Parallel & Concurrent Haskell 5: Server Applications

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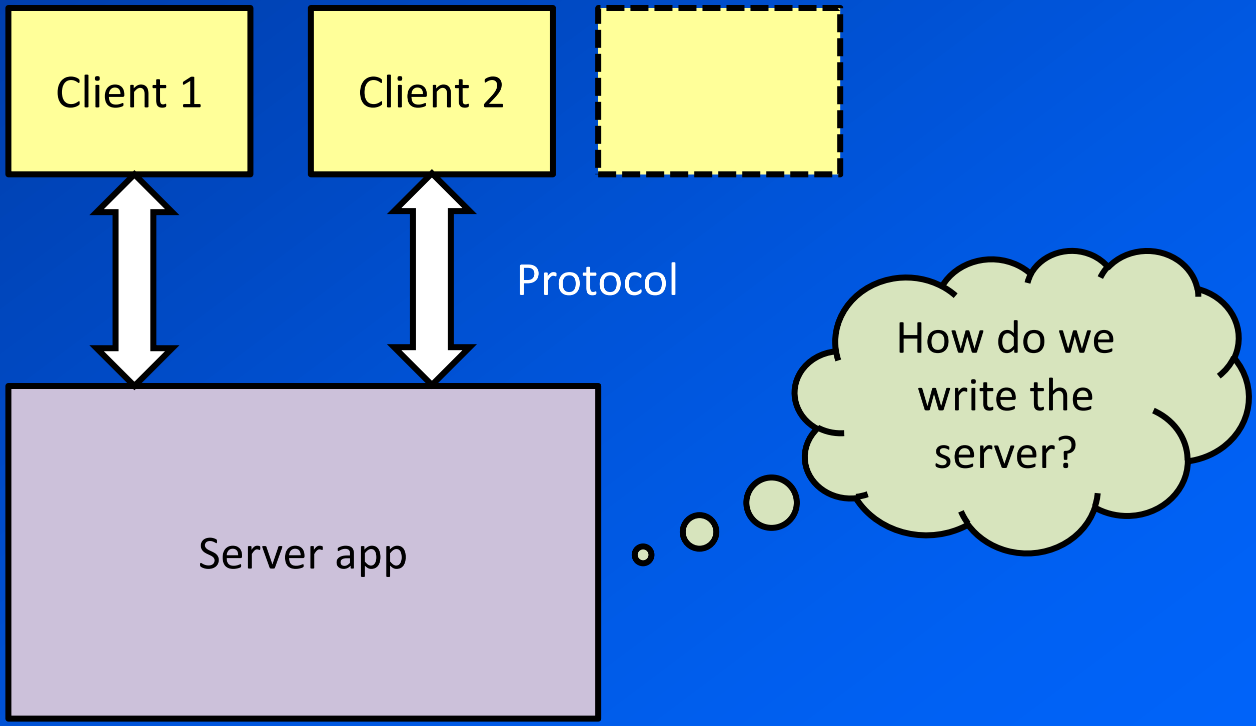
Overview

- Chapter 14 in the notes
- Building a simple multi-client network server
  - no shared state
  - one thread per client
- Error handling
- More complex example: a chat server
  - shared state
  - managing multiple threads per client

Setup

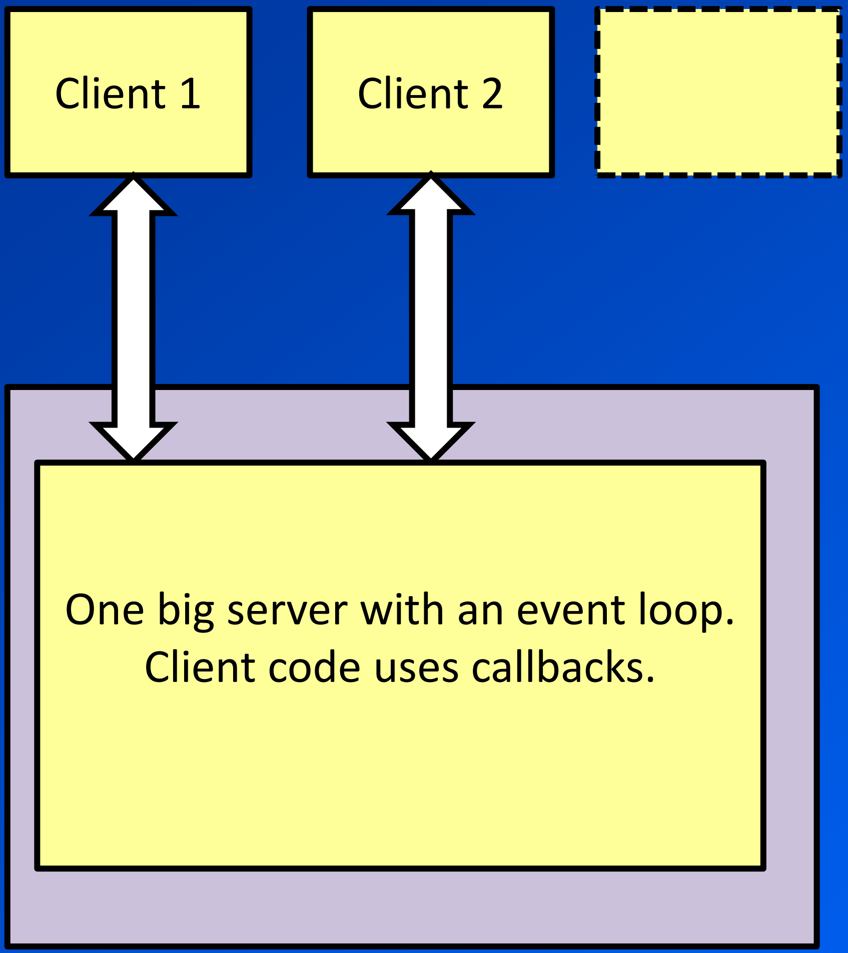


e.g.

- web server
- mail server
- database server
- …

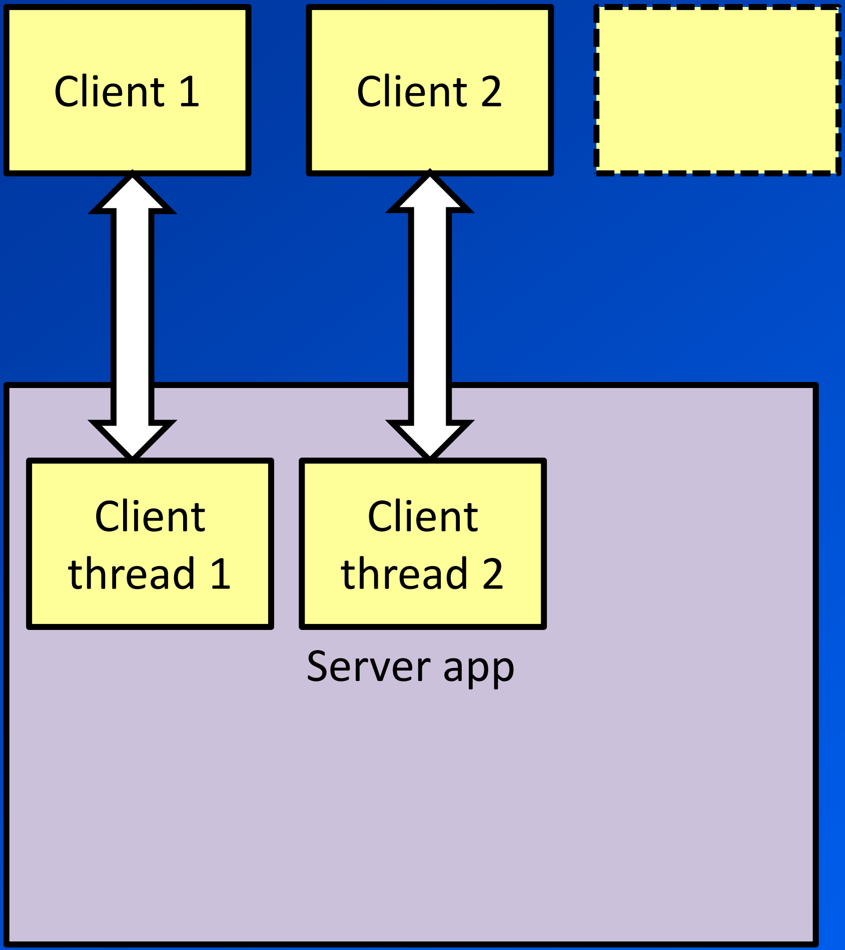
Background:
Threads vs. Events

Without concurrency


Client 1
Client 2
One big server with an event loop.
Client code uses callbacks.

- e.g. node.js
- Advantages
  - performance (?)
  - simplicity: no mutable shared state
- Disadvantages
  - coding with callbacks is painful
  - clients can accidentally block each other
  - No parallelism

Concurrency



- One thread per client
- Advantages:
  - the interaction with a single client is straight-line code
  - clients cannot accidentally block each other
  - automatically uses multiple cores
- Disadvantages
  - performance?
  - shared state?

Disadvantages?

- Performance:
  - In GHC threads are very lightweight
  - When many threads are blocked on I/O, a single thread handles the interaction with the OS, using epoll(). (the “IO manager thread”)
  - Typical for a single core using 1 thread per client:
    - 100K+ simultaneous connections
    - 10K+ requests/sec
- Mutable shared state:
  - shared state is less of a problem in Haskell: e.g. use STM

Threads or events?

- Long running debate
- See e.g. "Why Events Are A Bad Idea (for high-concurrency servers)" Rob von Behren, Jeremy Condit and Eric Brewer (HotOS IX, 2003)
- In Haskell we think we provide a nice point in the design space:
  - threads at the programmer level, for ease of programming and abstraction
  - implemented using event-based techniques (epoll() etc.), which eliminates many of the traditional disadvantages of threads

End of background!
Let’s write some code.

Simple example

- Sample: `server.hs`
- Server accepts connections on port 44444
- Loop:
  - Client sends an integer *n*
  - Server replies with *2n*
- If client sends “end”, the connection is terminated

- Code for the interaction with a single client

```haskell
talk :: Handle -> IO ()
talk h = do
  hSetBuffering h LineBuffering
  loop
 where
  loop = do
    line <- hGetLine h
    if line == "end"
       then hPutStrLn h ("Thank you for using the " ++
                         "Haskell doubling service.")
       else do hPutStrLn h (show (2 * (read line :: Integer)))
               loop
```

- Handle is bound to the network socket

- The main program

```
main :: IO ()
main = withSocketsDo $ do
   sock <- listenOn (PortNumber (fromIntegral port))
   printf "Listening on port %d\n" port
   forever $ do
      (handle, host, port) <- accept sock
      printf "Accepted connection from %s: %s\n" host (show port)
      forkIO (talk handle `finally` hClose handle)

port :: Int
port = 44444
```

```
finally :: IO a -> IO b -> IO b
```

Demo

- Note 1: making the server concurrent required zero changes to the `talk` function that interacts with a single client.
- Note 2: the server will use multiple cores if we compile with -threaded

- Q: what happens when an error occurs?
  1. if the user types a non-number?
  2. if the user closes the connection?
- Q: if we wanted to handle the case of the user typing a non-number, what should we do?

A more complex example: a chat server

```
$ nc localhost 44444
What is your name?
Simon
*** Simon has connected
*** Andres has connected
Hi there!
<Simon>: Hi there!
<Andres>: Hello
/kick Andres
you kicked Andres
*** Andres has disconnected
/quit
$
```

Behaviour

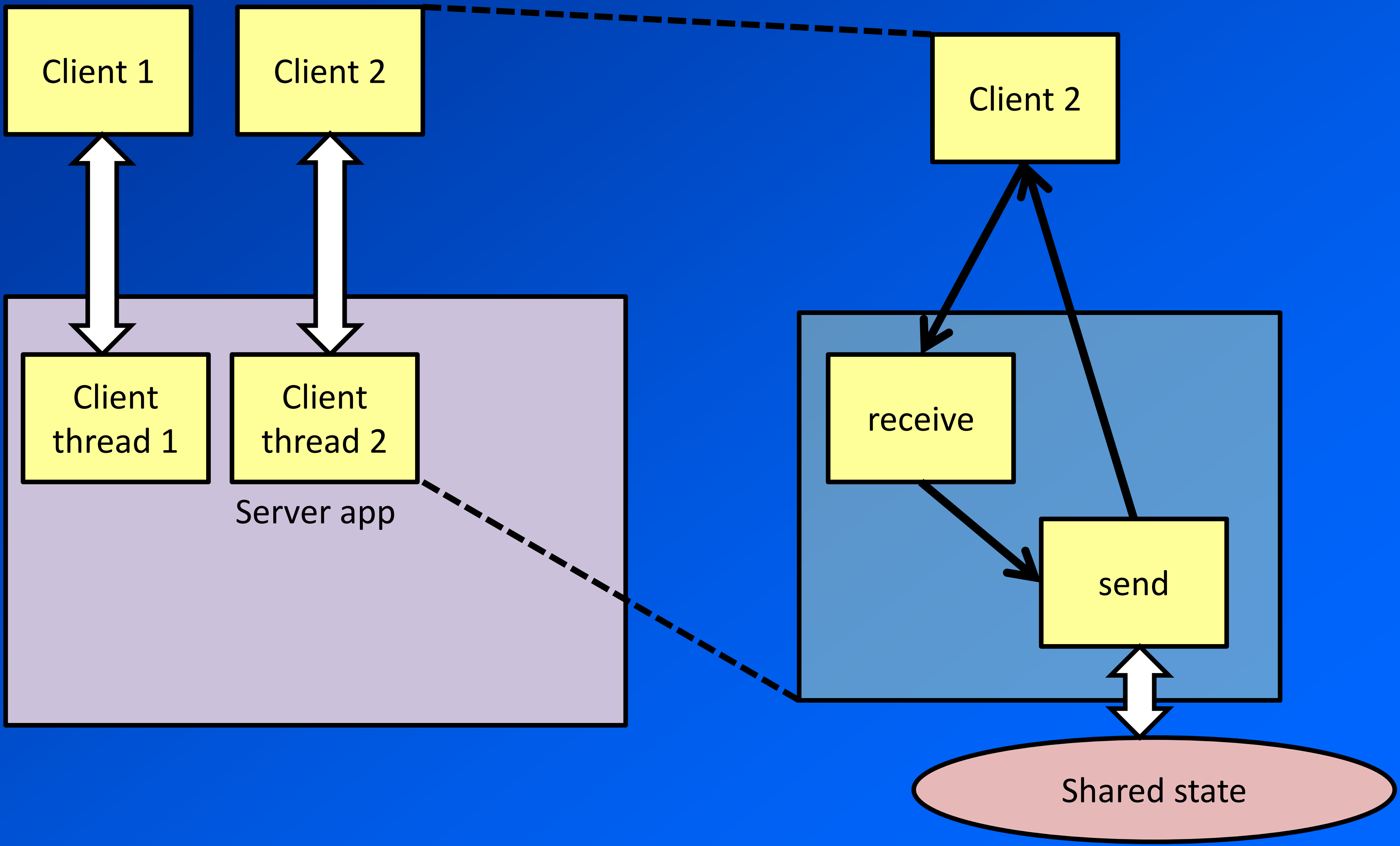
- On client connection, the server first asks for the user’s name before entering the command loop
- Commands:
  - /tell <name> <msg>
    - message a specific user
  - /kick <name>
    - forcibly disconnect another user
  - /quit
    - disconnect the current user
  - <anything else>
    - broadcast to all users
- All clients are informed of connections/disconnections

Why is this harder?

- We have some shared state:
  - the clients that are currently connected
- We need to think about consistency
  - what happens if two users try to kick each other?
  - our choice: exactly one succeeds
  - what happens if two users simultaneously log in with the same name?
  - again: exactly one succeeds
- The client interaction cannot be programmed in a single thread
  - we need to receive network input *and* events from other clients (broadcast, tell, kick, client connected or disconnected)
  - no way to do both in one thread

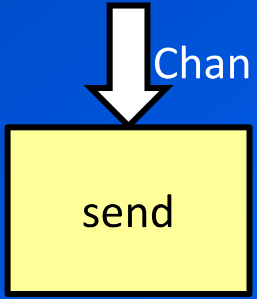
Design

- Must have only one thread that sends information back to the client, otherwise some locking would be needed to prevent interleaving
- Simplest approach is to have two threads:
  - receive forwards the network traffic from the client to a channel (only)
  - send does everything else, including sending data back to the client


Client 1
Client 2
Client thread 1
Client thread 2
Server app
Client 2
receive
send
Shared state

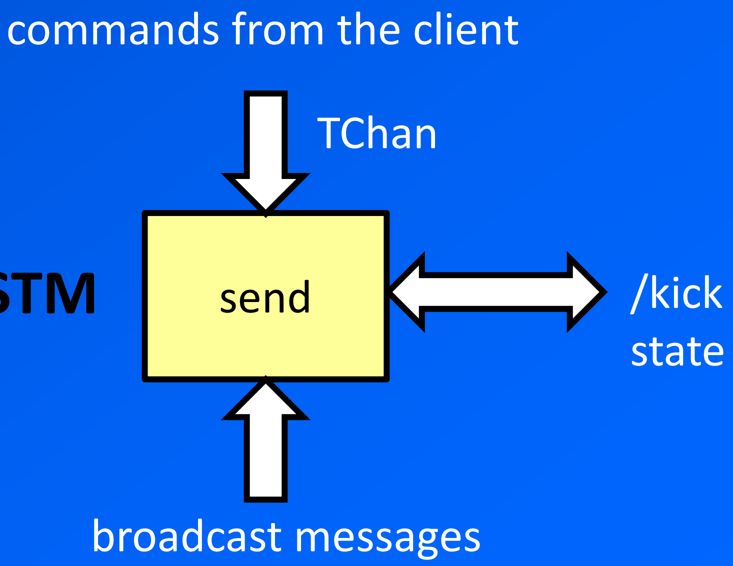
- How should the send thread wait for events? Two alternatives:
  - using MVars: all events must go down a single Chan, and the send thread processes events one at a time from the Chan
  - using STM: we can have multiple event sources, and the send thread uses `orElse` to wait for an event on any of them

- commands from the client
- broadcast messages
- /kick commands



MVar

STM



- Using MVar/Chan would make it difficult to guarantee consistency for multiple kicks, because there could be multiple kick messages in-flight simultaneously
- Using STM, we can guarantee atomic access to the shared state
- So we’ll use STM…

- Client types

```haskell
type ClientName = String

data Client = Client
  { clientName     :: ClientName
  , clientHandle   :: Handle
  , clientKicked   :: TVar (Maybe String)
  , clientSendChan :: TChan Message
  }

data Message = Notice String
             | Tell ClientName String
             | Broadcast ClientName String
             | Command String

newClient :: ClientName -> Handle -> STM Client
```

- We could use two channels to send messages to the client, but one is simpler.

- Sending a message to a client:

```
sendMessage :: Client -> Message -> STM ()
sendMessage Client{..} msg =
    writeTChan clientSendChan msg
```

- Client{..} is a *record wild card.* We could have written:

```
sendMessage Client{ clientName     = clientName
                  , clientHandle   = clientHandle
                  , clientKicked   = clientKicked
                  , clientSendChan = clientSendChan
                  } msg =
    writeTChan clientSendChan msg
```

- Server state

```
data Server = Server
  { clients :: TVar (Map ClientName Client)
  }

newServer :: IO Server
newServer = do
  c <- newTVarIO Map.empty
  return Server { clients = c }
```

- All the clients will have access to the Server state, because they need to be able to send messages to each other.

- Broadcast a message to all clients

```
broadcast :: Server -> Message -> STM ()
broadcast Server{..} msg = do
    clientmap <- readTVar clients
    mapM_ (\client -> sendMessage client msg)
          (Map.elems clientmap)
```

So far...

```
type ClientName = String

data Client
data Server

data Message

newServer :: IO Server
newClient :: ClientName -> Handle -> STM Client

sendMessage :: Client -> Message -> STM ()
broadcast   :: Server -> Message -> STM ()
```

- Now go top-down, write the rest of the code

```
main :: IO ()
main = withSocketsDo $ do
  server <- newServer
  sock <- listenOn (PortNumber (fromIntegral port))
  printf "Listening on port %d\n" port
  forever $ do
      (handle, host, port) <- accept sock
      printf "Accepted connection from %s: %s\n" host (show port)
      fork (talk server handle `finally` hClose handle)

port :: Int
port = 44444
```

Defining talk

- Overall plan:
  - ask the user for their name
  - if the name already exists, ask again
  - otherwise, create a Client and insert it into the Server state
    - NB. make sure the Client is removed from the state if the connection is closed, or an error occurs
  - Notify other clients of the new connection
  - Set up the threads and start processing

```haskell
talk :: Server -> Handle -> IO ()
talk server@Server{..} handle = do
    hSetNewlineMode handle universalNewlineMode
    hSetBuffering handle LineBuffering
    readName
  where
    readName = do
      hPutStrLn handle "What is your name?"
      name <- hGetLine handle
      clientmap <- atomically $ readTVar clients
      if Map.member name clientmap
         then do
           hPrintf handle "The name %s is in use“ name
           readName
         else do
           client <- atomically $ newClient name handle
           atomically $
              writeTVar clients
                  (Map.insert name client clientmap)
           ...
```

Not enough atomicity here, let’s try again

```
checkAddClient :: Server -> ClientName -> Handle -> IO (Maybe Client)
checkAddClient server@Server{..} name handle = atomically $ do
    clientmap <- readTVar clients
    if Map.member name clientmap
       then return Nothing
       else do
         client <- newClient name handle
         writeTVar clients (Map.insert name client clientmap)
         broadcast server $ Notice $ name ++ " has connected"
         return (Just client)
```

- Checks for and adds the new client atomically
  - returns (Just client) if successful
  - or Nothing otherwise

Back to talk...

```
talk :: Server -> Handle -> IO ()
talk server@Server{..} handle = do
    hSetNewlineMode handle universalNewlineMode
    hSetBuffering handle LineBuffering
    readName
  where
    readName = do
      hPutStrLn handle "What is your name?"
      name <- hGetLine handle
      m <- checkAddClient server name handle
      case m of
         Nothing -> do
           hPrintf handle "The name %s is in use“ name
           readName
         Just client -> do
           runClient server client
              `finally` removeClient server name
```

Strictly speaking we should plug the hole between checkAddClient and finally (see the notes...)

removeClient is quite straightforward:

```
removeClient :: Server -> ClientName -> IO ()
removeClient server@Server{..} name = atomically $ do
    clientmap <- readTVar clients
    writeTVar clientmap (Map.delete name m)
    broadcast server (Notice (name ++ " has disconnected“))
```

Now to start up the client threads.

```
runClient :: Server -> Client -> IO ()
```

- Overall plan:
  - create a receive thread to forward network traffic to the clientSendChan
  - create a send thread to watch clientSendChan and clientKicked
  - if *either* of these threads dies or returns, we want to close the connection and clean up (i.e. runClient should return or throw an exception)
  - there should be no possibility that a thread is left running after the client has disconnected.

- Let’s package up this behaviour behind a new abstraction:

```
concurrently :: IO () -> IO () -> IO ()
```

- this runs both IO actions concurrently, such that
  - if either one returns, the other is killed, and concurrently then returns
  - if either one throws an exception, then the other is killed and concurrently re-throws the exception in the current thread.
- Not hard to build (later...)
- Note: actually we have three threads per client!

```haskell
runClient :: Server -> Client -> IO ()
runClient server@Server{..} client@Client{..}
 = concurrently send receive
 where
    send = join $ atomically $ do
        k <- readTVar clientKicked
        case k of
            Just reason -> return $
                hPutStrLn clientHandle $
                      "You have been kicked: " ++ reason
            Nothing -> do
                msg <- readTChan clientSendChan
                return $ do
                    continue <- handleMessage server client msg
                    when continue $ send

    receive = forever $ do
       msg <- hGetLine clientHandle
       atomically $ sendMessage client $ Command msg
```

Note we check clientKicked first – cannot process any other commands if we are kicked.

```haskell
handleMessage :: Server -> Client -> Message -> IO Bool
handleMessage server client@Client{..} message =
  case message of
     Notice msg         -> output $ "*** " ++ msg
     Tell name msg      -> output $ "*" ++ name ++ "*: " ++ msg
     Broadcast name msg -> output $ "<" ++ name ++ ">: " ++ msg
     Command msg ->
       case words msg of
           ["/kick", who] -> do
               join $ atomically $ kick server client who
               return True
           "/tell" : who : what -> do
               atomically $ tell server clientName who (unwords what)
               return True
           ["/quit"] ->
               return False
           ('/':_):_ -> do
               hPutStrLn clientHandle $
                    "Unrecognised command: " ++ msg
               return True
           _ -> do
               atomically $ broadcast server $
                                Broadcast clientName msg
               return True
 where
   output s = do hPutStrLn clientHandle s; return True
```

```haskell
tell :: Server -> ClientName -> ClientName -> String -> STM ()
tell Server{..} from who msg = do
    clientmap <- readTVar clients
    case Map.lookup who clientmap of
        Nothing -> return ()
        Just client -> sendMessage client $ Tell from msg

kick :: Server -> Client -> ClientName -> STM (IO ())
kick Server{..} client@Client{clientHandle=handle} who = do
    clientmap <- readTVar clients
    case Map.lookup who clientmap of
        Nothing ->
           return $ hPutStrLn handle (who ++ " is not connected")
        Just victim -> do
           writeTVar (clientKicked victim) $
                 Just ("by " ++ clientName client)
           return $ hPutStrLn handle ("you kicked " ++ who)
```

Demo

Defining ‘concurrently’ (the nice way, using STM; for the hard way see the notes)

```haskell
data Async a = Async ThreadId (TMVar (Either SomeException a))

forkFinally :: IO a -> (Either SomeException a -> IO ())
            -> IO ThreadId
forkFinally action and_then =
  mask $ \restore ->
    forkIO $ try (restore action) >>= and_then

async :: IO a -> IO (Async a)
async action = do
   var <- newEmptyTMVarIO
   t <- forkFinally action (\r -> atomically $ putTMVar var r)
   return (Async t var)

waitSTMThrow :: Async a -> STM a
waitSTMThrow (Async _ var) = do
   r <- readTMVar var
   case r of
     Left a -> return a
     Right e -> throwSTM e

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

```
withAsync :: IO a -> (Async a -> IO b) -> IO b
withAsync action inner = bracket (async action) cancel inner

concurrently :: IO a -> IO b -> IO ()
concurrently left right =
  withAsync left $ \a ->
  withAsync right $ \b ->
  atomically $
    (void $ waitSTMThrow a)
      `orElse`
    (void $ waitSTMThrow b)
```

Summary

- Dealing with clients that must respond both to network and local events:
  - use two threads
    - forward messages from the network to a local channel
    - then use STM with orElse to multiplex events from the channel and other event sources (clientKicked in our case)
  - to manage the two threads, we used the concurrently abstraction:

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

    - some similarity with Erlang's linked processes

Summary (cont)

- Global consistency guarantees are easier to manage with STM – just do atomic operations on the state.
  - No need to worry about fine-grained vs. coarse-grained locking
- Take particular care with atomicity at startup/shutdown
  - no loopholes where a thread might be left behind if something goes wrong