universität innsbruck

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Advanced Functional Programming

Week 11 – Concurrent Channels, Asynchronous Actions, Cancellations and Timeouts

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Last Week

- parallelism
  - use multiple cores to speed up computation
  - high-level interface via strategies
    - separate what is computed from how it is computed
    - `expr `using` rpar` – evaluate `expr` in parallel to WHNF
    - `expr `using` parList rseq` – evaluate each list element in parallel to WHNF
    - `expr `using` parList rdeepseq` – evaluate each list element in parallel to normal form
  - underlying mechanism: `runEval` and `Eval`-monad
  - example: parallel quicksort
- concurrency
  - separate threads for different tasks
  - thread creation via `forkIO`
  - low-level communication via `MVar`s
    - blocking operations `takeMVar` and `getMVar`
  - if main thread ends, then all other threads will be stopped
  - example: logger thread with one-message buffer

Higher Level Interfaces for Concurrency – Channels

Channels

- design of `MVar a`: store at most one value of type `a`
- aim: design a channel, i.e., an arbitrary length FIFO buffer
- advantage: in logger application, sending some log-message is not blocking, even if there are pending log-messages
- data structure design
  - single linked list
  - all references in the list will be `MVar`s
  - references to both ends of the list
- data structure in Haskell

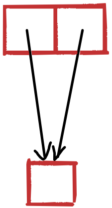
```haskell
type Stream a = MVar (Item a)
data Item a = Item a (Stream a)

data Chan a = Chan {
    readVar  :: MVar (Stream a),
    writeVar :: MVar (Stream a)
  }
```

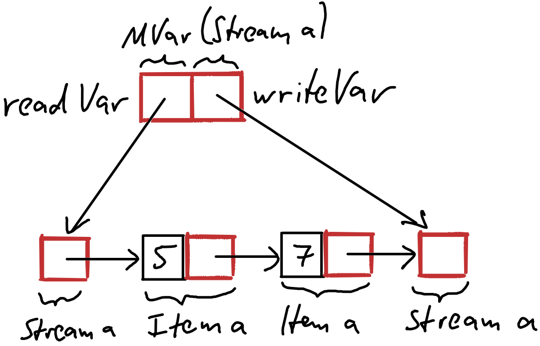
Channels Illustrated

- data structure

```
type Stream a = MVar (Item a)
data Item a = Item a (Stream a)
data Chan a = Chan { readVar, writeVar  :: MVar (Stream a) }
```

- left: empty channel; right: channel with elements 5 and 7;
  black: normal values; red: MVars





Channel Operations

```haskell
newChan :: IO (Chan a)
newChan = do
  hole <- newEmptyMVar
  rVar <- newMVar hole
  wVar <- newMVar hole
  return $ Chan { readVar = rVar, writeVar = wVar }
```

```haskell
writeChan :: Chan a -> a -> IO ()
writeChan c val = do
  newHole <- newEmptyMVar
  oldHole <- takeMVar (writeVar c)
  putMVar oldHole $ Item val newHole
  putMVar (writeVar c) newHole
```

```haskell
readChan :: Chan a -> IO a
readChan c = do
  rVar <- takeMVar (readVar c)
  Item x next <- takeMVar rVar
  putMVar (readVar c) next
  return x
```

Example Application: Improved Logger

- adjusting the logger to use a channel is trivial: use `Chan`-operations instead of `MVar`-operations
  - old code

```haskell
newtype Logger =
  Logger (MVar LogCommand)
initLogger = do
  m <- newEmptyMVar
...
  loop = do
    cmd <- takeMVar m
...
logMessage (Logger m) s
  = putMVar m (Message s)
logStop (Logger m) = do
  s <- newEmptyMVar
  putMVar m (Stop s)
  takeMVar s
```

  - new code

```haskell
newtype Logger =
  Logger (Chan LogCommand)
initLogger = do
  c <- newChan
...
  loop = do
    cmd <- readChan c
...
logMessage (Logger c) s
  = writeChan c (Message s)
logStop (Logger c) = do
  s <- newEmptyMVar
  writeChan c (Stop s)
  takeMVar s
```

Testing the Logger (`cabal run Demo11 -- logger`)

- code for testing the modified logger

```
message s i = "message " ++ show i ++ " of " ++ s
announceLogMessage l m = do
  putStrLn $ "sending message to logger: " ++ m
  logMessage l m

mainLogger = do
  l <- initLogger
  forkIO $ mapM_ (announceLogMessage l . message "fork 1") [1..100]
  forkIO $ mapM_ (announceLogMessage l . message "fork 2") [1..100]
  mapM_ (announceLogMessage l . message "main thread") [1..100]
  logStop l
```

  - `announceLogMessage` immediately prints a message, before it is send to logger
  - in total, three threads send 100 messages each
  - logger starts its main loop with 2 seconds delay (delay inserted into Logger-code)
- result: all `"sending message..."` outputs are immediately done, no blocking

Extending the Channel-Code – Multicasts

- channel code also supports multicast-operations, i.e., one writer and several readers
- preparation: `readMVar` in order to read, but not consume some content in an `MVar`

```
readMVar :: MVar a -> IO a
readMVar m = do
  x <- takeMVar m
  putMVar m x
  return x
```

- duplication of channel for multicasts
  - both channels will read all upcoming write operations of either channel
  - duplicated channel will initially be empty

```
dupChan :: Chan a -> IO (Chan a)
dupChan c = do
  hole <- readMVar (writeVar c)
  newRVar <- newMVar hole
  return $ Chan { readVar = newRVar, writeVar = writeVar c }
```

- in implementation of `readChan`, operation `takeMVar` has to replaced by `readMVar`

Testing Channel Duplication (`cabal run Demo11 -- channel`)

- testing code

```haskell
mainChannel = do
  c <- newChan
  mapM_ (writeChan c) ['a' .. 'l']
  d <- dupChan c
  forkIO $ do
    mapM_ (writeChan c) ['k' .. 's']
    forever (readChan c >>= \ a -> putStrLn $ "read from c: " ++ [a])
  forkIO $ do
    mapM_ (writeChan d) ['t' .. 'z']
    forever (readChan d >>= \ a -> putStrLn $ "   read from d: " ++ [a])
  threadDelay $ 1000
```

  - letters a..l are only in channel c, they will not be copied to d
  - letters k..s are send to c and will become visible in both channels
  - letters t..z are send to d and will become visible in both channels
  - main thread stops execution after 1ms and kills both forked threads
- result: a..z are received via c, k..z via d, but order of k..z is not fixed, might be ktlumv...

Final Remarks on MVars and Channels

- operation `readMVar` is already predefined
  - predefined version differs from presented implementation: it is ensured that `takeMVar` and `putMVar` operation are performed atomically
  - consequence: no possibility that thread is interrupted between these two operations in the predefined version
- `Chan a` is also predefined
  - `https://hackage.haskell.org/package/base/docs/Control-Concurrent-Chan.html`
  - package offers one further primitive for getting full channel content as lazy list (similar to `readFile` and `hGetContents`)

```
getChanContents :: Chan a -> IO [a]
```

Higher Level Interfaces for Concurrency – ASync

Aim: Asynchronous I/O

- task: perform asynchronous I/O
  - I/O is performed in background while main thread is doing other tasks
  - running example: download some websites in the background
  - utilized interface based on `Network.HTTP.Conduit` (requires some cabal packages)

```
getURL :: String -> IO ByteString
```

- first implementation is based on `forkIO` and `MVar`

Asynchronous I/O via forkIO and MVar: cabal run Demo11 -- url1

- source code

```
mainGetURL1 = do
  m1 <- newEmptyMVar
  m2 <- newEmptyMVar
  forkIO $ do
    r <- getURL "http://www.wikipedia.org/wiki/Red"
    putMVar m1 r
  forkIO $ do
    r <- getURL "http://www.wikipedia.org/wiki/Green"
    putMVar m2 r
  r1 <- takeMVar m1
  r2 <- takeMVar m2
  print (B.length r1, B.length r2)     -- B = ByteString
```

- code is rather verbose
- try to abstract pattern for asynchronous action execution

An Interface for Asynchronous Actions

- interface should provide a way to turn I/O-actions into asynchronous actions
- also waiting on results should be possible
- implementation works by synchronization on some `MVar`

```
data Async a = Async (MVar a)

async :: IO a -> IO (Async a)
async action = do
  var <- newEmptyMVar
  forkIO (do r <- action; putMVar var r)
  return (Async var)

wait :: Async a -> IO a
wait (Async var) = readMVar var
```

- `readMVar` instead of `takeMVar`, so that multiple `wait`s are supported

Change of Application (`cabal run Demo11 -- url2`)

- application code becomes much cleaner

```
mainGetURL2 = do
  a1 <- async $ getURL "http://www.wikipedia.org/wiki/Red"
  a2 <- async $ getURL "http://www.wikipedia.org/wiki/Green"
  -- do something in between
  r1 <- wait a1
  r2 <- wait a2
  print (B.length r1, B.length r2)
```

Combined with Other Monadic Combinators (cabal run Demo11 -- url3)

- process list of websites, include time information

```
timeit a = do start <- getCurrentTime; x <- a; end <- getCurrentTime;
              return (x, end `diffUTCTime` start)

timeDownload url = do
  (page, time) <- timeit $ getURL url
  putStrLn $ "downloaded " ++ url
     ++ " (" ++ show (B.length page) ++ " bytes, " ++ show time ++ ")"

sites = ["http://www.bing.com", ..., "http://www.duckduckgo.com"]

mainGetURL3 = do
 as <- mapM (async . timeDownload) sites  -- start concurrent download
 mapM_ wait as                            -- and wait on completion
```

Error Handling with Async (`cabal run Demo11 -- url3bad`)

- let us modify the list of websites, so that some website is not existing (or disable internet connection, or cause some other problem leading to an exception)

```
sitesBad = ["http://www.bing.com",
            "http://someurlThatDoesNot.Exist",
            "http://www.metager.de",
            "http://www.duckduckgo.com"]

mainGetURL3bad = do
 as <- mapM (async . timeDownload) sitesBad
 mapM_ wait as
```

- execution results in deadlock

```
downloaded http://www.bing.com (52477 bytes, 0.201074s)
... exception error message: ConnectionFailure  ...
Demo11: thread blocked indefinitely in an MVar operation
```

- reason: because of exception during download action, `putMVar` is not executed in `async`

Error Handling with Async – Extend `Async` (1/1)

- aims
  - forward exceptions in asynchronous actions to thread that invokes `wait`
  - ensure that exceptions do not lead to deadlock, by always filling `MVars` of `async`
- solution: modify and extend `Async`

```
data Async a = Async (MVar (Either SomeException a))

async :: IO a -> IO (Async a)
async action = do
  var <- newEmptyMVar :: MVar (Either SomeException a)
  forkIO $ do { r <- try action; putMVar var r }
  return $ Async var

waitCatch :: Async a -> IO (Either SomeException a)
waitCatch (Async var) = readMVar var
```

Error Handling with Async – Extend `Async` (2/2)

- we also modify `wait` in a way that exceptions from the forked thread are re-thrown in the thread that invokes `wait`

```
waitCatch :: Async a -> IO (Either SomeException a) -- previous slide

wait :: Async a -> IO a
wait a = do
  r <- waitCatch a
  case r of
    Left e  -> throwIO e
    Right a -> return a
```

Merging of Asyncs

- situation
  - assume there are multiple asynchronous actions
  - aim: wait until the first one is completed
  - task: integration into Async-framework
- solution via one more MVar
- for each asynchronous action, a new thread is created that tries to write into this MVar
- implementation in Haskell

```
waitAny :: [Async a] -> IO a
waitAny as = do
  m <- newEmptyMVar
  let forkWait a = forkIO $ do r <- try (wait a); putMVar m r
  mapM_ forkWait as
  wait (Async m)
```

Application for Merging of Asyncs (`cabal run Demo11 -- url5`)

- application stays on high level

```
mainGetURL5 = do
  let download url = (,) url <$> getURL url
  as <- mapM (async . download) sites
  (url, r) <- waitAny as
  putStrLn $ url ++ " was first (" ++ show (B.length r) ++ " size)"
```

- remarks
  - `waitAny` really just waits on any asynchronous action to complete
  - the other actions are not aborted, but will continue to run in the background
  - if `main = mainGetURL5` then this effect will not be visible, since the main thread stops soonish after invoking `waitAny` and then the runtime system stops all other threads

Cancellation and Timeouts

Cancellation of Tasks

- cancellations of tasks may desirable for several reasons
  - user of web browser clicks "stop"-button, e.g., to stop downloads
  - prover spawns several alternative search algorithms to find a successful proof; as soon as first search algorithm is successful, the other searches should be stopped
- two parties
  - (C) a controller thread that wants to cancel some other thread
  - (W) a worker thread, that should be cancelled
- two cancellation policies
  - (P) polling: (W) regularly asks (C) whether it should stop
  - (A) asynchronous cancellation: (W) is interrupted by (C) and will be stopped
- tradeoff
  - danger of (P): if (W) does not query regularly, then system becomes inresponsive
  - danger of (A): if (W) is interrupted and immediately killed, then it cannot release locks, close files, kill external spawned processes, etc.
- imperative languages usually take (P) as default: danger of inconsistent state of (A)
- Haskell takes (A) as default: pure computations cannot poll

Asynchronous Exceptions

- exception handling has been handled before
- however, there are two kinds of exceptions
  - synchronous exceptions
    - occurence is anticipated
    - example: if code performs `readFile`, it is clear that this might lead to an I/O-exception
  - asynchronous exceptions
    - these are raised by a different thread and are not anticipated
    - example: code that just computes some complex function and then prints the result does not expect any exception
- in Haskell, asynchronous exceptions can be thrown via

```
throwTo :: Exception e => ThreadId -> e -> IO ()
```

  - `ThreadId` is obtained from `forkIO`
  - `throwTo tid` has no effect, if thread `tid` is already finished

Extending Async Again for Cancellations

- aim: implement `cancel :: Async a -> IO ()`
- solution: extend datatype `Async` by `ThreadId`

```
data Async a = Async ThreadId (MVar (Either SomeException a))

cancel (Async t var) = throwTo t ThreadKilled

async :: IO a -> IO (Async a)
async action = do
  var <- newEmptyMVar
  t <- forkIO $ do { r <- try action; putMVar var r }
  return $ Async t var
```

- `ThreadKilled` exception is usually used for cancelling threads
- note: this version of `Async` is available in module `Control.Concurrent.Async`
- also available: `waitAnyCancel :: [Async a] -> IO (Async a, a)`,
  like `waitAny`, but with cancellation of remaining asynchronous actions

Asynchronous Exceptions for Timeouts

- aim: run some IO action within a given time limit

```
timeout :: Int -> IO a -> IO (Maybe a)
```

- implementation available in module `System.Timeout`
- semantics
  - `timeout t m` is `Just <$> m`, provided the result is computed within `t` microseconds (approximately)
  - `timeout t m` is `Nothing`, if timeout occurs
- implementation is based on asynchronous exceptions
  - a separate thread is spawned, which throws a timeout exception after delay `t`
  - this exception is catched and turned into a `Nothing` result

Catching Asynchronous Exceptions

- module `Control.Exception` provides high-level functions that take care of releasing some resource, even in case of (asynchronous) exceptions
- we illustrate `bracket` in more detail
- ```
  bracket :: IO a              (require resource)
    -> (a -> IO b)             (finally release resource)
    -> (a -> IO c)             (compute in-between)
    -> IO c                    (result of in-between computation)
  ```
- if an exception occurs, the release code is executed and then the exception is re-thrown
- example
  ```
  bracket (openFile "filename" ReadMode) hClose
    (\ handle -> do { ... })
  ```
- further high-level exception handling functions
  - `bracketOnError` is like `bracket`, but release only happens if exception occurs
  - `finally`, `onException`, ... are specialized versions of `bracket`(`onError`)
  ```

Application

- with functions like `bracket` and `timeout` and `waitAnyCancel` it is now possible to implement sophisticated search-strategies, e.g., in termination proof search
- example
  - search in parallel for some LPO and some other termination order (for at most 5 seconds)
  - with 2 seconds delay, try tree-automata based termination techniques (for at most 10 seconds)
  - take the first successful result of any of the above techniques
  - iterate this process until either a full termination proof has been established, or all techniques fail
- `bracket` and similar functions should be used to reliably kill externally spawned processes if the own thread is cancelled

Exercises

- see Haskell files

Literature

- Simon Marlow, Parallel and Concurrent Programming in Haskell, 2013, O'Reilly, Chapters 7 – 9
- https://hackage.haskell.org/package/base/docs/Control-Concurrent-Chan.html
- https://hackage.haskell.org/package/async/docs/Control-Concurrent-Async.html
- https://hackage.haskell.org/package/base/docs/Control-Exception.html