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

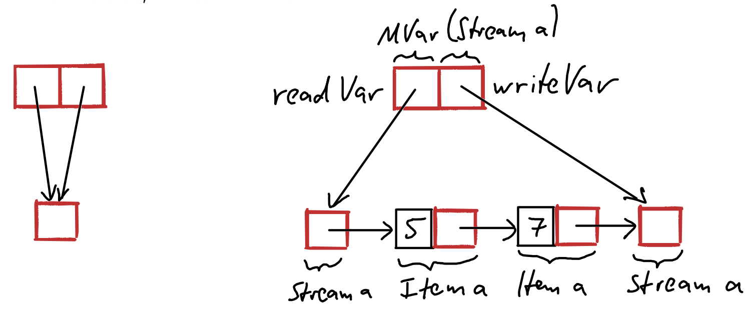
```haskell
type Stream a = MVar (Item a)
data Item a = Item a (Stream a)

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

Channels Illustrated

- data structure

```haskell
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

```haskell
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 be replaced by `readMVar`

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

- testing code

```
mainChannel = do
 c <- newChan
 mapM_ (writeChan c) ['a' .. 'k']
 d <- dupChan c
 forkIO $ do
   mapM_ (writeChan c) ['l' .. '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..k are only in channel `c`, they will not be copied to `d`
  - letters l..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`, l..z via `d`, but order of l..z is not fixed, might be ltmunv...

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

```haskell
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)

```haskell
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

```haskell
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

```haskell
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 be 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

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