

Advanced Functional Programming 2011-2012, period 2

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9. Exceptions, Networking, Concurrency

9.1 Handle-based IO



Handles

Most basic IO functions such as getLine, putStr have a cousin that works on an arbitrary **handle**.

System.IO

```
data Handle -- abstract -- opening files openFile :: FilePath \rightarrow IOMode \rightarrow IO Handle openBinaryFile :: FilePath \rightarrow IOMode \rightarrow IO Handle
```

Using handles

System.IO

-- operating on handles

hClose :: Handle \rightarrow IO ()

 $hIsTerminalDevice :: Handle \rightarrow IO Bool$

 $\mathsf{hSetBuffering} \qquad :: \mathsf{Handle} \to \mathsf{BufferMode} \to \mathsf{IO} \; ()$

hFlush :: Handle \rightarrow IO ()

-- input/output on handles

 $\begin{array}{ll} \mathsf{hPutStr} & :: \mathsf{Handle} \to \mathsf{String} \to \mathsf{IO} \ () \\ \mathsf{hGetLine} & :: \mathsf{Handle} \to \mathsf{IO} \ \mathsf{String} \\ \mathsf{hGetContents} & :: \mathsf{Handle} \to \mathsf{IO} \ \mathsf{String} \end{array}$

-- standard handles

:: Handle stdout :: Handle stdin stderr :: Handle





Terminal 10

Most terminal IO functions are special cases of the handle IO functions:

 $\begin{aligned} &\mathsf{putStr} :: \mathsf{String} \to \mathsf{IO}\ () \\ &\mathsf{putStr}\ \mathsf{s} = \mathsf{hPutStr}\ \mathsf{stdout}\ \mathsf{s} \end{aligned}$

getLine :: IO String

 $\mathsf{getLine} = \mathsf{hGetLine} \ \mathsf{stdin}$

 ${\tt getContents} :: {\sf IO} \ {\sf String}$

getContents = hGetContents stdin

Buffering

Buffering is often a source of unexpected behaviour.

- ▶ No buffering: everything is directly read or written.
- ► Line-buffering: everything up to the next newline is buffered and then read or written at once.
- ▶ Block-buffering: blocks of a certain size are buffered and then read or written at once.

Terminals should typically be line-buffered, files are typically block-buffered. The stderr output is typically not buffered.



Lazy IO

Another pitfall is the use of lazy IO:

 $\mbox{hGetContents} :: \mbox{Handle} \rightarrow \mbox{IO String} \\ \mbox{getContents} :: \mbox{IO String} \\$

getContents = hGetContents stdin

 $\mbox{readFile} :: \mbox{FilePath} \rightarrow \mbox{IO String} \\ \mbox{readFile name} = \mbox{openFile name ReadMode} \ggg \mbox{hGetContents} \\$

The function hGetContents internally makes use of

System.IO.Unsafe.unsafeInterleaveIO :: IO a ightarrow IO a

This function delays an IO computation of type IO a and returns it as a thunk of type a.



The dangers of lazy IO

- ▶ The whole file is returned as a string, but it is only read when the string is evaluated.
- Lazy IO is only safe if the underlying files are essentially static and do not change.
- ▶ If the file changes in the meantime, unexpected effects can occur.
- ▶ The use of lazy IO in Haskell is often considered a mistake.

9.2 (Extensible) Exceptions





Exceptions

- ► IO operations are a common source of exceptions in Haskell.
- ▶ GHC has a very general exception handling mechanism.
- ► Exceptions have been changed for GHC-6.10.1 so that the exception mechanism is more extensible.

The Exception class

```
 \begin{array}{ll} \textbf{class} \ (\mathsf{Typeable} \ \mathsf{e}, \mathsf{Show} \ \mathsf{e}) \Rightarrow \mathsf{Exception} \ \mathsf{e} \ \mathsf{where} \\ \mathsf{toException} & :: \mathsf{e} \to \mathsf{SomeException} \\ \mathsf{fromException} & :: \mathsf{SomeException} \to \mathsf{Maybe} \ \mathsf{e} \\ -- \ \mathsf{default} \ \mathsf{implementations} \\ \mathsf{toException} & = \mathsf{SomeException} \\ \mathsf{fromException} \ (\mathsf{SomeException} \ \mathsf{e}) = \mathsf{cast} \ \mathsf{e} \\ \\ \textbf{data} \ \mathsf{SomeException} \ \mathsf{::} \ \forall \mathsf{e}. (\mathsf{Exception} \ \mathsf{e}) \Rightarrow \mathsf{e} \to \mathsf{SomeException} \\ \\ \mathsf{SomeException} \ \colon \forall \mathsf{e}. (\mathsf{Exception} \ \mathsf{e}) \Rightarrow \mathsf{e} \to \mathsf{SomeException} \\ \end{aligned}
```

Another existential type. This syntax of declaring datatypes was introduced together with GADTs (later in the course). We just list the types of the constructors.



Excursion: GADT syntax

Every datatype can alternatively be defined by listing the types of its constructors. Kind signatures should be given for parameterized types:

```
\begin{array}{ccc} \textbf{data} \; \mathsf{Tree} :: * \to * \; \textbf{where} \\ \mathsf{Leaf} \; :: \mathsf{a} & \to \mathsf{Tree} \; \mathsf{a} \\ \mathsf{Node} :: \mathsf{Tree} \; \mathsf{a} \to \mathsf{Tree} \; \mathsf{a} \end{array}
```

Excursion: GADT syntax

Every datatype can alternatively be defined by listing the types of its constructors. Kind signatures should be given for parameterized types:

Existential types are very natural to define in this syntax. Recall the Stream type:

```
data Stream :: * where
     \mathsf{Stream} :: (\mathsf{s} \to \mathsf{Step} \; \mathsf{s}) \to \mathsf{s} \to \mathsf{Int} \to \mathsf{Stream}
\begin{array}{ll} \textbf{data} \ \mathsf{Step} :: * \to * \ \textbf{where} \\ \mathsf{Done} :: & \mathsf{Step} \ \mathsf{s} \end{array}
    Yield :: Word8 \rightarrow s \rightarrow Step s
 Skip :: s \rightarrow Step s
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```

Excursion: Typeable – dynamic typing in Haskell

- ► The type TypeRep holds run-time type information.
- ► The function cast is safe if no two types get the same TypeRep and the equality function on TypeRep is sane.
- ► Unfortunately, this cannot yet be enforced in Haskell's class system.



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Excursion: Typeable – deriving instances

- ▶ Defining good instances of Typeable is critical for the safety of a program.
- ► Therefore, Typeable instances should best not be defined by hand.

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Excursion: Typeable – deriving instances

- ▶ Defining good instances of Typeable is critical for the safety of a program.
- ► Therefore, Typeable instances should best not be defined by hand.
- ► In GHC, you can **derive** instances of Typeable when enabling the DeriveDataTypeable language extension.
- ► The class Typeable shows how we can integrate dynamic typing into a statically type language (available via Data.Dynamic):

```
data Dynamic -- abstract, contains a TypeRep toDyn :: (Typeable a) \Rightarrow a \rightarrow Dynamic fromDyn :: (Typeable a) \Rightarrow Dynamic \rightarrow Maybe a -- uses cast
```



Working with exceptions

Control. Exception. Extensible

```
-- throwing exceptions throw :: (Exception e) \Rightarrow e \rightarrow a throwIO :: (Exception e) \Rightarrow e \rightarrow IO a -- handling exceptions try :: (Exception e) \Rightarrow IO a \rightarrow IO (Either e a) catch :: (Exception e) \Rightarrow IO a \rightarrow (e \rightarrow IO a) \rightarrow IO a handle :: (Exception e) \Rightarrow (e \rightarrow IO a) \rightarrow IO a \rightarrow IO a
```

While exceptions can be thrown everywhere, they can only be caught in an IO context.



Implementation of catch

- ► Given a particular thrown exception of type e, use toException to turn it into SomeException.
- ► Next, use fromException to see if we we can turn it into type e' of the handler.
- ▶ If the type of the handler matches, then call it.
- ▶ Otherwise, re-throw the exception.



Example: catching an exception

```
\label{eq:mport_preduced} \begin{split} & \textbf{import} \  \, \text{Prelude hiding (catch)} \\ & \textbf{import} \  \, \text{Control.Monad} \\ & \textbf{import} \  \, \text{Control.Exception.Base} \\ & \textbf{import} \  \, \text{Control.Exception.Extensible} \\ & \text{safeRead} :: \text{FilePath} \rightarrow \text{IO (Maybe String)} \\ & \text{safeRead name} = \\ & \text{catch (liftM Just (readFile name))} \\ & & (\lambda(\texttt{e} :: \text{IOException}) \rightarrow \\ & & \text{putStrLn "Error"} \gg \text{return Nothing)} \end{split}
```

- Omitting the type annotation IOException triggers a type error – why?
- ► The type annotation requires enabling a language extension: PatternSignatures for GHC-6.8, and ScopedTypeVariables for GHC-6.10.



9.3 Networking





Sockets

- Sockets allow processes to communicate via the network.
- ► A server listens on a particular network port for incoming connections.
- ▶ A client can connect to a host on a particular port.
- Once a connection has been established, two-way communication via the socket becomes possible.
- In Haskell, a high-level socket library is offered by the Network module.
- ► A much more detailed network socket library is available via the Network Socket module.

Communicating via sockets

Network

```
-- initialization with Sockets Do :: IO a \rightarrow IO a -- server-side listen On :: Port ID \rightarrow IO Socket accept :: Socket \rightarrow IO (Handle, Host Name, Port Number) s Close :: Socket \rightarrow IO () -- client-side connect To :: Host Name \rightarrow Port ID \rightarrow IO Handle
```

More on sockets

Use withSocketsDo as an initializer:

 $\mathsf{main} = \mathsf{withSocketsDo}\,\$\,\mathsf{realMain}$

- ▶ The function listenOn opens a socket. It does not block.
- Both connectTo on the client side and accept on the server side block until a connection has been established.
- ► A socket gives both the client and the server a handle to communicate over.
- ▶ Both server and client can terminate an individual connection by closing the handle.
- ▶ The server can also close the entire socket.
- ▶ It is usually a good idea to let the server fork a new thread upon accepting a connection and continue to listen for more connections on the original thread.

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9.4 Threads



Working with threads

Control.Concurrent

```
-- creating a thread forkIO :: IO () \rightarrow IO ThreadId -- managing current thread threadDelay :: Int \rightarrow IO () yield :: IO () myThreadId :: IO ThreadId -- managing other threads killThread :: ThreadId \rightarrow IO () throwTo :: (Exception e) \Rightarrow ThreadId \rightarrow e \rightarrow IO ()
```

Forking a new thread

forkIO $:: IO () \rightarrow IO ThreadId$

- ▶ Note that IO () is also the type of main. We can thus run a whole program in its own thread.
- Any thread can create new threads.
- Haskell threads are very lightweight. They are created and scheduled by the Haskell runtime system and do not require creation of an OS thread.
- ▶ If the main program ends, all its threads are stopped too.
- You can explicitly control other threads by killing them or sending them exceptions via their thread ids.

Threads and shared data

How to communicate between threads?

- Using IORefs to share data between threads is unsafe.
- ► Generally, when working with threads, you have to watch out that they don't interfere with each other (while writing files, for example).



Unsafe shared data demonstration

```
\begin{split} \text{test n} &= \textbf{do} \\ & \quad \quad \times \leftarrow \text{newIORef } 0 \\ & \quad \quad \text{mapM}_{-} \left( \text{forkIO} \circ \text{writer } \times \right) \left[ 1 \ldots n \right] \\ & \quad \quad \text{writer } \times 0 \end{split} writer x m = \do \text{writeIORef } \times \text{m} \tag{readIORef } \times \text{when } \left( m \neq n \right) \left( \text{putStrLn } (\text{show m}) \right) \text{writer } \times m \end{array}
```

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MVars

Control.Concurrent.MVar

```
\begin{array}{lll} \textbf{data} \ \mathsf{MVar} & -- \ \mathsf{abstract} \\ \mathsf{newMVar} & :: \ \mathsf{a} \to \mathsf{IO} \ (\mathsf{MVar} \ \mathsf{a}) \\ \mathsf{newEmptyMVar} :: \ \mathsf{IO} \ (\mathsf{MVar} \ \mathsf{a}) \\ \mathsf{readMVar} & :: \ \mathsf{MVar} \ \mathsf{a} \to \mathsf{IO} \ \mathsf{a} \\ \mathsf{putMVar} & :: \ \mathsf{MVar} \ \mathsf{a} \to \mathsf{a} \to \mathsf{IO} \ () \\ \mathsf{takeMVar} & :: \ \mathsf{MVar} \ \mathsf{a} \to \mathsf{IO} \ \mathsf{a} \\ \end{array}
```

- Unlike an IORef, an MVar can be empty.
- Using putMVar works only if the MVar is empty before. If the MVar is not yet empty, the call blocks.
- ▶ Using takeMVar leaves the MVar empty in the process. If the MVar is empty, the call blocks.
- ► Using MVars, we can implement other concurrency abstractions such as semaphores or channels.

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Using MVars to implement semaphores

► A semaphore controls that no more than a particular number of clients access a particular resource.

```
 \textbf{newtype} \ \mathsf{QSem} = \mathsf{QSem} \ (\mathsf{MVar} \ (\mathsf{Int}, [\mathsf{MVar} \ ()]))
```

- ► The first component of the pair indicates how many clients can still access the resource; the list implements a queue of waiting threads.
- ▶ Note the nested use of MVars.



Creating a new semaphore

```
\begin{array}{l} \mathsf{newQSem} :: \mathsf{Int} \to \mathsf{IO} \; \mathsf{QSem} \\ \mathsf{newQSem} \; \mathsf{initial} = \end{array}
         \mathsf{sem} \leftarrow \mathsf{newMVar}\;(\mathsf{initial},[\,])
              return (QSem sem)
```

Waiting for a semaphore

```
\label{eq:partial_sem} \begin{split} \text{waitQSem} &:: \mathsf{QSem} \to \mathsf{IO} \; () \\ \text{waitQSem} \; (\mathsf{QSem \; sem}) &= \end{split}
        (avail, blocked) \leftarrow takeMVar sem
        if avail > 0 then
            putMVar sem (avail -1,[])
        else
            do
                block \leftarrow newEmptyMVar
                putMVar sem (0, blocked + [block])
                takeMVar block
```

The last call waits for the empty MVar to be filled.



Signalling a semaphore

```
\begin{split} & \mathsf{signalQSem} :: \mathsf{QSem} \to \mathsf{IO} \ () \\ & \mathsf{signalQSem} \ (\mathsf{QSem} \ \mathsf{sem}) = \\ & \quad \quad \mathsf{do} \\ & \quad \quad (\mathsf{avail}, \mathsf{blocked}) \leftarrow \mathsf{takeMVar} \ \mathsf{sem} \\ & \quad \quad \mathsf{case} \ \mathsf{blocked} \ \mathsf{of} \\ & \quad \quad [] \qquad \quad \to \mathsf{putMVar} \ \mathsf{sem} \ (\mathsf{avail} + 1, []) \\ & \quad \quad (\mathsf{block} : \mathsf{blocked'}) \to \mathsf{do} \\ & \quad \quad \quad \mathsf{putMVar} \ \mathsf{sem} \ (0, \mathsf{blocked'}) \\ & \quad \quad \mathsf{putMVar} \ \mathsf{block} \ () \end{split}
```

The last call signals the blocked thread that it can continue.



Channels

FIFO channels to communicate data safely between threads. Channels are a very useful and much more high-level abstraction than MVars or semaphores.

Control Concurrent Chan

data Chan -- abstract newChan :: IO (Chan a) dupChan :: Chan $a \rightarrow IO$ (Chan a) unGetChan :: Chan $a \rightarrow a \rightarrow IO$ () readChan :: Chan $a \rightarrow IO$ a writeChan :: Chan $a \rightarrow a \rightarrow IO$ ()

9.5 Software Transactional Memory





Software Transactional Memory (STM)

- ► An alternative implementation of concurrency abstractions in GHC.
- ▶ Use ideas from database systems.
- ▶ Threads can start transactions.
- ► Transactions are guaranteed to be run atomically.
- ► The implementation keeps a log of all the memory accesses during a transaction, but does not actually perform any writes yet.
- ▶ At the end of a transaction, the log is checked against the memory. If the memory is still consistent, the transaction is committed. Otherwise, it is restarted.

STM is lock-free

- STM does not use locking.
- Deadlocks cannot occur.
- However, large transactions can take a huge number of retries, so STM works best if transactions are kept as small as possible.

STM and Haskell

- Generally, it is difficult to log all side effects during a transaction.
- ▶ In Haskell, we can easily use the type system to keep track of such effects.
- ► The Haskell STM implementation introduces an STM monad, which is (again) a restricted form of the IO monad.
- Only TVars can be accessed within the STM monad, which are a logged version of IORefs.
- ▶ It is thus easy to guarantee the safety of STM in Haskell.



STM interface

STM in Haskell is provided by the stm package.

Control.Concurrent.STM

```
data STM -- abstract instance Monad STM -- running a transaction atomically :: STM a \rightarrow IO a -- TVars newTVar :: a \rightarrow STM (TVar a) newTVarIO :: a \rightarrow IO (TVar a) readTVar :: TVar a \rightarrow STM a writeTVar :: TVar a \rightarrow a \rightarrow STM ()
```

Thread example using STM

```
\label{eq:continuous_problem} \begin{array}{ll} \mathsf{test}\;\mathsf{n} & = \mathbf{do} \\ & \mathsf{x} \leftarrow \mathsf{newTVarIO}\;0 \\ & \mathsf{mapM}_{-}\left(\mathsf{forkIO} \circ \mathsf{w}\right. \end{array}
                                 mapM_{-} (forkIO \circ writer x) [1..n]
                                 writer \times 0
writer x m = do
                                  n \leftarrow atomically \$ do
                                       writeTVar \times m
                                       readTVar x
                                  when (m \not\equiv n) $ putStrLn $ show m
                                  writer x m
```



Implementing MVar using STM





Implementing MVar using STM

```
type MVar a = TVar (Maybe a)
newEmptyMVar :: STM (MVar a)
newEmptyMVar = newTVar Nothing
```

```
 \begin{array}{c} \mathsf{takeMVar} :: \mathsf{MVar} \; \mathsf{a} \to \mathsf{STM} \; \mathsf{a} \\ \mathsf{takeMVar} \; \mathsf{m} = \frac{\mathsf{do}}{\mathsf{v}} \\ & \mathsf{x} \leftarrow \mathsf{readTVa} \end{array} 
                                                x \leftarrow readTVar m
                                                  case x of
                                                         Nothing \rightarrow retry
                                                         Just v \rightarrow do
                                                                                                writeTVar m Nothing
                                                                                                 return v
```

The function putMVar is similar.





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More STM combinators

Control.Concurrent.STM

retry :: STM a

Request to retry the current transaction. Will usually block the thread until one of the TVars read from is updated by another thread.

orElse :: STM a ightarrow STM a ightarrow STM a

If the first action retries, the second action is tried next.

In addition, STM supports checking for invariants, catching exceptions in the STM monad, and it has an implementation of MVars and Chans that can be used in the STM monad – TMVars and TChans.

Interesting papers

- "Tackling the Awkward Squad" by Simon Peyton-Jones on IO, concurrency, exceptions and foreign function calls
- "An Extensible Dynamically-Typed Hierarchy of Exceptions" by Simon Marlow – the paper where extensible exceptions for Haskell were introduced
- "Haskell Session Types with (Almost) No Class session types give you advanced typed communication between different threads.
- "Composable memory transactions" by Tim Harris, Simon Marlow, Simon Peyton Jones, and Maurice Herlihy – the paper where STM for Haskell was introduced

Next lecture

