Parallel & Concurrent Haskell 3: Concurrent Haskell

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Concurrent Haskell

- Recap:
  - concurrent programming is about *threads of control*
  - concurrency is necessary for dealing with multiple sources of input/output:
    - network connections
    - GUI, user input
    - database connections
  - *threads of control* let you handle multiple input/output sources in a *modular* way: the code for each source is written separately

Summary

- In this part of the course we’re going to cover
  - Basic concurrency
    - forking threads
    - communication and synchronisation
  - Asynchronous exceptions
    - cancellation
    - timeouts

Forking threads

```
forkIO :: IO () -> IO ThreadId
```

- creates a new thread to run the IO ()
- new thread runs “at the same time” as the current thread and other threads

Interleaving example

```haskell
import Control.Concurrent
import Control.Monad
import System.IO

main = do
  hSetBuffering stdout NoBuffering
  forkIO (forever (putChar 'A'))
  forkIO (forever (putChar 'B'))
  threadDelay (10^6)
```

```haskell
forkIO :: IO () -> ThreadId

forever :: m a -> m a
putChar :: Char -> IO ()
threadDelay :: Int -> IO ()
```

```
$ ghc fork.hs
[1 of 1] Compiling Main             ( fork.hs, fork.o )
Linking fork ...
$ ./fork | tail -c 300
AAAAAAAABABABABABABABABABABABABABABABABABABABABABAB
ABABABABABABABABABABABABABABABABABABABABABABABABABAB
ABABABABABABABABABABABABABABABABABABABABABABABABABAB
ABABABABABABABABABABABABABABABABABABABABABABABABABAB
$
```

ThreadId

```
forkIO :: IO () -> IO ThreadId
```

- what can you do with a ThreadId?
  - check status with GHC.Conc.threadStatus (useful for debugging):

```
> import Control.Concurrent
> do { t <- forkIO (threadDelay (10^6)); GHC.Conc.threadStatus t }
ThreadRunning
> do { t <- forkIO (threadDelay (10^6)); yield; GHC.Conc.threadStatus t }
ThreadBlocked BlockedOnMVar
```

- Also:
  - compare for equality
  - kill / send exceptions (later...)

A note about performance

- GHC's threads are *lightweight*

```
> ./Main 1000000 1 +RTS -s
Creating pipeline with 1000000 processes in it.
Pumping a single message through the pipeline.
Pumping a 1 messages through the pipeline.
       n    create     pump1     pump2  create/n   pump1/n   pump2/n
                 s         s         s        us        us        us
 1000000     5.980     1.770     1.770      5.98      1.77      1.77
```

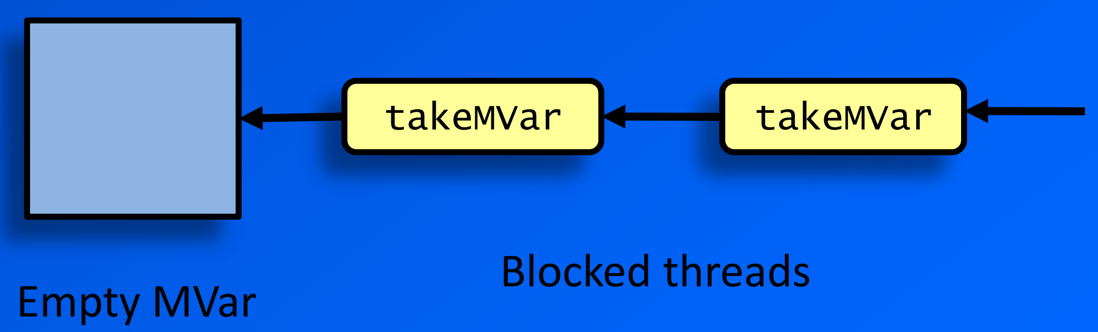
- 10^6 threads requires 1.5Gb – 1.5k/thread
  - most of that is stack space, which grows/shrinks on demand
- cheap threads makes it feasible to use them liberally, e.g. one thread per client in a server

Communication: MVars

- MVar is the basic communication primitive in Haskell.

```
data MVar a  -- abstract

newEmptyMVar :: IO (MVar a)
takeMVar     :: MVar a -> IO a
putMVar      :: MVar a -> a -> IO ()
```



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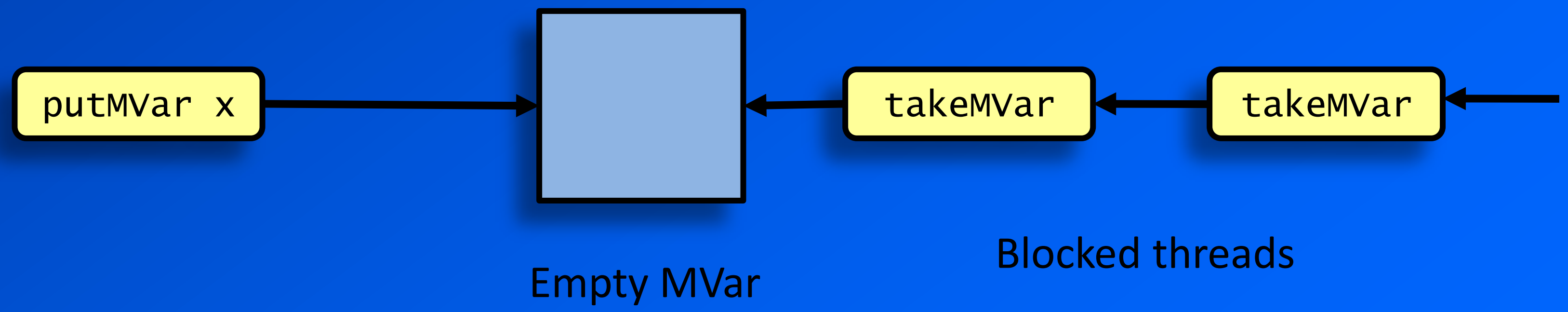

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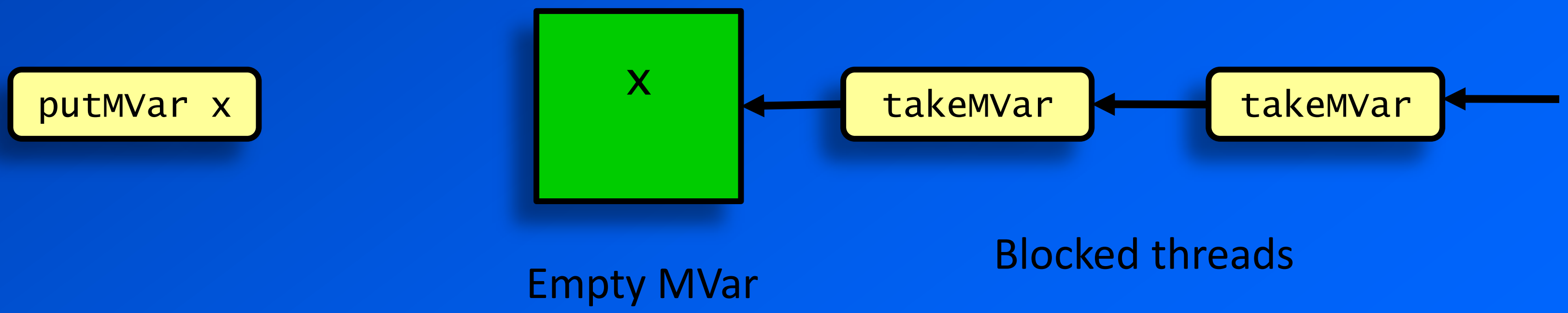

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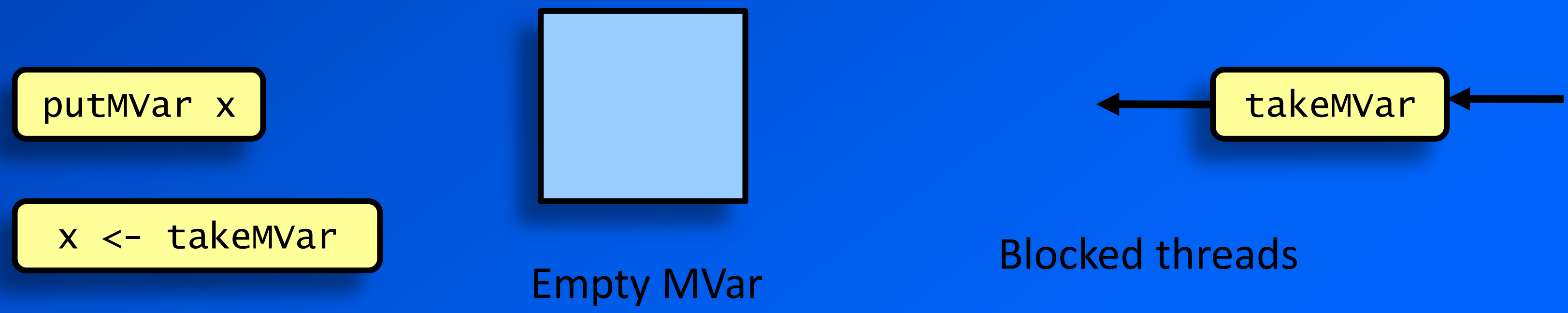

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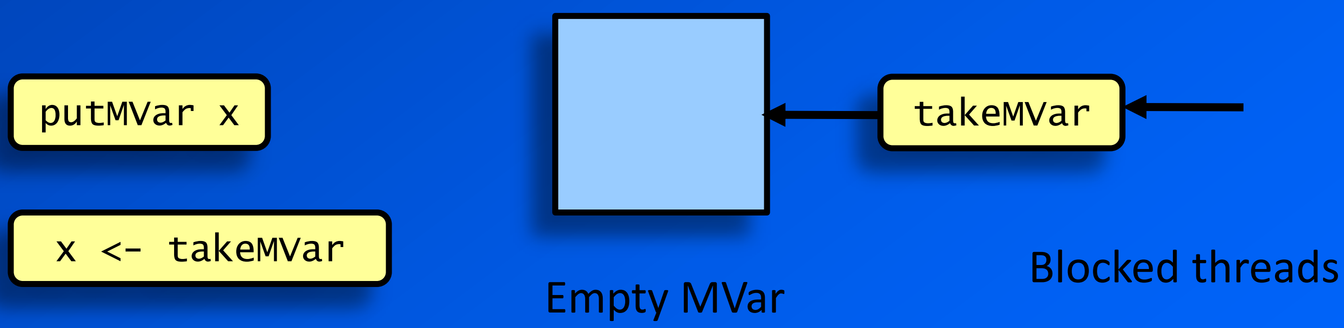

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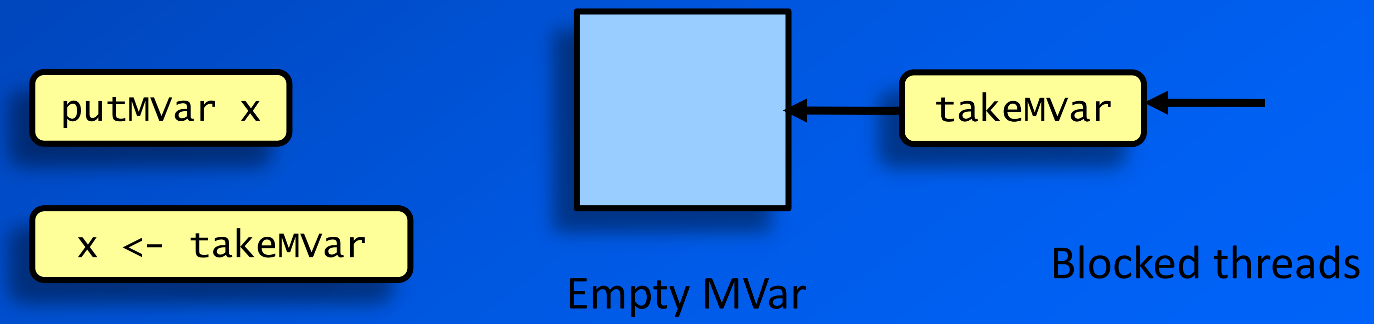

- And conversely: putMVar blocks when the MVar is full.

Examples

```
do m <- newEmptyMVar
   forkIO $ putMVar m 'a‘
   takeMVar m
```

Examples

```
do m <- newEmptyMVar
   forkIO $ putMVar m 'a‘
   takeMVar m
```

```
> do m <- newEmptyMVar; forkIO $ putMVar m 'a'; takeMVar m
'a'
>
```

Examples

```
do m <- newEmptyMVar
   forkIO (takeMVar m >>= print)
   putMVar m 'a'
```

Examples

```
do m <- newEmptyMVar
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```
> do m <- newEmptyMVar; forkIO (takeMVar m >>= print);
putMVar m 'a'
'a'>
```

Examples

```
do m <- newEmptyMVar
   forkIO (takeMVar m >>= print)
   putMVar m 'a'
```

```
> do m <- newEmptyMVar; forkIO (takeMVar m >>= print);
putMVar m 'a'
'a'>
```

```
> do m <- newEmptyMVar; forkIO (threadDelay 1000 >>
takeMVar m >>= print); putMVar m 'a'
> 'a‘
```

```haskell
do m <- newEmptyMVar
   forkIO (do putMVar m 'a'; putMVar m 'b')
   takeMVar m >>= print
   takeMVar m >>= print
```

```
do m <- newEmptyMVar
   forkIO (do putMVar m 'a'; putMVar m 'b')
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   takeMVar m >>= print
```

```
> do m <- newEmptyMVar; forkIO (do putMVar m 'a'; putMVar
m 'b'); takeMVar m >>= print; takeMVar m >>= print
'a'
'b'
```

```haskell
do m <- newEmptyMVar
   takeMVar m
```

```haskell
do m <- newEmptyMVar
   takeMVar m
```

```
> do m <- newEmptyMVar; takeMVar m
^CInterrupted.
>
```

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do m <- newEmptyMVar
   takeMVar m
```

```
> do m <- newEmptyMVar; takeMVar m
^CInterrupted.
>
```

```
$ ./deadlock
deadlock: thread blocked indefinitely in an MVar operation
$
```

- Sometimes GHC can detect that a thread is deadlocked and send it an exception (BlockedIndefinitelyOnMVar)
- You can catch this exception if you want.
  - default behaviour is for the thread to die silently when it receives this exception => thread has been GC’d

```haskell
do m <- newEmptyMVar
   forkIO (putMVar m 'a')
   forkIO (putMVar m 'b')
   takeMVar m
```

```haskell
do m <- newEmptyMVar
   forkIO (putMVar m 'a')
   forkIO (putMVar m 'b')
   takeMVar m
```

```
> do m <- newEmptyMVar; forkIO (putMVar m 'a'); forkIO
(putMVar m 'b'); takeMVar m
'a'
```

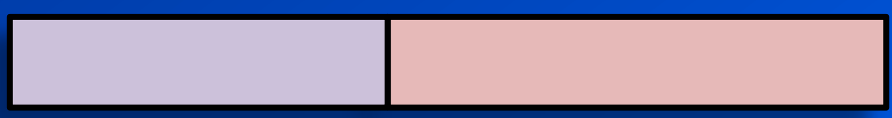
```haskell
do m <- newEmptyMVar
   forkIO (putMVar m 'a')
   forkIO (putMVar m 'b')
   takeMVar m
```

```
> do m <- newEmptyMVar; forkIO (putMVar m 'a'); forkIO
(putMVar m 'b'); takeMVar m
'a'
```

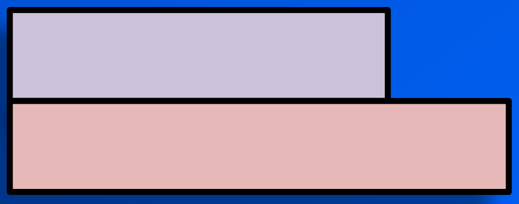
- What about the thread that lost the race?
- It deadlocks, receives the BlockedIndefinitelyOnMVar exception, and dies.

Example: overlapping I/O

- One common use for concurrency is to overlap multiple I/O operations
  - overlapping I/O reduces latencies, and allows better use of resources



sequential I/O



overlapped I/O

- overlapping I/O is easy with threads: just do each I/O operation in a separate thread
  - the runtime takes care of making this efficient, even when there are 100k+ blocked I/O operations
- e.g. downloading multiple web pages

Downloading URLs

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

```
do
   m1 <- newEmptyMVar
   m2 <- newEmptyMVar

   forkIO $ do
     r <- getURL "http://www.wikipedia.org/wiki/Shovel"
     putMVar m1 r

   forkIO $ do
     r <- getURL "http://www.wikipedia.org/wiki/Spade"
     putMVar m2 r

   r1 <- takeMVar m1
   r2 <- takeMVar m2
   return (r1,r2)
```

Abstract the common pattern

- Fork a new thread to execute an IO action, and later wait for the result

```haskell
newtype Async a = Async (MVar a)

async :: IO a -> IO (Async a)
async io = do
  m <- newEmptyMVar
  forkIO $ do r <- io; putMVar m r
  return (Async m)

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

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

Using Async....

```
do
   a1 <- async $ getURL "http://www.wikipedia.org/wiki/Shovel"
   a2 <- async $ getURL "http://www.wikipedia.org/wiki/Spade"
   r1 <- wait m1
   r2 <- wait m2
   return (r1,r2)
```

A driver to download many URLs

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

main = mapM (async.http) sites >>= mapM wait
 where
   http url = do
     (page, time) <- timeit $ getURL url
     printf "downloaded: %s (%d bytes, %.2fs)\n"
        url (B.length page) time
```

```
downloaded: http://www.google.com (14524 bytes, 0.17s)
downloaded: http://www.bing.com (24740 bytes, 0.18s)
downloaded: http://www.wikipedia.com/wiki/Spade (62586 bytes, 0.60s)
downloaded: http://www.wikipedia.com/wiki/Shovel (68897 bytes, 0.60s)
downloaded: http://www.yahoo.com (153065 bytes, 1.11s)
```

An MVar is many things...

- *a lock*
  - MVar () behaves like a lock: full is unlocked, empty is locked
  - Can be used as a mutex to protect some other shared state, or a critical region
- *one-place channel*
  - Since an MVar holds at most one value, it behaves like an asynchronous channel with a buffer size of one
- *a container for shared state*
  - e.g. MVar (Map key value)
  - convert persistent data structure into ephemeral
  - efficient (but there are other choices besides MVar)
- *building block*
  - MVar can be used to build many different concurrent data structures/abstractions...

MVar = container for shared state

```haskell
import Data.Map as Map
import Control.Concurrent

type Name = String
type PhoneNum = String
type PhoneBook = Map Name PhoneNum

insertName :: MVar PhoneBook -> Name -> PhoneNum -> IO ()
insertName m name num = do
  book <- takeMVar m
  putMVar m (Map.insert name num book)

lookupNumber :: MVar PhoneBook -> Name -> IO (Maybe PhoneNum)
lookupNumber m name = do
  book <- readMVar m
  return (Map.lookup name book)
```

MVar = container for shared state

- taking the MVar locks the state
- putting the MVar updates the state and unlocks it again
- we can make *any* Haskell data structure into shared state this way. No need for special concurrent versions of data structures.
- Lazy evaluation can be used to avoid locking the state for too long:

```
book <- takeMVar m
putMVar m (Map.insert name num book)
```

  – Note that the insert is lazy, the MVar was only locked briefly (but beware of space leaks)

Unbounded buffered channels

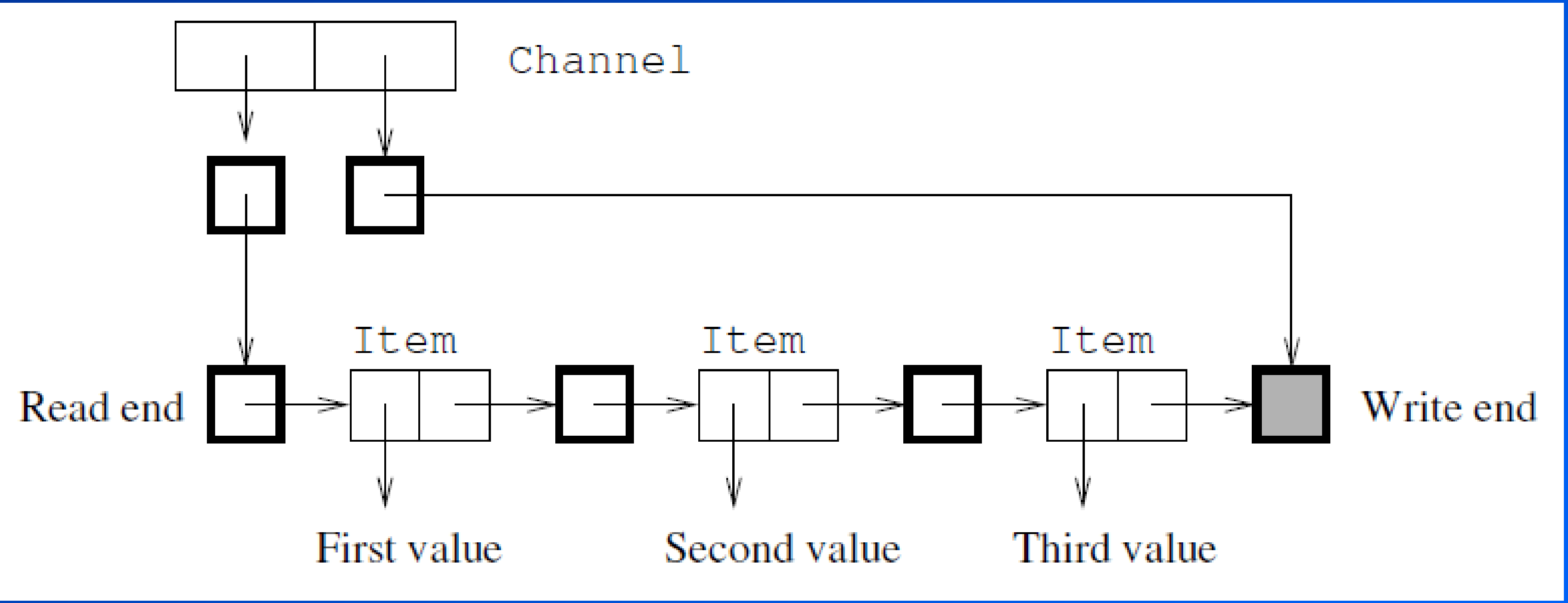
- Interface:

```
data Chan a -- abstract

newChan   :: IO (Chan a)
writeChan :: Chan a -> a -> IO ()
readChan  :: Chan a -> IO a
```

- write does not block (indefinitely)
- we are going to implement this with MVars
- can we just use `data Chan a = MVar [a]`
- No: think about how readChan will block when the channel is empty
- but in both of these, writers and readers will conflict with each other

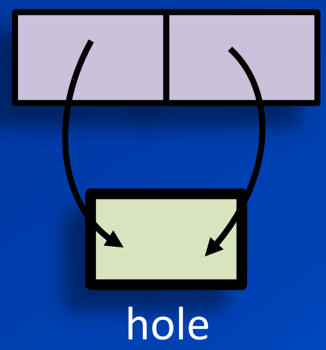
Structure of a channel




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

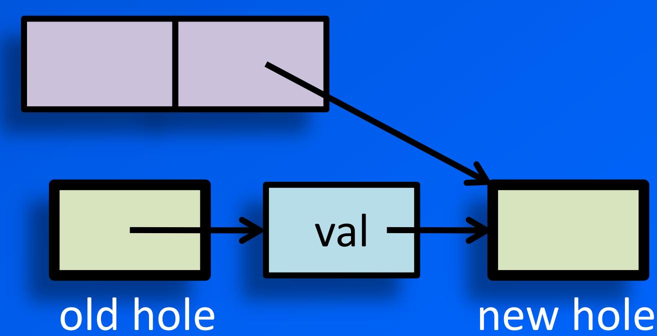
data Chan a = Chan (MVar (Stream a))
                   (MVar (Stream a))
```

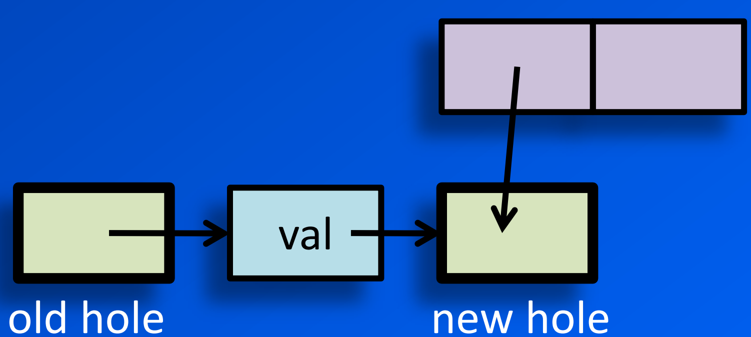
Implementation




```
newChan :: IO (Chan a)
newChan = do
   hole   <- newEmptyMVar
   readVar  <- newMVar hole
   writeVar <- newMVar hole
   return (Chan readVar writeVar)
```

```
writeChan :: Chan a -> a -> IO ()
writeChan (Chan _ writeVar) val = do
  new_hole <- newEmptyMVar
  old_hole <- takeMVar writeVar
  putMVar writeVar new_hole
  putMVar old_hole (Item val new_hole)
```






```
readChan :: Chan a -> IO a
readChan (Chan readVar _) = do
  stream <- takeMVar readVar
  Item val new <- takeMVar stream
  putMVar readVar new
  return val
```

Concurrent behaviour

- Multiple readers:
  - 2nd and subsequent readers block here

```
readChan :: Chan a -> IO a
readChan (Chan readVar _) = do
  stream <- takeMVar readVar
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  putMVar readVar new
  return val
```

- Multiple writers:
  - 2nd and subsequent writers block here

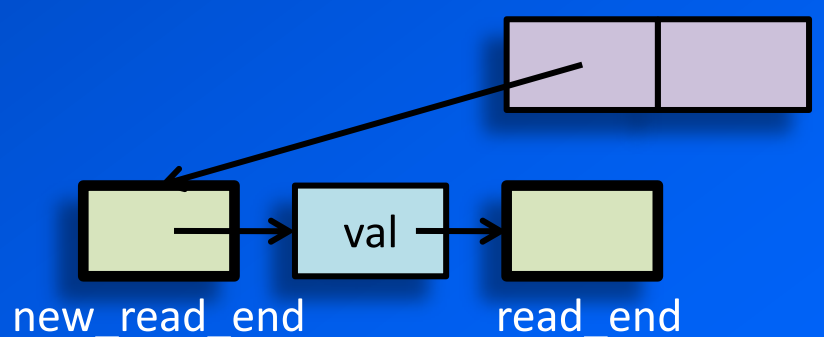
```
writeChan :: Chan a -> a -> IO ()
writeChan (Chan _ writeVar) val = do
  new_hole <- newEmptyMVar
  old_hole <- takeMVar writeVar
  putMVar writeVar new_hole
  putMVar old_hole (Item val new_hole)
```

- a concurrent read might block on old_hole until writeChan fills it in at the end

Adding more operations

- Add an operation for pushing a value onto the read end: `unGetChan :: Chan a -> a -> IO ()`
- Doesn't seem too hard:

```
unGetChan :: Chan a -> a -> IO ()
unGetChan (Chan readVar _) val = do
   new_read_end <- newEmptyMVar
   read_end <- takeMVar readVar
   putMVar new_read_end (Item val read_end)
   putMVar readVar new_read_end
```



But...

- This doesn't work as we might expect:

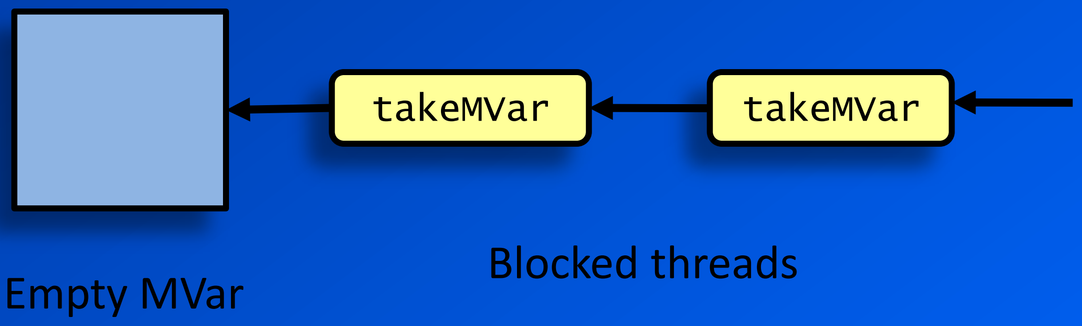
```
> c <- newChan :: IO (Chan String)
> forkIO $ do v <- readChan c; print v
ThreadId 217
> writeChan c "hello"
"hello"
> forkIO $ do v <- readChan c; print v
ThreadId 243
> unGetChan c "hello"
... blocks ....
```

- we don't expect unGetChan to block
- but it needs to call takeMVar on the read end, and the other thread is currently holding that MVar
- No way to fix this...
- Building larger abstractions from MVars can be tricky
- Software Transactional Memory is much easier (later...)

Why go to all this trouble?

- Couldn’t we just build channels into the language, like Erlang, Go etc.?
  - MVar is a more fundamental primitive
  - You can build more than just channels with MVar, e.g. shared state
  - Haskell’s approach is to provide simple but powerful abstractions
  - Channels *are* provided (Control.Concurrent.Chan)

A note about fairness



- Threads blocked on an MVar are processed in FIFO order
- No thread can be blocked indefinitely, provided there is a regular supply of putMVars (*fairness*)
- Each putMVar wakes exactly *one* thread, *and* performs the blocked operation atomically (*single-wakeup*)

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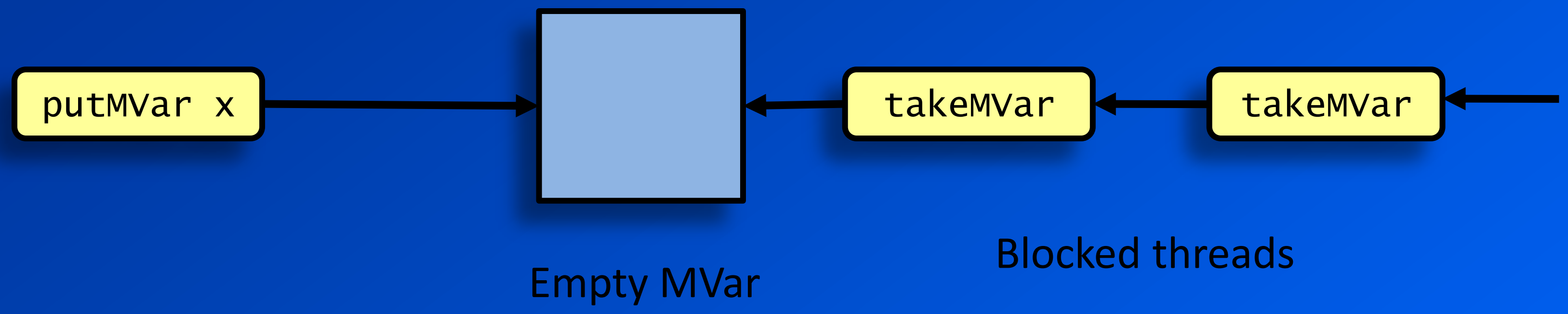

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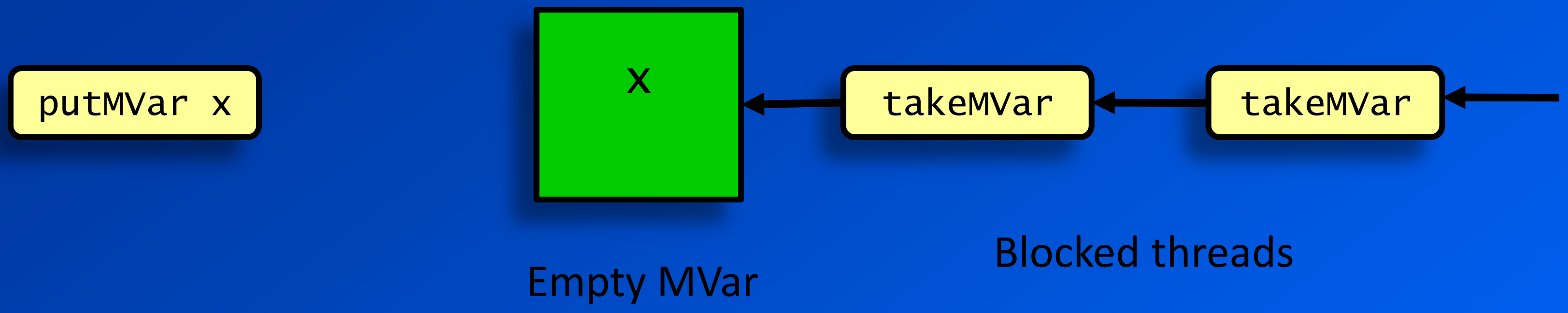

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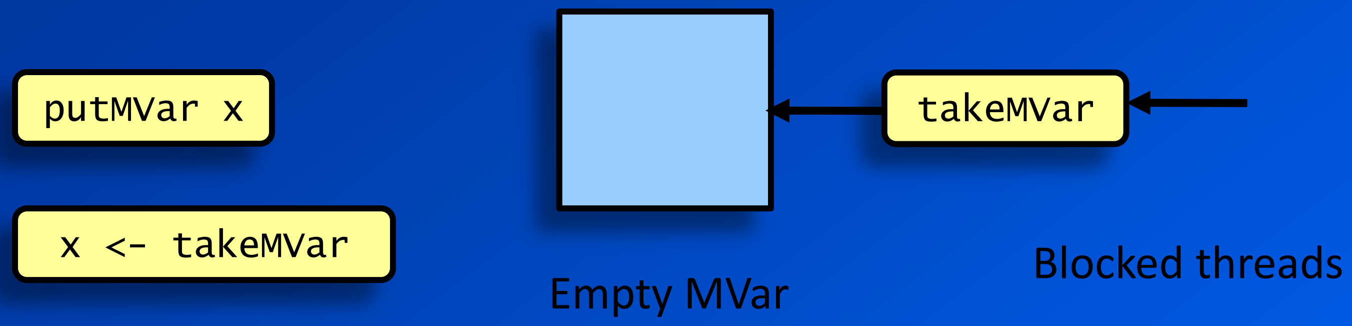

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MVars and contention

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Linking fork ...
$ ./fork | tail -c 300
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ABABABABABABABABABABABABABABABABABABABABABABABABABABAB
ABABABABABABABABABABABABABABABABABABABABABABABABABABAB
```

- Fairness can lead to alternation when two threads compete for an MVar
  - thread A: takeMVar (succeeds)
  - thread B: takeMVar (blocks)
  - thread A: putMVar (succeeds, and wakes thread B)
  - thread A: takeMVar again (blocks)
  - cannot break the cycle, unless a thread is pre-empted while the MVar is full
- MVar contention can be expensive!

break…

Cancellation/interruption

(asynchronous exceptions)

Motivation

- Often we want to interrupt a thread. e.g.
  - in a web browser, the user presses “stop”
  - in a server application, we set a time-out on each client, close the connection if the client does not respond within the required time
  - if we are computing based on some input data, and the user changes the inputs via the GUI

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  - because fully-asynchronous interruption is too hard to program with, in an imperative language.
  - Most code is modifying state, so asynchronous interruption will often leave state inconsistent.

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- Why?
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  - Most code is modifying state, so asynchronous interruption will often leave state inconsistent.
- In Haskell, most computation is pure, so
  - completely safe to interrupt
  - furthermore, pure code *cannot* poll
- Hence, interruption in Haskell is asynchronous
  - more robust: don’t have to remember to poll
  - but we do have to be careful with state in IO code

Interrupting a thread

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

- Throws the exception e in the given thread
- So interruption appears as an exception
  - this is good – we need exception handlers to clean up in the event of an error, and the same handlers will work for interruption too.
  - Code that is already well-behaved with respect to exceptions will be fine with interruption.

```
bracket (newTempFile "temp")
        (\file -> removeFile file)
        (\file -> ...)
```

  - threads can also *catch* interruption exceptions and do something – e.g. useful for time-out

Example

- Let’s extend the async API with cancellation
- So far we have:

```
newtype Async a = Async (MVar a)

async :: IO a -> IO (Async a)
async io = do
  m <- newEmptyMVar
  forkIO $ do r <- io; putMVar m r
  return (Async m)

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

- we want to add:

```
cancel :: Async a -> IO ()
```

- cancel is going to call throwTo, so it needs the ThreadId. Hence we need to add ThreadId to Async.

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

async :: IO a -> IO (Async a)
async io = do
  m <- newEmptyMVar
  t <- forkIO $ do r <- io; putMVar m r
  return (Async t m)

cancel :: Async a -> IO ()
cancel (Async t _) = throwTo t ThreadKilled
```

- but what about wait? previously it had type:

```haskell
wait :: Async a -> IO a
```

- but what should it return if the Async was cancelled?

- Cancellation is an exception, so wait should return the exception that was thrown.
  - This also means that wait will correctly handle exceptions caused by errors.

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


async :: IO a -> IO (Async a)
async io = do
  m <- newEmptyMVar
  t <- forkIO (do r <- try action; putMVar m r)
  return (Async t m)

wait :: Async a -> IO (Either SomeException a)
wait (Async _ var) = takeMVar var
```

```
try :: Exception e => IO a -> IO (Either e a)
```

Example

```
main = do
  as <- mapM (async.http) sites

  forkIO $ do
     hSetBuffering stdin NoBuffering
     forever $ do
        c <- getChar
        when (c == 'q') $ mapM_ cancel as

  rs <- mapM wait as
  printf "%d/%d finished\n" (length (rights rs)) (length rs)
```

Hit ‘q’ to stop the downloads

```
$ ./geturlscancel
downloaded: http://www.google.com (14538 bytes, 0.17s)
downloaded: http://www.bing.com (24740 bytes, 0.22s)
q2/5 finished
$
```

- Points to note:
  - We are using a large/complicated HTTP library underneath, yet it supports interruption automatically
  - Having asynchronous interruption be the default is very powerful
  - However: dealing with truly mutable state and interruption still requires some care...

Masking asynchronous exceptions

- Problem:
  - call takeMVar
  - perform an operation (f :: a -> IO a) on the value
  - put the new value back in the MVar
  - if an interrupt or exception occurs anywhere, put the old value back and propagate the exception

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catch :: Exception e => IO a -> (e -> IO a) -> IO a
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problem m f = mask $ \restore -> do
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- during execution of (\restore -> ...), asynchronous exceptions are *masked* (blocked until the masked portion returns)
- The value passed in as the argument restore is a function (:: IO a -> IO a) that can be used to restore the previous state (unmasked or masked) inside the masked portion.

- So did this solve the problem?

```
problem m f = mask $ \restore -> do
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```

- async exceptions cannot be raised in the red portions... so we always safely put back the MVar, restoring the invariant
- But: what if takeMVar blocks?
  - We are inside mask, so the thread cannot be interrupted. Bad!!
  - We didn't really want to mask takeMVar, we only want it to atomically enter the masked state when takeMVar takes the value

- Solution:

> - Operations that block are declared to be *interruptible.*
> - An interruptible operation may receive asynchronous exceptions while blocked, even inside mask.

- How does this help?
  - takeMVar is now interruptible, so the thread can be interrupted while blocked
  - in general, it is now very hard to accidentally write code that is uninterruptible for long periods (it has to be in a busy loop)
- Think of mask as ***switch to polling mode***
  - interruptible operations poll
  - we know which ops poll, so we can use exception handlers
  - asynchronous exceptions become ***synchronous*** inside mask

- hmm, don't we have another problem now?

```
problem m f = mask $ \restore -> do
  a <- takeMVar m
  r <- restore (f a) `catch` \e -> do putMVar m a; throw e
  putMVar m r
```

- putMVar is interruptible too!
- interruptible operations only receive asynchronous exceptions if they actually block
  - In this case, we can ensure that putMVar will never block, by requiring that all accesses to this MVar use a take/put pair, not just a put.
  - Alternatively, use the non-blocking version of putMVar, tryPutMVar

Async-exception safety

- IO code that uses state needs to be made safe in the presence of async exceptions
- ensure that invariants on the state are maintained if an async exception is raised.
- We make this easier by providing combinators that cover common cases.
- e.g. the function problem we saw earlier is a useful way to safely modify the contents of an MVar:

```
modifyMVar_ :: MVar a -> (a -> IO a) -> IO ()
```

Making Chan safe

- We had this:

```
writeChan :: Chan a -> a -> IO ()
writeChan (Chan _ writeVar) val = do
  new_hole <- newEmptyMVar
  old_hole <- takeMVar writeVar
  putMVar writeVar new_hole
  putMVar old_hole (Item val new_hole)
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danger!

- use mask_

```
writeChan (Chan _ writeVar) val = do
  new_hole <- newEmptyMVar
  mask_ $ do
    old_hole <- takeMVar writeVar
    putMVar writeVar new_hole
    putMVar old_hole (Item val new_hole)
```

Recap

- Basic concurrency operations:
  - forkIO
    - lightweight: make lots of them
  - MVar, takeMVar, putMVar
    - generalises mutexes, 1-place channels, state containers
- Asynchronous exceptions:
  - throwTo
    - throw an exception to another thread
  - mask
    - prevent exceptions from being thrown here for a while