Parallel and Concurrent Haskell
Part II

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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
    - forkIO
    - MVars
  - Asynchronous exceptions
    - cancellation
    - timeout
  - Software Transactional Memory

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
AAAAAAAAABABABABABABABABABABABABABABABABABABABABAB
ABABABABABABABABABABABABABABABABABABABABABABABABAB
ABABABABABABABABABABABABABABABABABABABABABABABABAB
ABABABABABABABABABABABABABABABABABABABABABABABABAB
$
```

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*

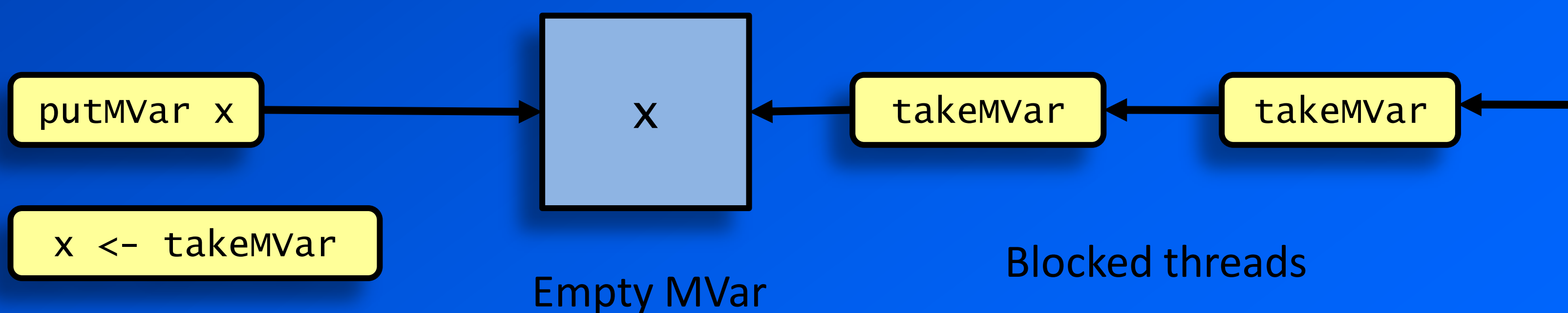
```
> ./Main 1000000 1 +RTS -s
Creating pipeline with 1000000 processes in it.
Pumping a single message through the pipeline.
Pumping a 1 messages through the pipeline.
       n    create     pump1     pump2  create/n   pump1/n   pump2/n
                 s         s         s        us        us    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

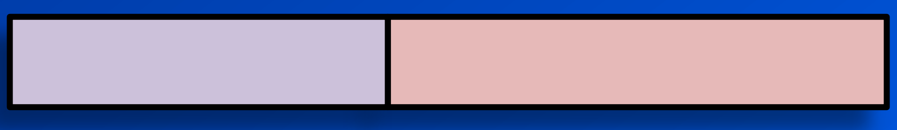
```
data MVar a  -- abstract

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



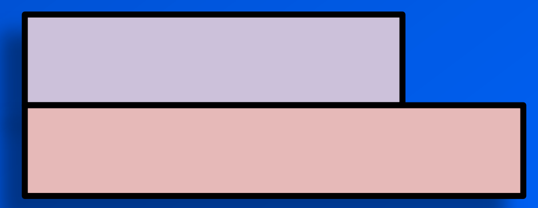
- And conversely: putMVar blocks when the MVar is full.

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 in a separate thread
  - the runtime takes care of making this efficient
- e.g. downloading two 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

```
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
```

```
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 also...

- *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
- *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...

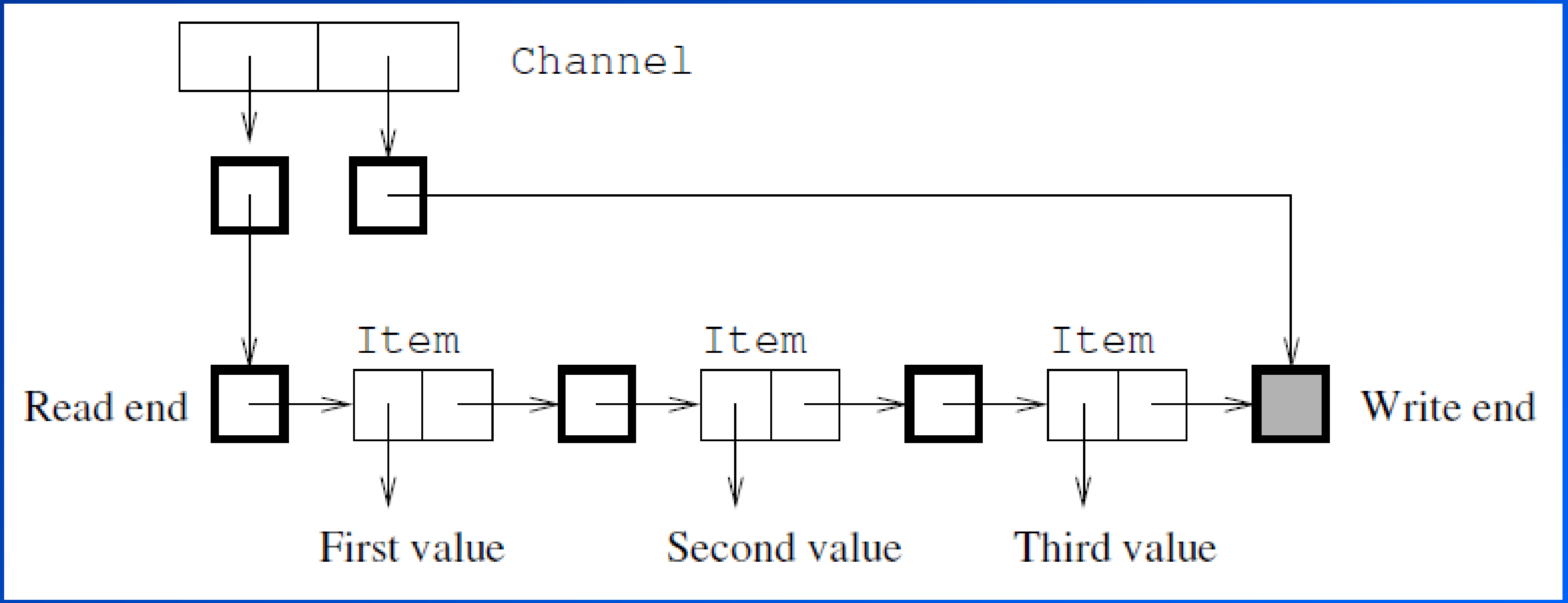
Unbounded buffered channels

- Interface:

```
data Chan a -- abstract

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

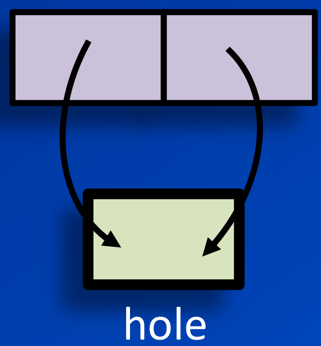
- write does not block (indefinitely)
- we are going to implement this with MVars
- one easy solution is just `data Chan a = MVar [a]`
- or perhaps... `data Chan a = MVar (Sequence a)`
- but in both of these, writers and readers will conflict with each other

Structure of a channel



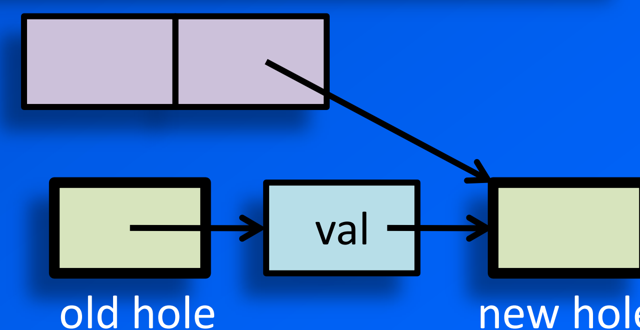

```
type Stream a = MVar (Item a)
data Item a   = Item a (Stream a)

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

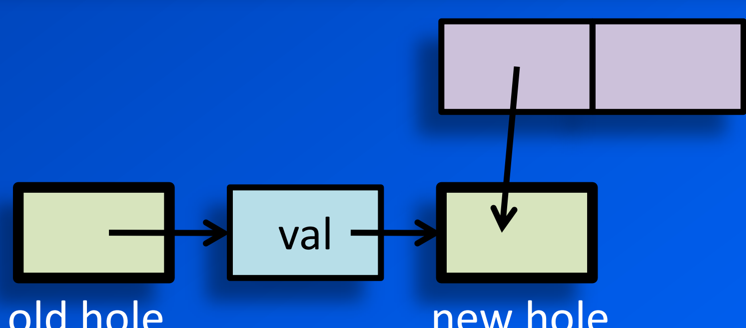
Implementation




```
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
  Item val new <- takeMVar stream
  putMVar readVar new
  return val
```

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

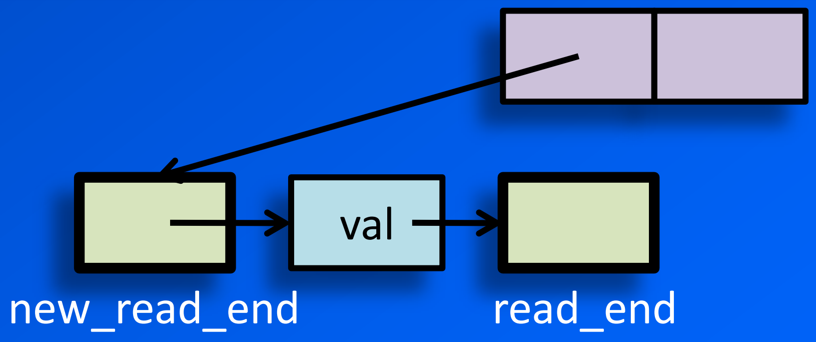
```
writeChan :: Chan a -> a -> IO ()
writeChan (Chan _ writeVar) val = do
  new_hole <- newEmptyMVar
  old_hole <- takeMVar writeVar
  putMVar writeVar new_hole
  putMVar old_hole (Item val new_hole)
```

- 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
```



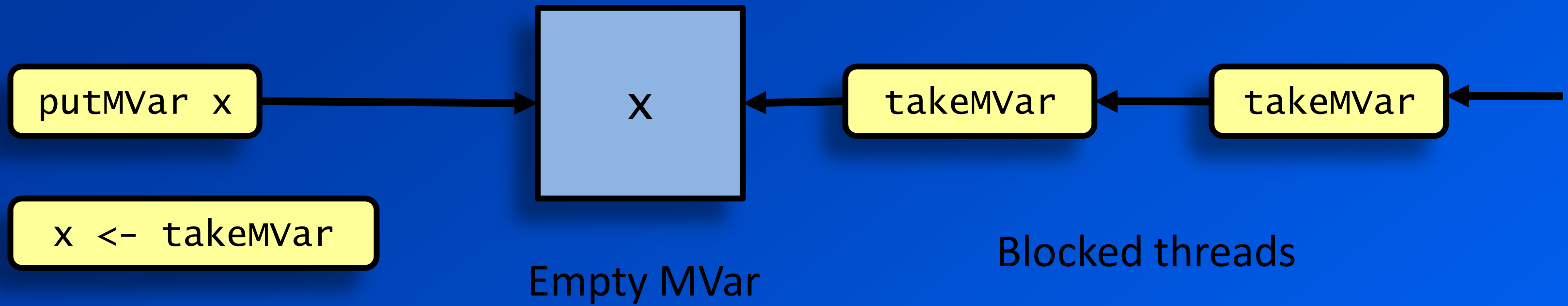
But...

- 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...)

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*)

MVars and contention

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

- 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!

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

Isn’t interrupting a thread dangerous?

- Most languages take the polling approach:
  - you have to explicitly check for interruption
  - maybe built-in support in e.g. I/O operations
- Why?
  - 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.
- 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 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.

```
newtype 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:

```
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.

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

async :: IO a -> IO (Async a)
async io = do
  m <- newEmptyMVar
  t <- forkIO ((do r <- action; putMVar var (Right r))
                  `catch` \e -> putMVar var (Left e))
  return (Async t m)

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

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

Attempt 2

Attempt 1

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

- Clearly we need a way to manage the delivery of asynchronous exceptions during critical sections.
- Haskell provides mask for this purpose:

```
mask :: ((IO a -> IO a) -> IO b) -> IO b
```

- Use it like this:

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

- mask takes as its argument a function (\restore -> ...)
- 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
  a <- takeMVar m
  r <- restore (f a) `catch` \e -> do putMVar m a; throw e
  putMVar m r
```

- 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*
> and may receive asynchronous exceptions, 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 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)
```

danger!

- use modifyMVar_

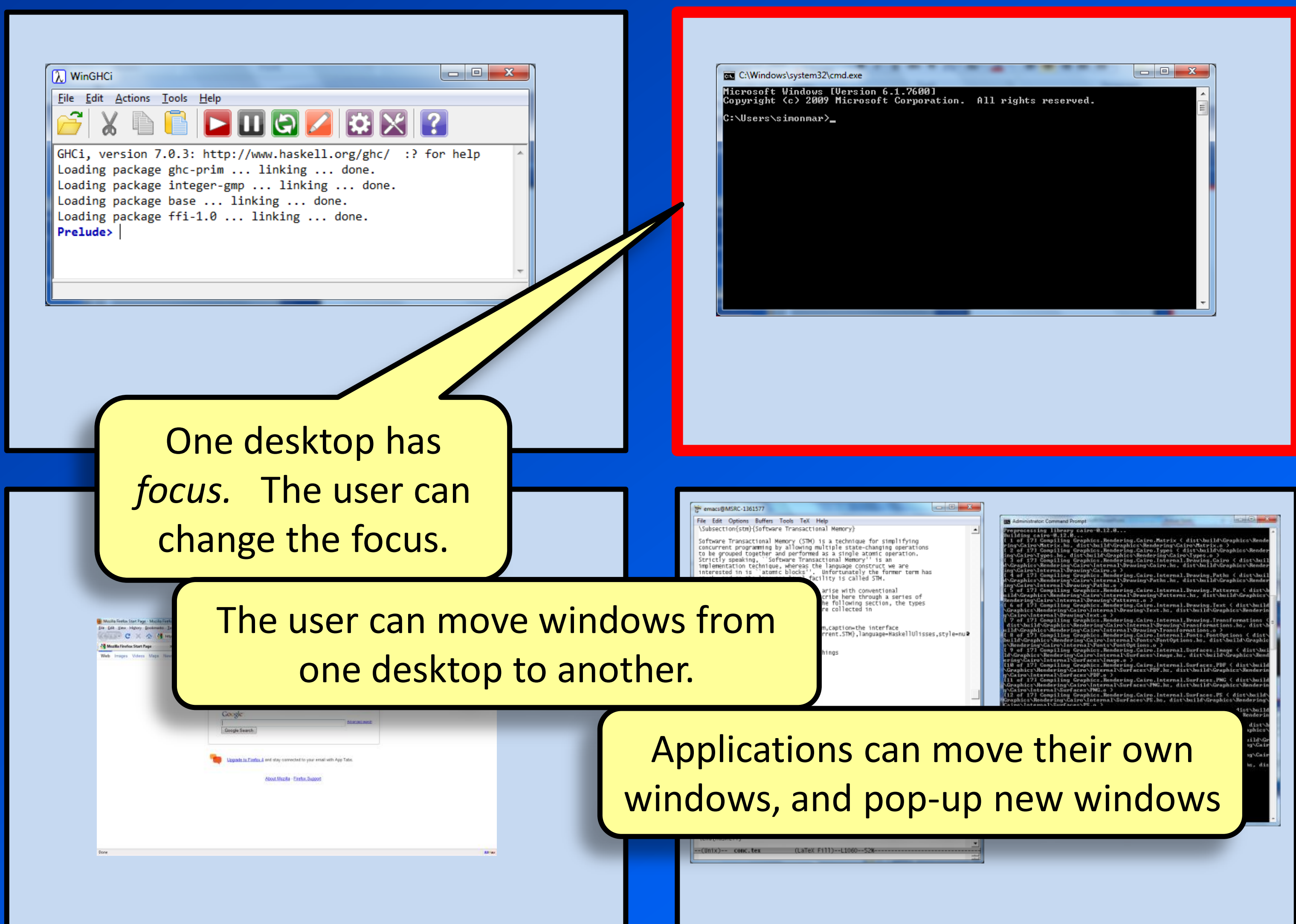
```
writeChan (Chan _ writeVar) val = do
  new_hole <- newEmptyMVar
  modifyMVar_ writeVar $ \old_hole -> do
    putMVar old_hole (Item val new_hole)
    return new_hole
```

Software Transactional Memory

Software transactional memory

- An alternative to MVar for managing
  - shared state
  - communication
- STM has several advantages:
  - compositional
  - much easier to get right
  - much easier to manage error conditions (including async exceptions)

Example: a window-manager



How to implement this?

- Suppose we want to structure the window manager in several threads, one for each input/output stream:
  - One thread to listen to the user
  - One thread for each client application
  - One thread to render the display
- The threads share the state of the desktops – how should we represent it?

Option 1: a single MVar

```
type Display = MVar (Map Desktop (Set Window))
```

- Advantages:
  - simple
- Disadvantages:
  - single point of contention. (not only performance: one misbehaving thread can block everyone else.)
- representing the Display by a process (aka the actor model) suffers from the same problem
- Can we do better?

Option 2: one MVar per Desktop

```
~~type Display = MVar (Map Desktop (Set Window))~~
type Display = Map Desktop (MVar (Set Window))
```

- This avoids the single point of contention, but a new problem emerges. Try to write an operation that moves a window from one Desktop to another:

```
moveWindow :: Display -> Window -> Desktop -> Desktop
           -> IO ()
moveWindow disp win a b = do
  wa <- takeMVar ma
  wb <- takeMVar mb
  putMVar ma (Set.delete win wa)
  putMVar mb (Set.insert win wb)
 where
  ma = fromJust (Map.lookup a disp)
  mb = fromJust (Map.lookup b disp)
```

```haskell
moveWindow :: Display -> Window -> Desktop -> Desktop
           -> IO ()
moveWindow disp win a b = do
  wa <- takeMVar ma
  wb <- takeMVar mb
  putMVar ma (Set.delete win wa)
  putMVar mb (Set.insert win wb)
 where
  ma = fromJust (Map.lookup a disp)
  mb = fromJust (Map.lookup b disp)
```

Be careful to take both Mvars before putting the results, otherwise another thread could observe an inconsistent intermediate state

- Ok so far, but what if we have two concurrent calls to moveWindow:

```
Thread 1: moveWindow disp w1 a b
Thread 2: moveWindow disp w2 b a
```

- Thread 1 takes the MVar for Desktop a
- Thread 2 takes the MVar for Desktop b
- Thread 1 tries to take the MVar for Desktop b, and blocks
- Thread 2 tries to take the MVar for Desktop a, and blocks
- DEADLOCK (“Dining Philosophers”)

How can we solve this?

- Impose a fixed ordering on MVars, make takeMVar calls in the same order on every thread
  - painful
  - the whole application must obey the rules (including libraries)
  - error-checking can be done at runtime, but complicated (and potentially expensive)

STM solves this

```
type Display = Map Desktop (TVar (Set Window))

moveWindow :: Display -> Window -> Desktop -> Desktop -> IO ()

moveWindow disp win a b = atomically $ do
  wa <- readTVar ma
  wb <- readTVar mb
  writeTVar ma (Set.delete win wa)
  writeTVar mb (Set.insert win wb)
 where
  ma = fromJust (Map.lookup a disp)
  mb = fromJust (Map.lookup b disp)
```

- The operations inside atomically happen indivisibly to the rest of the program (it is a *transaction*)
- ordering is irrelevant – we could reorder the readTVar calls, or interleave read/write/read/write

- Basic STM API:

```
data STM a -- abstract
instance Monad STM -- amongst other things

atomically :: STM a -> IO a

data TVar a -- abstract
newTVar   :: STM (TVar a)
readTVar  :: TVar a -> STM a
writeTVar :: TVar a -> a -> STM ()
```

- The implementation does not use a global lock: two transactions operating on disjoint sets of TVars can proceed simultaneously

Composability

- STM is composable
- e.g. write an operation to swap two windows

```
swapWindows :: Display
            -> Window -> Desktop
            -> Window -> Desktop
            -> IO ()
```

- with MVars we would have to write a special-purpose routine to do this...

- with STM we can build on what we already have:

```
swapWindows :: Display
            -> Window -> Desktop
            -> Window -> Desktop
            -> IO ()
swapWindows disp w a v b = atomically $ do
  moveWindowSTM disp w a b
  moveWindowSTM disp v b a
```

- (moveWindowSTM is just moveWindow without atomically – this is typically how STM operations are provided)
- STM allows us to *compose* stateful operations into larger transactions
  - thus allowing more reuse
  - and modularity – we don't have to know how moveWindowSTM works internally to be able to compose it.

STM and blocking

- So far we saw how to use STM to build atomic operations on shared state
- But concurrency often needs a way to manage *blocking* – that is, waiting for some condition to become true
  - e.g. a channel is non-empty
- Haskell's STM API has a beautiful way to express blocking too...

```
retry :: STM a
```

- that's it!
- the semantics of retry is just "try the current transaction again"
- e.g. block until a TVar contains a non-zero value:

```
atomically $ do
   x <- readTVar v
   if x == 0 then retry
             else return x
```

- busy-waiting is a possible implementation, but we can do better:
  - obvious optimisation: wait until some state has changed
  - specifically, wait until any TVars *accessed by this transaction so far* have changed (this turns out to be easy for the runtime to arrange)
  - so retry gives us blocking – the current thread is blocked waiting for the TVars it has read to change

Using blocking in the window manager

- We want a thread responsible for rendering the currently focussed desktop on the display
  - it must re-render when something changes
  - the user can change the focus
  - windows can move around
- there is a TVar containing the current focus:

```
type UserFocus = TVar Desktop
```

- so we can get the set of windows to render:

```
getWindows :: Display -> UserFocus -> STM (Set Window)
getWindows disp focus = do
  desktop <- readTVar focus
  readTVar (fromJust (Map.lookup desktop disp))
```

- Given:

```
render :: Set Window -> IO ()
```

- Here is the rendering thread:

```
renderThread :: Display -> UserFocus -> IO ()
renderThread disp focus = do
  wins <- atomically $ getWindows disp focus
  loop wins
 where
  loop wins = do
    render wins
    next <- atomically $ do
               wins' <- getWindows disp focus
               if (wins == wins')
                   then retry
                   else return wins'
    loop next
```

- so we only call render when something has changed.
- The runtime ensures that the render thread remains blocked until either
  - the focus changes to a different Desktop
  - the set of Windows *on the current Desktop* changes

- No need for explicit wakeups
  - the runtime is handling wakeups automatically
  - state-modifying code doesn’t need to know who to wake up – more modularity
  - no “lost wakeups” – a common type of bug with condition variables

Channels in STM

- Earlier we implemented channels with MVars
- Instructive to see what channels look like in STM
- Also we’ll see how STM handles composing transactions that block
- And how STM makes it much easier to handle exceptions (particularly asynchronous exceptions)

```haskell
data TChan a = TChan (TVar (TVarList a))
                     (TVar (TVarList a))

type TVarList a = TVar (TList a)
data TList a = TNil | TCons a (TVarList a)
```

- Why do we need TNil & TCons?
  - unlike MVars, TVars do not have an empty/full state, so we have to program it
- Otherwise, the structure is exactly the same as the MVar implementation

```haskell
readTChan :: TChan a -> STM a
readTChan (TChan read _write) = do
  listhead <- readTVar read
  head <- readTVar listhead
  case head of
    TNil -> retry
    TCons a tail -> do
      writeTVar read tail
      return a
```

Benefits of STM channels (1)

- Correctness is straightforward: do not need to consider interleavings of operations
  - (recall with MVar we had to think carefully about what happened with concurrent read/write, write/write, etc.)

Benefits of STM channels (2)

- more operations are possible, e.g.:

```
unGetTChan :: TChan a -> a -> STM ()
unGetTChan (TChan read _write) a = do
   listhead <- readTVar read
   newhead <- newTVar (TCons a listhead)
   writeTVar read newhead
```

- (this was not possible with MVar, trivial with STM)

Benefits of STM channels (3)

- Composable blocking. Suppose we want to implement

```
readEitherTChan :: TChan a -> TChan b -> STM (Either a b)
```

- we want to write a transaction like

```
readEitherTChan a b = atomically $
  (fmap Left $ readTChan a)
      `orElse`
  (fmap Right $ readTChan b)
```

```
orElse :: STM a -> STM a -> STM a
```

```
orElse :: STM a -> STM a -> STM a
```

- execute the first argument
- if it returns a value:
  - that is the value returned by orElse
- if it retries:
  - *discard any effects (writeTVars) it did*
  - execute the second argument
- orElse is another way to compose transactions: it runs *either* one or the other

Benefits of STM channels (4)

- Asynchronous exception safety.

> If an exception is raised during a transaction, the effects of the transaction are discarded, and the exception is propagated as normal

- error-handling in STM is trivial: since the effects are discarded, all invariants are restored after an exception is raised.
- Asynchronous exception safety comes for free!
- The simple TChan implementation is already async-exception-safe

STM summary

- Composable atomicity
- Composable blocking
- Robustness: easy error handling
- Don’t believe the anti-hype!
- Why would you still use MVar?
  - fairness
  - single-wakeup
  - performance

Lab

- Download the sample code here:

```
http://community.haskell.org/~simonmar/par-tutorial.tar.gz
```

- or get it with git:

```
git clone https://github.com/simonmar/par-tutorial.git
```

- code is in par-tutorial/code
- lab exercises are here:

```
http://community.haskell.org/~simonmar/lab-exercises.pdf
```