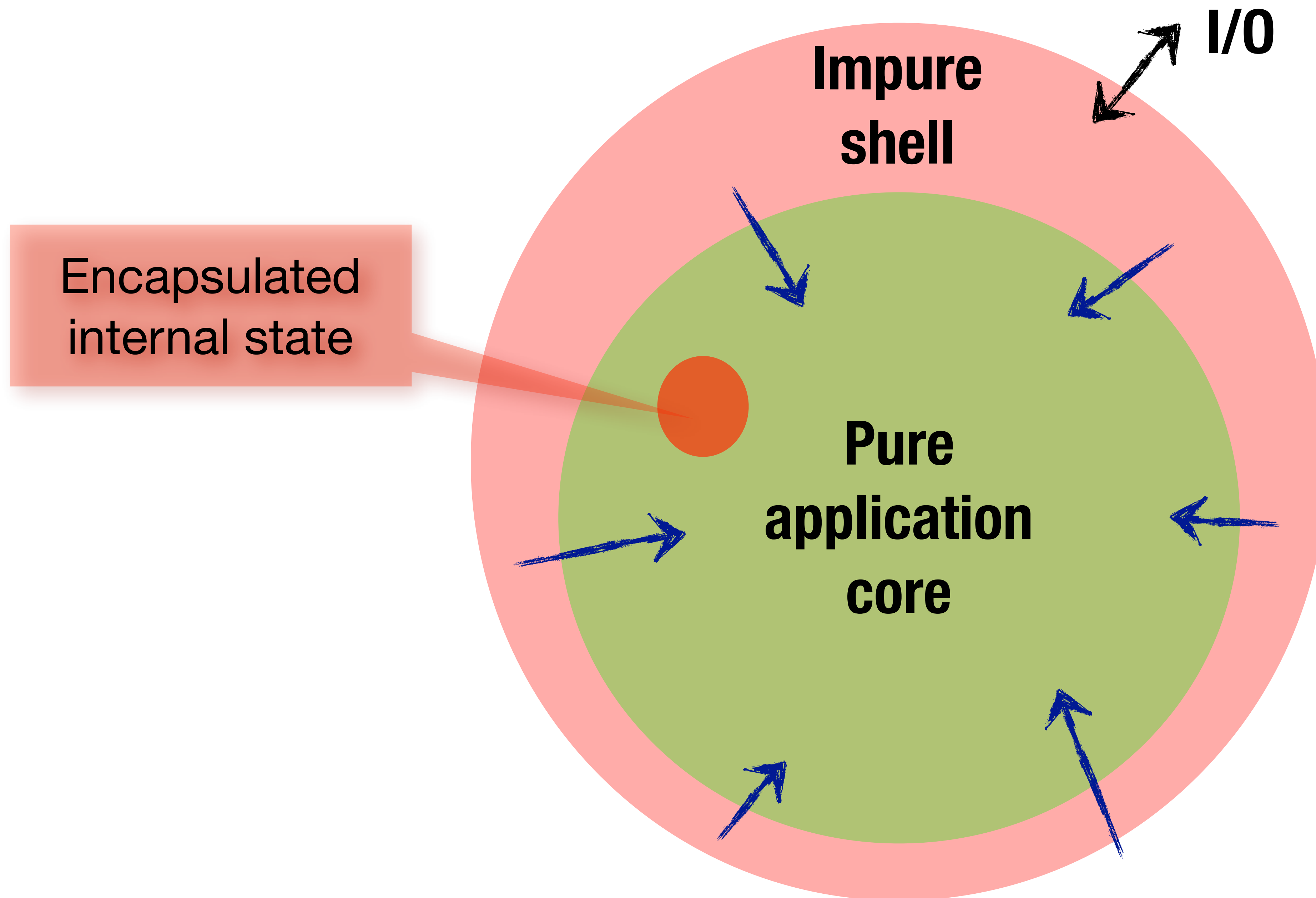
The pure-by-default architecture



Mutable variables in Haskell

Mutable variables in `IO` computations

```
data IORef a
newIORef   :: a               -> IO (IORef a)
readIORef  :: IORef a         -> IO a
writeIORef :: IORef a -> a -> IO ()
```

Let's look at an example

```haskell
import Data.IORef

printIORef :: IORef Int -> IO ()
printIORef ref
  = do
      v <- readIORef ref
      print v

main
  = do
      ref <- newIORef 10
      printIORef ref
      writeIORef ref 42
      printIORef ref
```

Two flavours of mutable variables

```
data IORef a
newIORef   :: a              -> IO (IORef a)
readIORef  :: IORef a        -> IO a
writeIORef :: IORef a -> a -> IO ()
```

can only be run from `main`

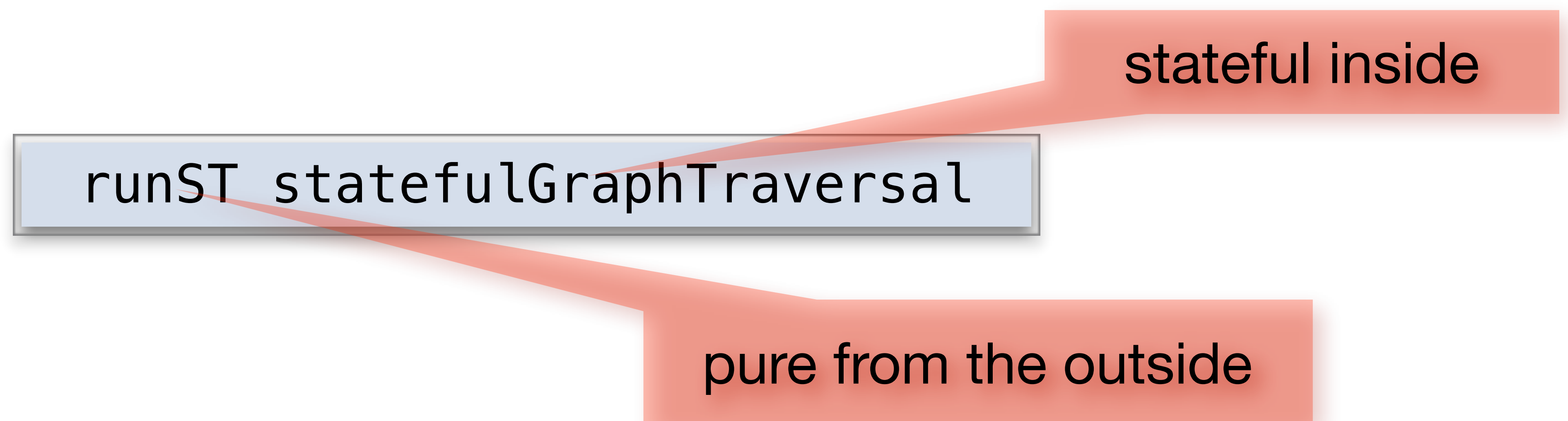
Let's look at an example

```
data STRef s a
newSTRef   :: a                -> ST s (STRef s a)
readSTRef  :: STRef s a        -> ST s a
writeSTRef :: STRef s a -> a -> ST s ()
```

run with `runST :: (forall s. ST s a) -> a`

Encapsulated state

- Some algorithms suggest stateful code
  - For example, a graph traversal marking visited nodes to spot cycles



- The type variable `s` in `STRef s a` represents a state thread
- It ensures that state from one `runST` invocation cannot leak into another

IO versus ST

```
data IORef a
newIORef   :: a                -> IO (IORef a)
readIORef  :: IORef a          -> IO a
writeIORef :: IORef a -> a -> IO ()
```

```
data STRef s a
newSTRef   :: a                    -> ST s (STRef s a)
readSTRef  :: STRef s a            -> ST s a
writeSTRef :: STRef s a -> a -> ST s ()
```

- Both `IO` and `ST s` mark the use of state
- Both can be used with the `do` notation

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