Concurrency unlocked

transactional memory
for
composable concurrency

Tim Harris
Maurice Herlihy
Simon Marlow
Simon Peyton Jones

Concurrent programming is very difficult

Despite lots of work (and some excellent tools) we still don't have much clue how to do it

Locks (market leader) are broken

- **Races**: due to forgotten locks
- **Deadlock**: locks acquired in “wrong” order.
- **Lost wakeups:** forgotten notify to condition variable
- **Error recovery tricky**: need to restore invariants and release locks in exception handlers
- **Simplicity vs scalability tension**
- ...but worst of all...

Locks do not compose

You cannot build a big working program from small working pieces

- A.withdraw(3): withdraw $3 from account A.
  Easy; use a synchronised method
- A.withdraw(3); B.deposit(3)
  Uh oh: an observer could see a state in which the money was in neither account

Loss of composition

- Expose the locking

  A.lock(); B.lock(); A.withdraw(3);
  B.deposit(3); A.unlock(); B.unlock()

- Uh oh. Danger of deadlock

```
if A<B then
        A.lock(); B.lock()
else
        B.lock(); A.lock()
end if
```

- Now transfer money from A's deposit account if A doesn't have enough money....

Composition of alternatives

- Method **m1** does a WaitAny(h1,h2) on two WaitHandles h1, h2. Ditto **m2**
- Can we WaitAny(**m1**,**m2**). No way!
- Instead, we break the abstraction and bubble up the WaitHandles we want to wait on to a top-level WaitAny, and then dispatch back to the handler code
- Same in Unix (select)

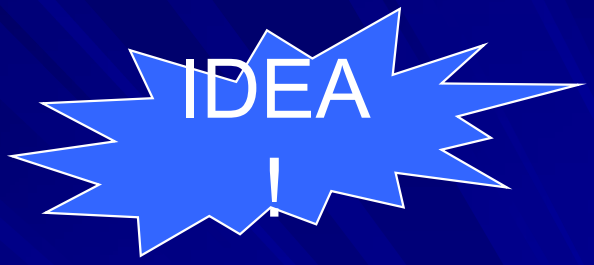
Locks emasculate our main weapon

Our main weapon in controlling program complexity is modular decomposition: build a big program by gluing together smaller ones

This way lies madness…

Transactional memory

```
atomic
      A.withdraw(3)
      B.deposit(3)
end
```



Herlihy/Moss ISCA 1993

- Steal ideas from the database folk
- **atomic** does what it says on the tin
- Directly supports what the programmer is trying to do: an atomic transaction against memory
- “Write the simple sequential code, and wrap **atomic** around it”.

How does it work?

Optimistic concurrency

```
atomic
    <body>
```

- Execute <body> without taking any locks
- Each read and write in <body> is logged to a thread-local transaction log
- Writes go to the log only, not to memory
- At the end, the transaction tries to **commit** to memory
- Commit may fail; then transaction is re-run

Transactional memory

- **No races**: no locks, so you can't forget to take one
- **No lock-induced deadlock**, because no locks
- **No lost wake-ups**, because no wake-up calls to forget [needs **retry**; wait a few slides]
- **Error recovery trivial**: an exception inside atomic aborts the transaction
- **Simple code is scalable**

Tailor made for (pure) functional languages!

- Every memory read and write has to be tracked
- So there had better not be too many of them
- The compiler had better not miss any effects
- Haskell programmers are fully trained in making effects explicit

STM in Haskell

STM monad; impoverished version of IO

atomic is a function, not a syntactic construct

```
atomic      :: STM a -> IO a
newTVar     :: a -> STM (TVar a)
readTVar    :: TVar a -> STM a
writeTVar   :: TVar a -> a -> STM ()
```

"Transactional variable"

```
incR :: TVar Int -> STM ()
incR r = do { v <- readTVar r
            ; writeTVar r (v+1) }

main = do { r <- atomic (newTVar 0)
          ; fork (atomic (incR r))
          ; atomic (incR r)
          ; ... }
```

STM in Haskell

```
atomic :: STM a -> IO a
newTVar :: a -> STM (TVar a)
readTVar :: TVar a -> STM a
writeTVar :: TVar a -> a -> STM ()
```

- Can’t fiddle with TVars outside atomic block [good]
- Can’t do IO inside atomic block [sad, but also good]

Transaction logs

Thread 1

```
atomic (do {
  v <- read bal ;
  write bal (v+1)
})
```

bal

6

Thread 2

```
atomic (do {
  v <- read bal ;
  write bal (v-3)
})
```

What	Value read	Value written
bal		

Transaction log

What	Value read	Value written
bal		

Transaction log

Transaction logs

Thread 1

```
atomic (do {
  v <- read bal ;
  write bal (v+1)
})
```

bal

6

Thread 2

```
atomic (do {
  v <- read bal ;
  write bal (v-3)
})
```

What	Value read	Value written
bal		

Transaction log

What	Value read	Value written
bal	6	

Transaction log

Transaction logs

Thread 1

```
atomic (do {
   v <- read bal ;
   write bal (v+1)
})
```

bal

6

Thread 2

```
atomic (do {
   v <- read bal ;
   write bal (v-3)
})
```

What	Value read	Value written
bal	6	

Transaction log

What	Value read	Value written
bal	6	

Transaction log

Transaction logs

Thread 1

```
atomic (do {
   v <- read bal ;
   write bal (v+1)
})
```

bal

6

Thread 2

```
atomic (do {
   v <- read bal ;
   write bal (v-3)
})
```

What	Value read	Value written
bal	6	7

Transaction log

What	Value read	Value written
bal	6	

Transaction log

Transaction logs

Thread 1

```
atomic (do {
   v <- read bal ;
   write bal (v+1)
})
```

bal

6

Thread 2

```
atomic (do {
   v <- read bal ;
   write bal (v-3)
})
```

What	Value read	Value written
bal	6	7

Transaction log

What	Value read	Value written
bal	6	3

Transaction log

Transaction logs

Thread 1

```
atomic (do {
   v <- read bal ;
   write bal (v+1)
})
```

bal

7

Thread 2

```
atomic (do {
   v <- read bal ;
   write bal (v-3)
})
```

- Thread 1 commits
- Shared ‘bal’ is written
- Transaction log discarded

What	Value read	Value written
bal	6	3

Transaction log

Transaction logs

Thread 1

```
atomic (do {
   v <- read bal ;
   write bal (v+1)
})
```

bal

7

Thread 2

```
atomic (do {
   v <- read bal ;
   write bal (v-3)
})
```

What	Value read	Value written

Transaction log

- Attempt to commit thread 2 fails, because value in memory ≠ value in log
- Transaction re-runs from the beginning

Two new ideas

Idea 1: modular blocking

```
withdraw :: TVar Int -> Int -> STM ()
withdraw acc n = do { bal <- readTVar acc
                    ; if bal < n then retry;
                    ; writeTVar acc (bal-n) }
```

```
retry :: STM ()
```

- **retry** means “abort the current transaction and re-execute it from the beginning”.
- Implementation avoids the busy wait by using reads in the transaction log (i.e. acc) to wait simultaneously on all read variables

No condition variables

- No condition variables!
- Retrying thread is woken up automatically when acc is written. No lost wake-ups!
- No danger of forgetting to test everything again when woken up; the transaction runs again from the beginning.
  e.g. atomic (do { withdraw a1 3
  ; withdraw a2 7 })

Idea 2: Choice

```
atomic (do {
   withdraw a1 3
       `orelse`
   withdraw a2 3
;  deposit b 3 })
```

Try this

...and if it retries, try this

...and and then do this

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

Choice is composable too

```
transfer :: TVar Int -> TVar Int
         -> TVar Int -> STM ()

transfer a1 a2 b = do
    { withdraw a1 3
        `orElse`
      withdraw a2 3

    ; deposit b 3
end
```

```
atomic
    (transfer a1 a2 b
        `orElse`
     transfer a3 a4 b)
```

- transfer has an orElse, but calls to transfer can still be composed with orElse

Summary

- Transactional memory is fantastic: a ray of light in the darkness
- It's a classic abstraction: a simple interface hides a complex and subtle implementation
- Like high-level language vs assembly code: whole classes of low-level errors are cut off at the knees
- No silver bullet: you can still write buggy programs
- STM is aimed at shared memory. Distribution is a whole different ball game (latency, failure, security, versioning); needs different abstractions.

Farsite project (Jon Howell MSR)

“Your idea of using the writes from one transaction to wake up sleepy transactions is wonderful. We wanted to report on the effect your paper draft has *already had* on our project.

“...I told JD that I'd try to hack the Harris-and-company unblocking scheme into our stuff, but that he should slap me around if it ended up taking too long. We decided to check in after three days, and abandon after five. It took a day and a half....

“...In summary, using your composable blocking model is wonderful: it rips out a big chunk of our control flow related to liveness, and takes with it a whole class of potential bugs.”

Odds and ends

Why “modular blocking”?

- Because **retry** can appear anywhere inside an atomic block, including nested deep within a call.
- Contrast:

  atomic (n > 0) { ...stuff... }

  which breaks the abstraction inside “...stuff...”
- Difficult to do that in a lock-based world, because you must release locks before blocking; but which locks?
- With TM, no locks => no danger of blocking while holding locks. This is a very strong property.

Exceptions

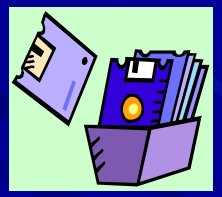
- STM monad supports exceptions:

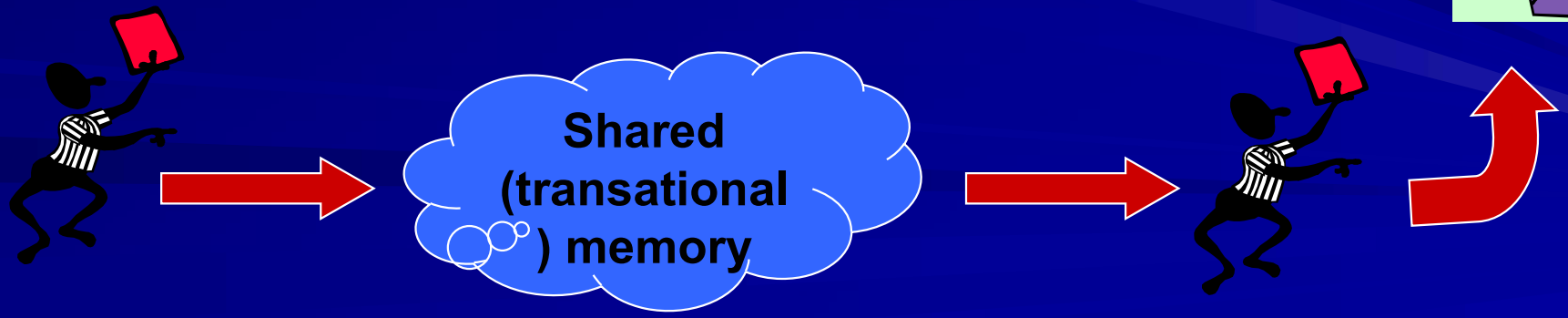
```
throw :: Exception -> STM a
catch :: STM a -> (Exception -> STM a) -> STM a
```

- In the call (atomic s), if s throws an exception, the transaction is aborted with no effect; and the exception is propagated into the IO monad
- No need to restore invariants, or release locks!

Input/output

- You can't do I/O in a memory transaction (because there's no general way to undo it)
- The STM monad ensures you don't make a mistake about this
- To support transactional I/O:





Transactional input

- Same plan as for output, where input request size is known
- Variable-sized input is harder, because if there is not enough data in the buffer, the transaction may block (as it should), but has no observable effect.
- So the I/O thread doesn't know to get more data :-(
- Still thinking about what to do about this…not sure it matters that much

Progress

- A worry: could the system “thrash” by continually colliding and re-executing?
- No: one transaction can be forced to re-execute only if another succeeds in committing. That gives a strong progress guarantee.
- But a particular thread could perhaps starve.

Is this all a pipe dream?

Surely it's impractical to log every read and write?

1. Do you want working programs or not?
2. Tim built an implementation of TM for Java that showed a 2x perf hit. Things can only improve!
3. We only need to log reads and writes to **persistent** variables (ones outside the transaction); many variables are not.
4. Caches already do much of this stuff; maybe we could get hardware support.
5. ...but in truth this is an open question

What we have now

- A complete implementation of transactional memory in Concurrent Haskell [in GHC 6.4]. Try it!
  http://haskell.org/ghc
- A C# transactional-memory library. A bit clunky, and few checks, but works with unchanged C# [Marurice Herlihy]
- PPoPP'05 paper
  http://research.microsoft.com/~simonpj

Open questions

- Are our claims that transactional memory supports “higher-level programming” validated by practice?
- You can’t do I/O within a transaction, because it can’t be undone. How inconvenient is that?
- Can performance be made good enough?
- Starvation: a long-running transaction may be repeatedly “bumped” by short transactions that commit

CML

- CML, a fine design, is the nearest competitor

```
receive :: Chan a -> Event a
guard :: IO (Event a) -> Event a
wrap :: Event a -> (a->IO b) -> Event b
choose :: [Event a] -> Event a
sync :: Event a -> IO a
```

- A lot of the program gets stuffed inside the events => somewhat inside-out structure

CML

- No way to wait for complex conditions
- No atomicity guarantees
- An event is a little bit like a transaction: it happens or it doesn't; but explicit user undo:

  wrapAbort :: Event a -> IO () -> Event a

- Events have a single "commit point". Non compositional:

  ??? :: Event a -> Event b -> Event (a,b)

Algebra

- Nice equations:
  - orElse is associative (but not commutative)
  - retry `orElse` s = s
  - s `orElse` retry = s
- [Haskell afficionados] STM is an instance of MonadPlus.

But what does it all mean?

- Everything so far is intuitive and arm-wavey
- But what happens if it's raining, and you are inside an orElse and you throw an exception that contains a value that mentions...?
- We need a precise specification

But what does it all mean?

- Small-step transition rules

I/O transitions $P; \Theta \xrightarrow{a} Q; \Theta'$

$$\mathbb{P}[\texttt{putChar}\ c]; \Theta \xrightarrow{!c} \mathbb{P}[\texttt{return}\ ()]; \Theta \qquad (PUTC)$$

$$\mathbb{P}[\texttt{getChar}]; \Theta \xrightarrow{?c} \mathbb{P}[\texttt{return}\ c]; \Theta \qquad (GETC)$$

$$\mathbb{P}[\texttt{forkIO}\ M]; \Theta \rightarrow (\mathbb{P}[\texttt{return}\ t] \mid M_t); \Theta \quad t \notin \mathbb{P}, \Theta, M \qquad (FORK)$$

Thread soup	P, Q	::=	$M_t \mid (P \mid Q)$
Heap	Θ	::=	$r \hookrightarrow M$
Allocations	Δ	::=	$r \hookrightarrow M$
Evaluation	$\mathbb{E}$	::=	$[\cdot] \mid \mathbb{E}\ \texttt{>>=}\ M \mid \texttt{catch}\ \mathbb{E}\ M$
contexts	$\mathbb{P}$	::=	$\mathbb{E}_t \mid (\mathbb{P} \mid P) \mid (P \mid \mathbb{P})$
Action	a	::=	$!c \mid ?c \mid \epsilon$

Administrative steps

$$\frac{M \;\rightarrow\; N}{\mathbb{P}[M];\ \Theta \;\rightarrow\; \mathbb{P}[N];\ \Theta}\ (ADMIN)$$

Administrative transitions $M \rightarrow N$

M	$\rightarrow$	V	if $\mathcal{V}[\![M]\!] = V$ and $M \not\equiv V$
`return` N `>>=` M	$\rightarrow$	$M\ N$	
`throw` N `>>=` M	$\rightarrow$	`throw` N	
`retry >>=` M	$\rightarrow$	`retry`	
`catch (throw` M`)` N	$\rightarrow$	$N\ M$	
`catch (return` M`)` N	$\rightarrow$	`return` M	

Transactions

Thread soup	P, Q	::=	$M_t \mid (P \mid Q)$
Heap	Θ	::=	$r \hookrightarrow M$
Allocations	Δ	::=	$r \hookrightarrow M$
Evaluation	$\mathbb{E}$	::=	$[\cdot] \mid \mathbb{E}\ \texttt{>>=}\ M \mid \texttt{catch}\ \mathbb{E}\ M$
contexts	$\mathbb{P}$	::=	$\mathbb{E}_t \mid (\mathbb{P} \mid P) \mid (P \mid \mathbb{P})$
Action	a	::=	$!c \mid ?c \mid \epsilon$

- atomic turns many STM steps (=>*) into one IO step (->):

$$\frac{M;\ \Theta, \{\} \stackrel{\star}{\Rightarrow} \texttt{return}\ N;\ \Theta', \Delta'}{\mathbb{P}[\texttt{atomic}\ M];\ \Theta \rightarrow \mathbb{P}[\texttt{return}\ N];\ \Theta'}\ (ARET)$$

- So what are the STM steps?

STM transitions

Thread soup	P, Q	$::=$	$M_t \mid (P \mid Q)$
Heap	Θ	$::=$	$r \hookrightarrow M$
Allocations	Δ	$::=$	$r \hookrightarrow M$
Evaluation	$\mathbb{E}$	$::=$	$[\cdot] \mid \mathbb{E}\,\texttt{>>=}\,M \mid \texttt{catch}\,\mathbb{E}\,M$
contexts	$\mathbb{P}$	$::=$	$\mathbb{E}_t \mid (\mathbb{P} \mid P) \mid (P \mid \mathbb{P})$
Action	a	$::=$	$\texttt{!}\,c \mid \texttt{?}\,c \mid \epsilon$

- Easy ones:

STM transitions $\quad M; \Theta, \Delta \Rightarrow N; \Theta', \Delta'$

$$\mathbb{E}[\texttt{readTVar}\ r];\ \Theta, \Delta \Rightarrow \mathbb{E}[\texttt{return}\ \Theta(r)];\ \Theta, \Delta \quad \text{if } r \in dom(\Theta)$$

$$\mathbb{E}[\texttt{writeTVar}\ r\ M];\ \Theta, \Delta \Rightarrow \mathbb{E}[\texttt{return}\ ()];\ \Theta[r \mapsto M], \Delta \quad \text{if } r \in dom(\Theta)$$

$$\mathbb{E}[\texttt{newTVar}\ M];\ \Theta, \Delta \Rightarrow \mathbb{E}[\texttt{return}\ r];\ \Theta[r \mapsto M], \Delta[r \mapsto M] \quad \text{if } r \notin dom(\Theta)$$

Retry

Thread soup	P, Q	$::=$	$M_t \mid (P \mid Q)$
Heap	Θ	$::=$	$r \hookrightarrow M$
Allocations	Δ	$::=$	$r \hookrightarrow M$
Evaluation	$\mathbb{E}$	$::=$	$[\cdot] \mid \mathbb{E}\,\texttt{>>=}\,M \mid \texttt{catch}\,\mathbb{E}\,M$
contexts	$\mathbb{P}$	$::=$	$\mathbb{E}_t \mid (\mathbb{P} \mid P) \mid (P \mid \mathbb{P})$
Action	a	$::=$	$\texttt{!}\,c \mid \texttt{?}\,c \mid \epsilon$

- Here are the rules for retry:

Retry

Thread soup	P, Q	::=	$M_t \mid (P \mid Q)$
Heap	Θ	::=	$r \hookrightarrow M$
Allocations	Δ	::=	$r \hookrightarrow M$
Evaluation	$\mathbb{E}$	::=	$[\cdot] \mid \mathbb{E}\,\texttt{>>=}\,M \mid \texttt{catch}\,\mathbb{E}\,M$
contexts	$\mathbb{P}$	::=	$\mathbb{E}_t \mid (\mathbb{P} \mid P) \mid (P \mid \mathbb{P})$
Action	a	::=	$!c \mid ?c \mid \epsilon$

- Here are the rules for retry:

  ...there are none
  (apart from an admin transition)...

- In particular, no rule for

  P[atomic retry], Θ -> ...

orElse

Thread soup	P, Q	$::=$	$M_t \mid (P \mid Q)$
Heap	Θ	$::=$	$r \hookrightarrow M$
Allocations	Δ	$::=$	$r \hookrightarrow M$
Evaluation	$\mathbb{E}$	$::=$	$[\cdot] \mid \mathbb{E}\ \texttt{>>=}\ M \mid \texttt{catch}\ \mathbb{E}\ M$
contexts	$\mathbb{P}$	$::=$	$\mathbb{E}_t \mid (\mathbb{P} \mid P) \mid (P \mid \mathbb{P})$
Action	a	$::=$	$!c \mid ?c \mid \epsilon$

$$\frac{M_1;\ \Theta, \Delta \stackrel{\star}{\Rightarrow} \texttt{return}\ N;\ \Theta', \Delta'}{\mathbb{E}[M_1\ \texttt{`orElse`}\ M_2];\ \Theta, \Delta \Rightarrow \mathbb{E}[\texttt{return}\ N];\ \Theta', \Delta'}\ (OR1)$$

First branch succeeds

$$\frac{M_1;\ \Theta, \Delta \stackrel{\star}{\Rightarrow} \texttt{retry};\ \Theta', \Delta'}{\mathbb{E}[M_1\ \texttt{`orElse`}\ M_2];\ \Theta, \Delta \Rightarrow \mathbb{E}[M_2];\ \Theta, \Delta'}\ (OR3)$$

First branch retries

$$\frac{M_1;\ \Theta, \Delta \stackrel{\star}{\Rightarrow} \texttt{throw}\ N;\ \Theta', \Delta'}{\mathbb{E}[M_1\ \texttt{`orElse`}\ M_2];\ \Theta, \Delta \Rightarrow \mathbb{E}[\texttt{throw}\ N];\ \Theta', \Delta'}\ (OR2)$$

First branch raises exception