Lightweight Concurrency Primitives for GHC

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The Problem

- GHC has rich support for concurrency & parallelism:
  - Lightweight threads (*fast*)
  - Transparent scaling on a multiprocessor
  - STM
  - par/seq
  - Multithreaded FFI
  - Asynchronous exceptions
- But…

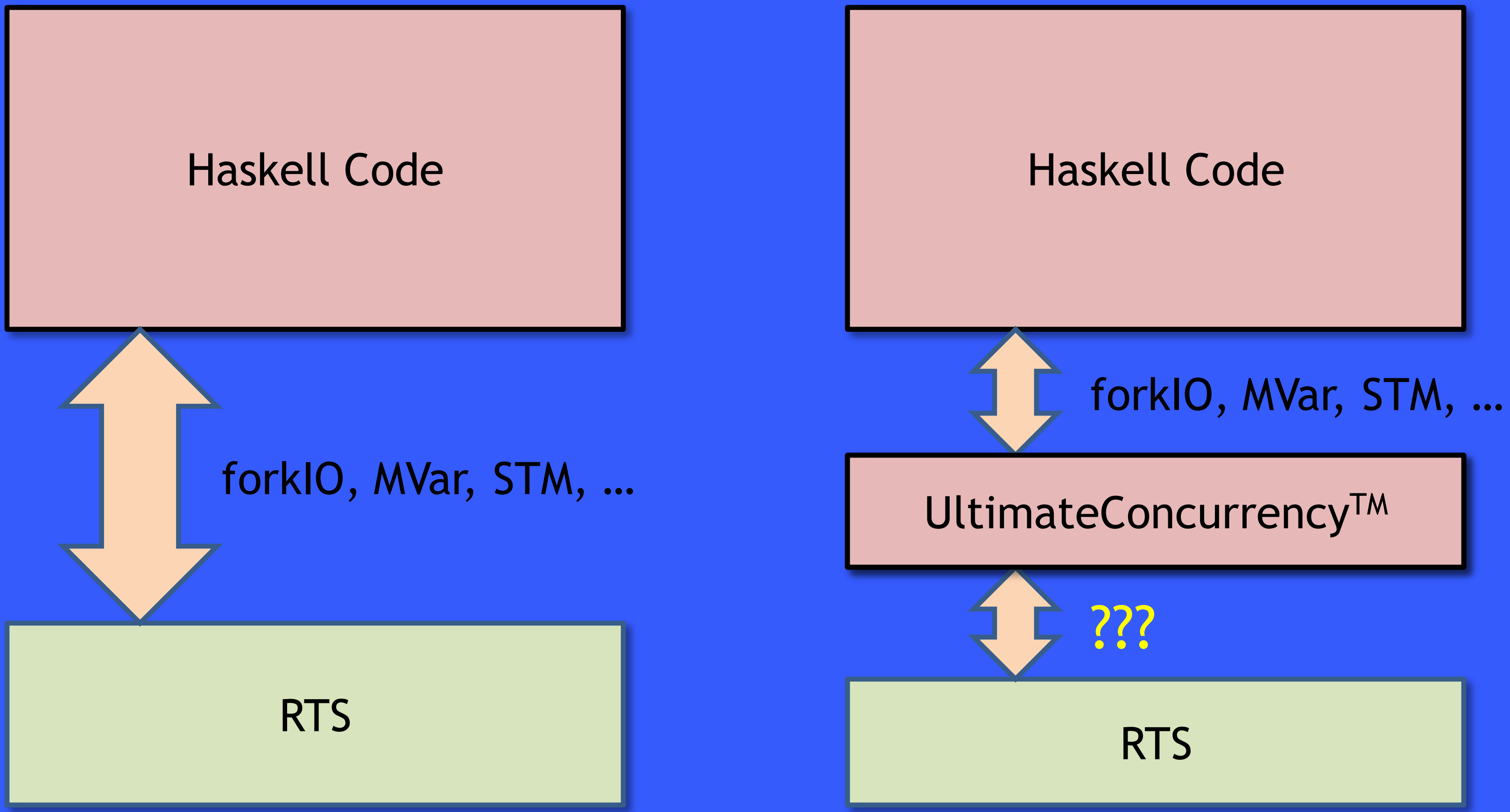
The Problem

- … it is *inflexible*.
  - The implementation is entirely in the runtime
  - Written in C
  - Modifying the implementation is hard: it is built using OS threads, locks and condition variables.
  - Can only be updated with a GHC release

Why do we care?

- The concurrency landscape is changing.
  - New abstractions are emerging; e.g. we might want to experiment with variants of STM
  - We might want to experiment with scheduling policies: e.g. STM-aware scheduling, or load-balancing algorithms
  - Our scheduler doesn't support everything: it lacks priorities, thread hierarchies/groups
  - Certain applications might benefit from application-specific scheduling
  - For running the RTS on bare hardware, we want a new scheduler

The Idea



Haskell Code

forkIO, MVar, STM, …

RTS

Haskell Code

forkIO, MVar, STM, …

UltimateConcurrency™

???

RTS

What is ???

- We call it the *substrate interface*
- The Rules of the Game:
  - as small as possible: mechanism, not policy
  - We must have lightweight threads
  - Scheduling, “threads”, blocking, communication, CPU affinity etc. are the business of the library
  - The RTS provides:
    - GC
    - multi-CPU execution
    - stack management
  - Must be enough to allow GHC’s concurrency support to be implemented as a library

The substrate

```
------- (1) Primitive Transaction Memory
data PTM a
data PVar a
instance Monad PTM
newPVar    :: a -> PTM (PVar a)
readPVar   :: PVar a -> PTM a
writePVar  :: PVar a -> a -> PTM ()
catchPTM   :: PTM a -> (Exception->PTM a)
           -> PTM a
atomicPTM  :: PTM a -> IO a

------- (2) Haskell Execution Context
data HEC
instance Eq HEC
instance Ord HEC
getHEC     :: PTM HEC
waitCond   :: PTM (Maybe a) -> IO a
wakeupHEC  :: HEC -> IO ()
```

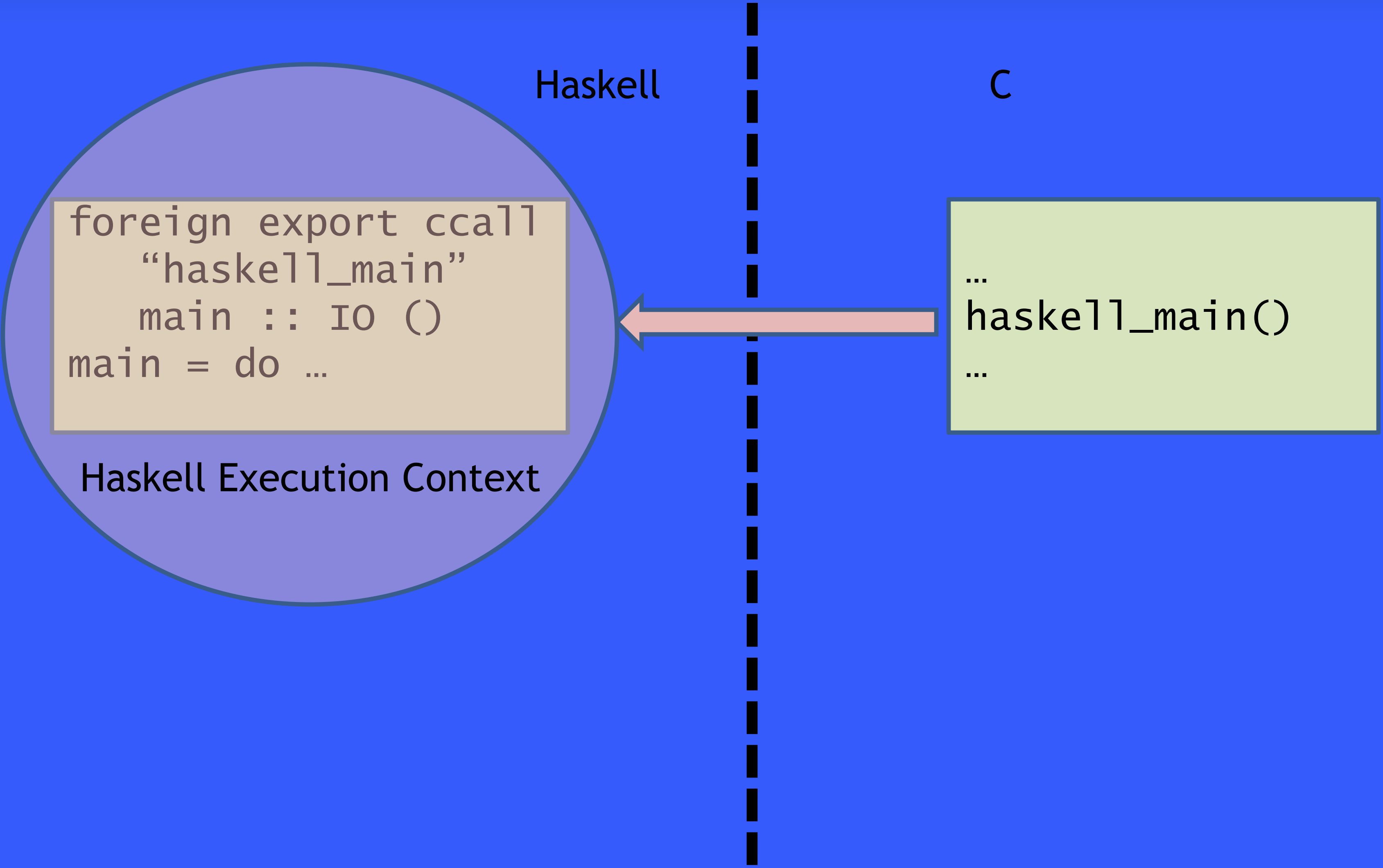
```
------- (3) Stack Continuation
data SCont
newSCont    :: IO () -> IO SCont
switch      :: (SCont -> PTM SCont)
            -> IO ()

------- (4) Thread Local States
data TLSKey a
newTLSKey   :: a -> IO (TLSKey a)
getTLS      :: TLSKey a -> PTM a
setTLS      :: TLSKey a -> a -> IO ()
initTLS     :: SCont -> TLSKey a -> a
            -> IO ()

------- (5) Asynchronous Exceptions
raiseAsync   :: Exception -> IO ()
deliverAsync :: SCont -> Exception
             -> IO ()

------- (6) Callbacks
rtsInitHandler :: IO ()
inCallHandler  :: IO a -> IO a
outCallHandler :: IO a -> IO a
timerHandler   :: IO ()
blockedHandler :: IO Bool -> IO ()
```

In the beginning…



```
foreign export ccall
   “haskell_main”
   main :: IO ()
main = do …
```

```
…
haskell_main()
…
```

Haskell execution context

- Haskell code executes inside a HEC
- HEC = OS thread (or CPU) + state needed to run Haskell code
  - Virtual machine state
  - Allocation area, etc.

```
data HEC
instance Eq HEC
instance Ord HEC
getHEC :: PTM HEC
```

- A HEC is created by (and only by) a foreign in-call.
- Where is the scheduler? I'll come back to that.

Synchronisation

- There may be multiple HECs running simultaneously. They need a way to synchronise access to shared data: scheduler data structures, for example.
- Use locks & condition variables?
  - Too hard to program with
  - Bad interaction with laziness:

```
do { takeLock lk
   ; rq <- read readyQueueVar
   ; rq' <- if null rq then ...
                       else ...
   ; write readyQueueVar rq'
   ; releaseLock lk }
```

  - (MVars have this problem already)

PTM

- Transactional memory?
  - A better programming model: compositional
  - Sidesteps the problem with laziness: a transaction holds no locks while executing
  - We don’t need *blocking* at this level (STM’s retry)

```
data PTM a
data PVar a
instance Monad PTM
newPVar     :: a -> PTM (PVar a)
readPVar    :: PVar a -> PTM a
writePVar   :: PVar a -> a -> PTM ()
catchPTM    :: PTM a -> (Exception -> PTM a) -> PTM a
atomicPTM   :: PTM a -> IO a
```

Stack continuations

- Primitive threads: the RTS provides multiple *stacks*, and a way to switch execution from one to anot

PTM very important!

```
data SCont
newSCont   :: IO () -> IO SCont
switch     :: (SCont -> PTM SCont) -> IO ()
```

Switches control to a new stack.
Can decide not to switch, by
returning the current stack.

Stack Continuations

- Stack continuations are *cheap*
- Implementation: just a stack object and a stack pointer.
- Using a stack continuation multiple times is an (un)checked runtime error.
- If we want to check that an SCont is not used multiple times, need a separate object.

Putting it together: a simple scheduler

- Design a scheduler supporting threads, cooperative scheduling and MVars.

```
runQueue :: [SCont]
runQueue <- newPVar []

addToRunQueue :: SCont -> PTM ()
addToRunQueue sc = do
  q <- readPVar runQueue
  writePVar runQueue (q++[sc])

data ThreadId = ThreadId SCont

forkIO :: IO () -> IO ThreadId
forkIO action = do
    sc <- newSCont action
    atomicPTM (addToRunQueue sc)
    return (ThreadId sc)
```

yield

- Voluntarily switches to the next thread on the run queue

```
popRunQueue :: IO SCont
popRunQueue = do
   scs <- readPVar runQueue
   case scs of
     [] -> error “deadlock!”
     (sc:scs) -> do
        writePVar runQueue scs
        return sc

yield :: IO ()
yield =
  switch $ \sc -> do
    addToRunQueue sc
    popRunQueue
```

MVar: simple communication

- MVar is the original communication abstraction from Concurrent Haskell

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

- takeMVar *blocks* if the MVar is empty
- takeMVar is fair (FIFO), and single-wakeup
- resp. putMVar

Implementing MVars

```
data MVar a = MVar (PVar (MVState a))
data MVState a = Full a [(a,      SCont)]
               | Empty  [(PVar a, SCont)]

takeMVar :: MVar a -> IO a
takeMVar (MVar mv) = do
  buf <- atomicPTM $ newPVar undefined
  switch $ \c -> do
   state <- readPVar mv
   case state of
    Full x [] -> do
      writePVar mv $ Empty []
      writePVar buf x
      return c
    Full x l@((y,wakeup):ts) -> do
      writePVar mv $ Full y ts
      writePVar buf x
      addToRunQueue wakeup
      return c
    Empty ts -> do
      writePVar mv $ Empty (ts++[(buf,c)])
      popRunQueue
  atomicPTM $ readPVar buf
```

This will hold the result

MVar is full, no other

MVar is full, there are other threads waiting to put. Wake up one thread and return.

MVar is empty: add this thread to the end of the

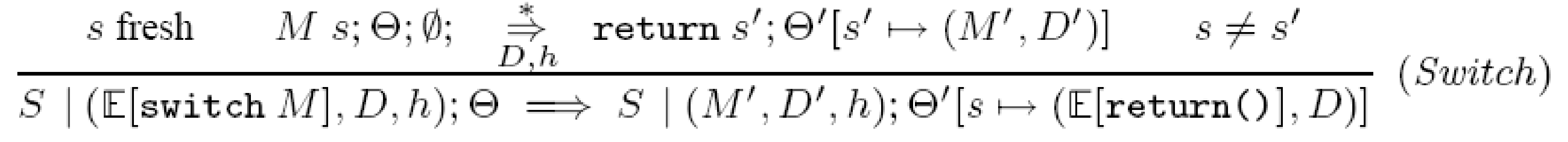
When switch returns, buf will contain the value we read.

PTM Wins

- This implementation of takeMVar still works in a multiprocessor setting!
- The tricky case:
  - one CPU is in takeMVar, about to sleep, putting the current thread on the queue
  - another CPU is in putMVar, taking the thread off the queue and running it
  - but switch hasn't returned yet: the thread is not ready to run. BANG!
- This problem crops up in many guises. Existing runtimes solve it with careful use of locks, e.g. a lock on the thread, or on the queue, not released until the last minute (GHC). Another solution is to have a flag on the thread indicating whether it is ready to run (CML).
- With PTM and switch this problem just doesn't exist: when switch's transaction commits, the thread is ready to run.

Semantics

- The substrate interface has an operational semantics (see paper)



$$\frac{s \text{ fresh} \qquad M\ s;\Theta;\emptyset; \ \overset{*}{\underset{D,h}{\Rightarrow}}\ \texttt{return}\, s';\Theta'[s' \mapsto (M',D')] \qquad s \neq s'}{S \mid (\mathbb{E}[\texttt{switch}\, M], D, h);\Theta \implies S \mid (M', D', h);\Theta'[s \mapsto (\mathbb{E}[\texttt{return()}], D)]}\ (\mathit{Switch})$$

- Now to flesh out the design…

Pre-emption

- The concurrency library should provide a *callbck handler*:

```
timerHandler :: IO ()
```

- the RTS causes each executing HEC to invoke `timerHandler` at regular intervals.
- We can use this in our simple scheduler to get pre-emption:

```
timerHandler :: IO ()
timerHandler = yield
```

Thunks

- If two HECs are evaluating the same thunk (suspension), the RTS may decide to suspend one of them[1]
- The current RTS keeps a list of threads blocked on thunks, and periodically checks whether any can be awakened.
- The substrate provides another callback:

```
blockedHandler :: IO Bool -> IO ()
```

can be used to poll

- Simplest implementation:

```
blockedHandler :: IO ()
blockedHandler = yield
```

[1] **Haskell on a Shared-Memory Multiprocessor** (Tim Harris, Simon Marlow, Simon Peyton Jones)

Thread-local state

- In a multiprocessor setting, one global run queue is a bad idea. We probably want one scheduler per CPU.
- A thread needs to ask “what is my scheduler?”: *thread-local state*
- Simple proposal:

```
data TLSKey a
newTLSKey  :: a -> IO (TLSKey a)
getTLS     :: TLSKey a -> PTM a
setTLS     :: TLSKey a -> a -> IO ()
initTLS    :: SCont -> TLSKey a -> a -> IO ()
```

Multiprocessors: sleeping HECs

- On a multiprocessor, we will have multiple HECs, each of which has a scheduler.
- When a HEC has no threads to run, it must idle somehow. Busy waiting would be bad, so we provide more functionality to put HECs to sleep:

```
waitCond   :: PTM (Maybe a) -> IO a
wakeupHEC  :: HEC -> IO ()
```

"execute the PTM transaction repeatedly until it returns Just a, then deliver a"

Poke the given HEC and make it re-execute its waitCond transaction.

  - A bit like STM's retry, but less automatic

Multiprocessor scheduler

- One scheduler (run queue) per CPU
- Scheduler has its own SCont

```
yield =
  switch $ \sc -> do
    addToRunQueue sc
    sched_var <- readTLS mySchedulerKey
    sched <- readPVar sched_var
    return sched

schedule sched_var = do
  thread <- waitCond popRunQueue
  switch $ \sc -> do
    writePVar sched_var sc
    return thread
```

Foreign calls

- Foreign calls and concurrency interact:
  - in-calls from multiple OS threads (Haskell as a multithreaded foreign API)
  - an out-call may block, we want to schedule another Haskell thread when this happens
  - out-calls can make in-calls (callbacks)
  - sometimes, out-calls need to be made in a particular OS thread ("bound threads")
- All of the above can be implemented in the concurrency library, all we need are some small additions to the substrate…

Foreign calls, cont.

- Two concurrency library callbacks:

```
inCallHandler  :: IO a -> IO a
outCallHandler :: IO a -> IO a
```

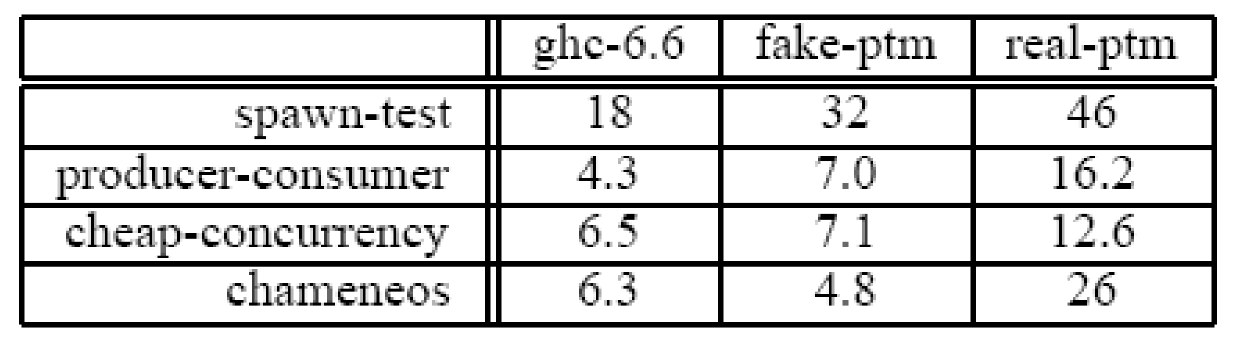
- When an in-call happens, the RTS
  - makes a new HEC,
  - executes inCallHandler (f args…)
  - inCallHandler can e.g. create a new scheduler, or add this thread to the run queue of an existing scheduler (GHC currently does the latter)
- For each out-call
  - the compiler generates outCallHandler (f args…)
  - outCallHandler can e.g. arrange to switch to another HEC to make the call, or wake up another HEC to schedule more Haskell threads.
- The scheduler support for the full FFI is complex, but the substrate is simple.

Asynchronous exceptions

- Phew

Performance

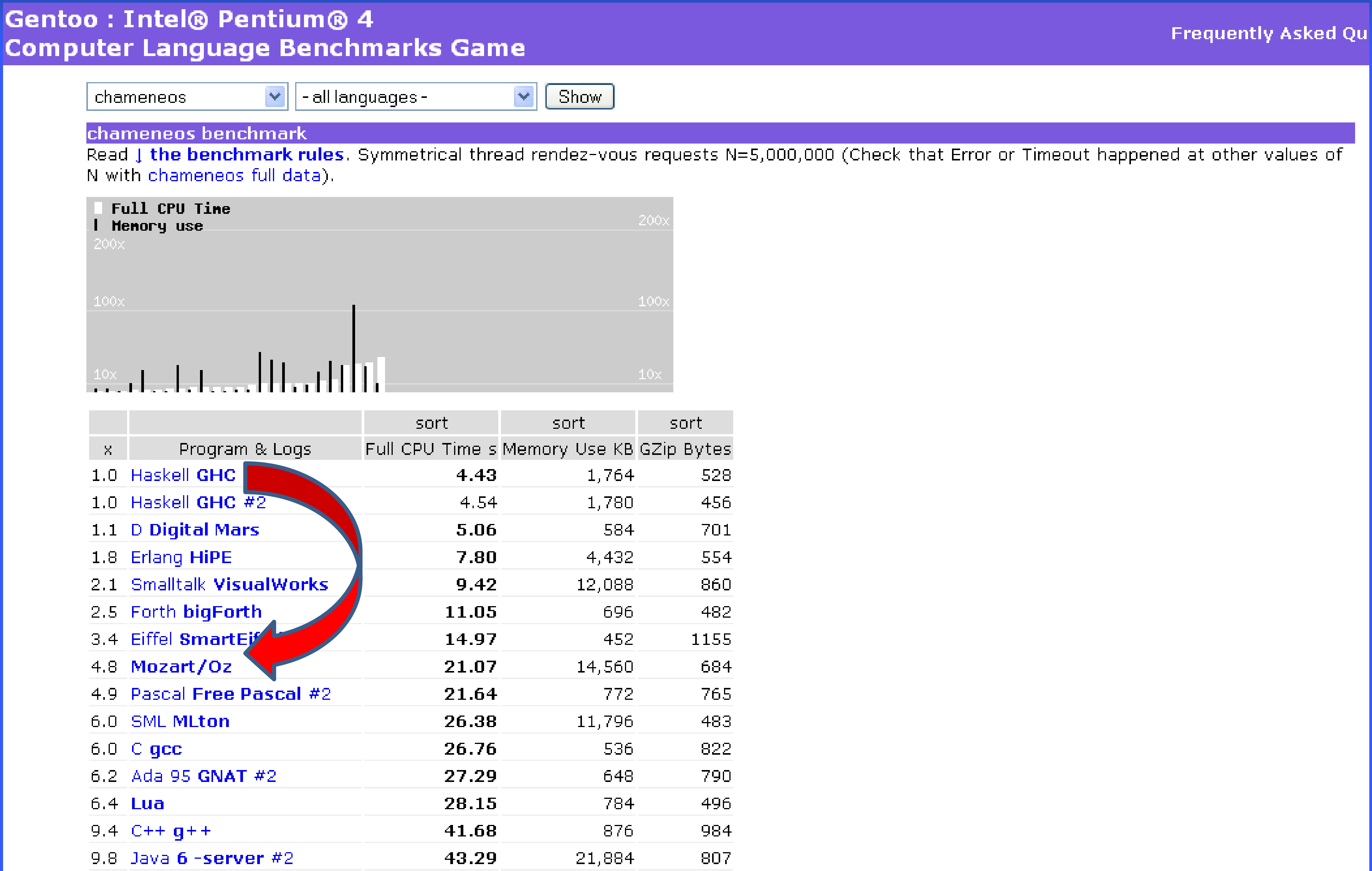
- Time in (s):



	ghc-6.6	fake-ptm	real-ptm
spawn-test	18	32	46
producer-consumer	4.3	7.0	16.2
cheap-concurrency	6.5	7.1	12.6
chameneos	6.3	4.8	26

- spawn-test: benchmarks forkIO
- the others benchmark MVar performance
- fake PTM: PTM implementation with no atomicity
- real PTM: based on existing STM implementation
- Prototype concurrency library is 2-4 times slower than existing RTS.

Performance



Gentoo : Intel® Pentium® 4
Computer Language Benchmarks Game

Frequently Asked Qu

chameneos benchmark

Read ↓ **the benchmark rules**. Symmetrical thread rendez-vous requests N=5,000,000 (Check that Error or Timeout happened at other values of N with chameneos full data).

		sort	sort	sort
x	Program & Logs	Full CPU Time s	Memory Use KB	GZip Bytes
1.0	Haskell **GHC**	**4.43**	1,764	528
1.0	Haskell **GHC** #2	4.54	1,780	456
1.1	D **Digital Mars**	**5.06**	584	701
1.8	Erlang **HiPE**	**7.80**	4,432	554
2.1	Smalltalk **VisualWorks**	**9.42**	12,088	860
2.5	Forth **bigForth**	**11.05**	696	482
3.4	Eiffel **SmartEi**	**14.97**	452	1155
4.8	**Mozart/Oz**	**21.07**	14,560	684
4.9	Pascal **Free Pascal** #2	**21.64**	772	765
6.0	SML **MLton**	**26.38**	11,796	483
6.0	C **gcc**	**26.76**	536	822
6.2	Ada 95 **GNAT** #2	**27.29**	648	790
6.4	**Lua**	**28.15**	784	496
9.4	C++ **g++**	**41.68**	876	984
9.8	Java 6 **-server** #2	**43.29**	21,884	807

The (lack of a) conclusion

- We get a great research platform…
- Is a factor of 2-4 a reasonable price to pay for the extra flexibility?
  - For concurrent programs, performance of concurrency is not usually the bottleneck
  - but the scheduler might be critical for *parallel* performance
  - STM on top of PTM is possible, but hairy
- Most users don’t care about the extra flexibilty
- better reliability (maybe), but is it really easier to debug?
- Have to worry about: the scheduler being pre-empted, blocking, running out of stack (non-issues with the C version)
- The “scheduler tax” is high: a scheduler must implement blocking, MVars, STM, FFI, asynchronous exceptions, par. Few people will write a scheduler, most likely we’ll provide an extensible one.
  - could we just make the existing scheduler extensible?
- Major issues for users are debugging concurrency, and debugging parallel performance. Does this enable improvements there?