Summer School on Language-Based Techniques for Concurrent and Distributed Software

Software Transactions: Language-Design

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Atomic

An *easier-to-use* and *harder-to-implement* primitive

```
withLk:
 lock->(unit->α)->α

let xfer src dst x =
withLk src.lk(fun()->
withLk dst.lk(fun()->
 src.bal <- src.bal-x;
 dst.bal <- dst.bal+x
))
```

```
atomic:
 (unit->α)->α

let xfer src dst x =
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 dst.bal <- dst.bal+x
)
```

lock acquire/release

(behave as if)
no interleaved computation

Why now?

Multicore unleashing small-scale parallel computers on the programming masses

Threads and shared memory remaining a key model

- Most common if not the best

Locks and condition variables not enough

- Cumbersome, error-prone, slow

Atomicity should be a hot area, and it is…

A big deal

Software-transactions research broad…

- Programming languages
  PLDI 3x, POPL, ICFP, OOPSLA, ECOOP, HASKELL
- Architecture
  ISCA, HPCA, ASPLOS
- Parallel programming
  PPoPP, PODC

… and coming together, e.g.,
TRANSACT & WTW at PLDI06

Our plan

- Motivation (and non-motivation)
  - With a “PL bias” and an overly skeptical eye
- Semantics semi-formally
- Language-design options and issues

Next lecture: Software-implementation approaches

- No mention of hardware (see Dwarkadas lecture)

Metapoint: Much research focused on implementations, but let’s “eat our vegetables”

Note: Examples in Caml and Java (metapoint: it largely doesn’t matter)

Motivation

- Flanagan gave two lectures showing why atomicity is a simple, powerful correctness property
  - Inside an atomic block, sequential reasoning is sound!
- Why check it if we can provide it
  - And he ignored deadlock
- Other key advantages of providing it
  - Easier for code evolution
  - Easier "blame analysis" at run-time
  - Avoid priority inversion

Code evolution

Atomic allows modular code evolution

- Race avoidance: global object→lock mapping
- Deadlock avoidance: global lock-partial-order

```
// x, y, and z are
// globals
void foo() {
synchronized(???){
 x.f1 = y.f2+z.f3;
}}
```

- Want to write **foo** to be race and deadlock free
  - What locks should I acquire? (Are **y** and **z** immutable?)
  - In what order?

Code evolution, cont'd

Not just new code is easier: fixing bugs

Flanagan's JDK example with atomics:

```
StringBuffer append(StringBuffer sb) {

 int len = atomic { sb.length(); }
 if(this.count + len > this.value.length)
   this.expand(…);
 atomic {
  sb.getChars(0,len,this.value,this.count);
 }

}
```

Code evolution, cont'd

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```

Blame analysis?

Atomic localizes errors

(Bad code messes up only the thread executing it)

```
void bad1(){
 x.balance -= 100;
}
void bad2(){
 synchronized(lk){
   while(true) ;
 }
}
```

- Unsynchronized actions by other threads are invisible to atomic
- Atomic blocks that are too long may get starved, but won't starve others
  - Can give longer time slices

Priority inversion

- Classic problem:

  High priority thread blocked on lock held by low priority thread

  But medium priority thread keeps running, so low priority can't proceed

  Result: medium > high

- Transactions are abortable "at any point", so we can abort the low, then run the high

Non-motivation

Several things make shared-memory concurrency hard

1. Critical-section granularity
   - Fundamental application-level issue?
   - Transactions no help beyond easier evolution?
2. Application-level progress
   - Strictly speaking, transactions avoid deadlock
   - But they can livelock
   - And the *application* can deadlock

The clincher

"Bad" programmers can destroy every advantage transactions have over locks

```
class SpinLock {
  volatile boolean b = false;
  void acquire() {
    while(true) {
      while(b) ; //optional spin
      atomic {
       if(b) continue; //test and set
       b = true;
       return; }
    }
  }
  void release() { atomic {b = false;} }
}
```

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Why an analogy

- Already gave some of the crisp technical reasons why atomic is better than locks
- An analogy isn’t logically valid, but can be
  - Convincing and memorable
  - Research-guiding

Software transactions are to concurrency as garbage collection is to memory management

Hard balancing acts

memory management

correct, small footprint?
- free too much:
  dangling ptr
- free too little:
  leak, exhaust memory

non-modular
- deallocation needs "whole-program is done with data"

concurrency

correct, fast synchronization?
- lock too little:
  race
- lock too much:
  sequentialize, deadlock

non-modular
- access needs "whole-program uses same lock"

Move to the run-time

- Correct [manual memory management / lock-based synhronization] requires subtle whole-program invariants
- [Garbage-collection / software-transactions] also requires subtle whole-program invariants, but localized in the run-time system
  - With compiler and/or hardware cooperation
  - Complexity doesn't increase with size of program
  - Can be "one-size-fits-most"

Much more

More similarities:

- Old way still there (reimplement locks or free-lists)
- Basic trade-offs
  - Mark-sweep vs. copy
  - Rollback vs. private-memory
- I/O (writing pointers / mid-transaction data)
- …

I now think "analogically" about each new idea!

See a "tech-report" on my web-page (quick, fun read)

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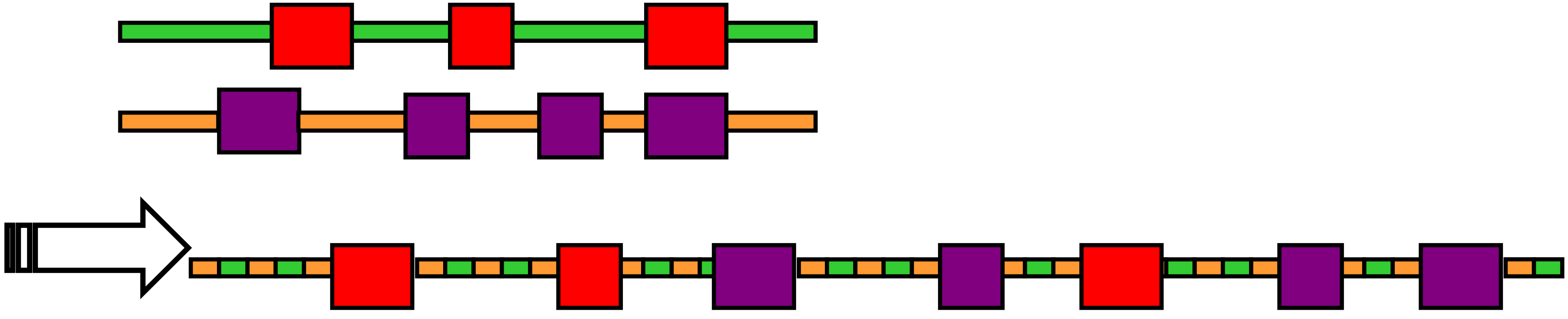
Strong atomicity

(behave as if) no interleaved computation

- Before a transaction “commits”
  - Other threads don’t “read its writes”
  - It doesn’t “read other threads’ writes”
- This is just the semantics
  - Can interleave more unobservably



Formalizing it

At the high-level, a formal small-step operational semantics is simple

- Atomic block "runs in 1 step"! [Harris et al PPoPP05]
- Recall from intro lecture:

"one thread, one step" $H,e \rightarrow H',e',o$

"program, one step" to $H,e1;\ldots;en \rightarrow H',e1';\ldots;em'$

Wrong

$$\frac{H,e \rightarrow H',e',o}{H,\text{atomic } e \rightarrow H',e',o} \qquad \frac{}{H,\text{atomic } v \rightarrow H,v,\text{None}}$$

Closer to right

The essence of atomic is that it's "all one step"

Note $\rightarrow^{*}$ is reflexive, transitive closure.

Ignoring fork

$$\frac{H, e \rightarrow^{*} H', v}{H, \text{atomic } e \rightarrow H', v}$$

Claim (unproven): Adding atomic to fork-free program has no effect

About fork (exercise): One step could create n threads

Incorporating abort (a.k.a. retry)

An explicit abort (a.k.a. retry) is a very useful feature.

Tiny example:

```
let xfer src dst x =
 atomic (fun()->
  dst.bal <- dst.bal+x;
  if(src.bal < x) abort;
  src.bal <- src.bal-x
 )
```

Formally: ***e*** `::=` ***…*** `| abort`

Non-determinism is elegant but unrealistic!

Lower-level

We could also define an operational semantics closer to an actual implementation

- Versioning of objects
- Locking of objects

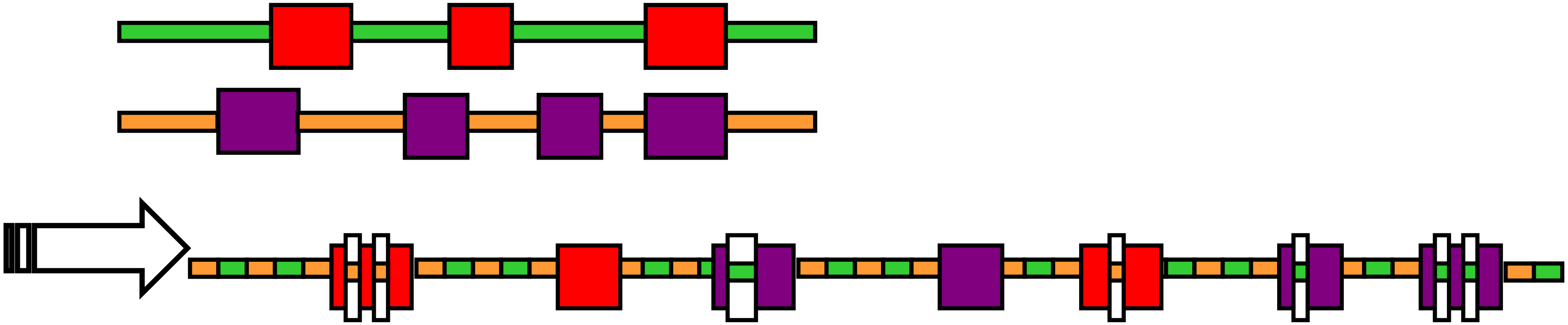
And prove such semantics equivalent to our "magic semantics"

See: [Vitek et al. ECOOP04]

Weak atomicity

(behave as if) no interleaved transactions

- Before a transaction "commits"
  - Other threads' transactions don't "read its writes"
  - It doesn't "read other threads' transactions' writes"
- This is just the semantics
  - Can interleave more unobservably



A lie

Bogus claim: "Under this 'definition', atomic blocks are still atomic w.r.t. each other"

Reality: Assuming no races with non-transactional code

```
   // invariant: x and y are even
atomic {     |   y=x;    |  atomic {
  ++x;       |           |   if(y%2==1)
  f();       |           |     bad();
  --x;       |           |  }
}
```

Note: The transactions might even access disjoint memory.

Is that so bad?

Assumptions are fine if they're true

- Programmer discipline
  - Good luck (cf. array-bounds in C)
- Race-detection technology
  - Whole-program analysis
- Type system
  - Much existing work should adapt
  - Avoiding code duplication non-trivial
  - Haskell uses a monad to segregate "transaction variables"

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Language-design issues

"fancy features" & interaction with other constructs

As time permits, with bias toward AtomCaml [ICFP05]:

- Strong vs. weak vs. type distinction on variables
- Interaction with exceptions
- Interaction with native-code
- Condition-variable idioms
- Closed nesting (flatten vs. partial rollback)
- Open nesting (back-door or proper abstraction?)
- Parallel nesting (parallelism within transactions)
- The orelse combinator
- Memory-ordering issues
- Atomic as a first-class function (elegant, unuseful?)

Exceptions

If code in atomic raises exception caught outside atomic, does the transaction abort?

We say no!

- atomic = "no interleaving until control leaves"
- Else atomic changes sequential semantics:

```
let x = ref 0 in
atomic (fun () -> x := 1; f())
assert((!x)=1) (*holds in our semantics*)
```

A *variant* of exception-handling that reverts state might be useful and share implementation (talk to Shinnar)

- But not about concurrency
- Has problems with the exception value

Exceptions

With “exception commits” and catch, the programmer can get “exception aborts”

```
atomic {
  try { s }
  catch (Throwable e) {
     abort;
  }
}
```

Handling I/O

- Buffering sends (output) easy and necessary
- Logging receives (input) easy and necessary

- But input-after-output does not work

```
let f () =
 write_file_foo();
 …
 read_file_foo()

let g () =
  atomic f; (* read won't see write *)
  f()       (* read may   see write *)
```

- I/O one instance of native code …

Native mechanism

- Previous approaches: no native calls in **`atomic`**
  - raise an exception
  - **`atomic`** no longer preserves meaning
- Can let the C code decide:
  - Provide 2 functions (in-atomic, not-in-atomic)
  - in-atomic can call not-in-atomic, raise exception, or do something else
  - in-atomic can *register* commit- & abort- actions (sufficient for buffering)
  - a pragmatic, imperfect solution (necessarily)
    - The “launch missiles problem”

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Critical sections

- Most code looks like this:

```
try
  lock m;
  let result = e in
  unlock m;
  result
with ex -> (unlock m; raise ex)
```

- And often this is easier and equivalent:

```
atomic(fun()-> e)
```

- But not always…

Non-atomic locking

Changing a lock acquire/release to atomic is *wrong* if it:

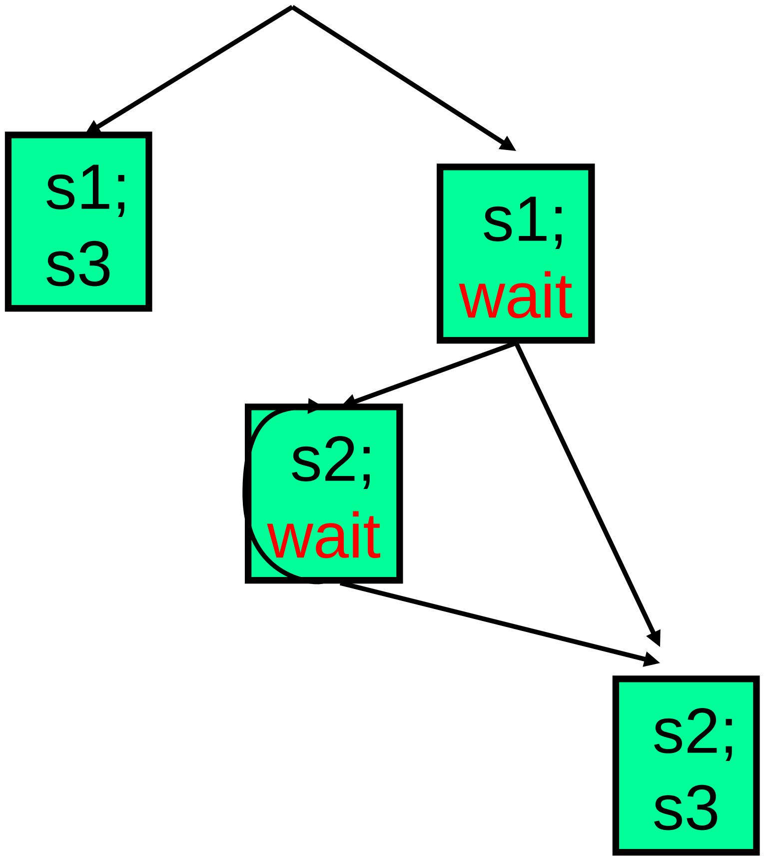
- Does something and "waits for a response"
- Calls native code
- Releases and reacquires the lock:

```
lock(m);
s1;
while(e){
  wait(m,cv);
  s2;
}
s3;
unlock(m);
```

If s1 and e are pure, wait can become an abort, else we really have multiple critical sections

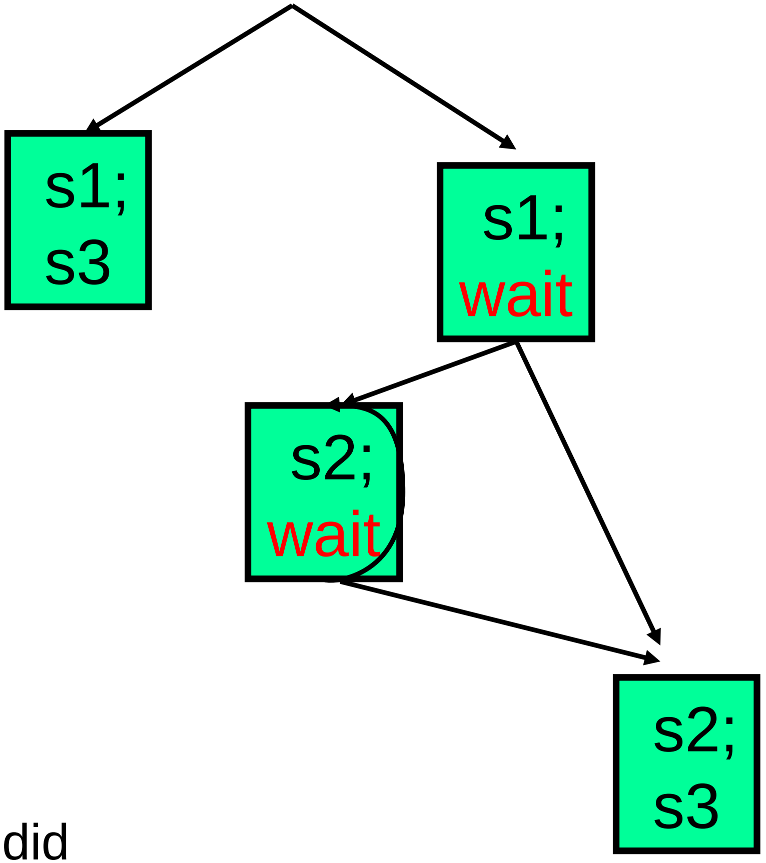
Atomic w.r.t. code holding `m`:

```
lock(m);
s1;
while(e){
  wait(m,cv);
  s2;
}
s3;
unlock(m);
```



Wrong approach #1

```
atomic {
 s1;
 if(e) wait(cv);
 else {s3;return;}
}
while(true){
atomic{
 s2;
 if(e) wait(cv);
 else {s3;return;}
}}
```

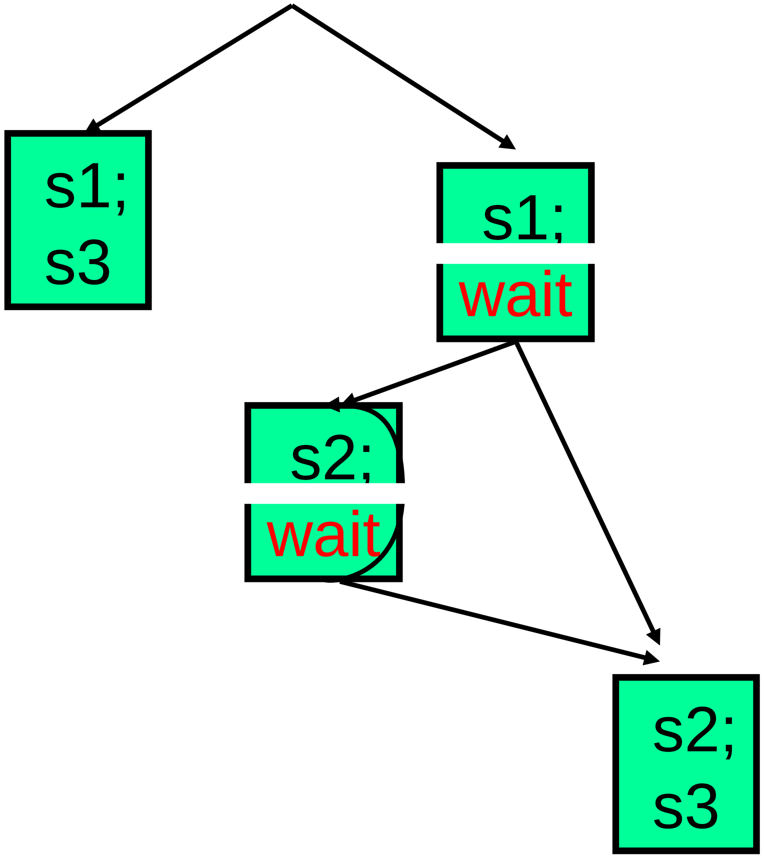


Cannot wait in atomic!

- Other threads can't see what you did
- You block and can't see signal

Wrong approach #2

```
b=false;
atomic {
 s1;
 if(e) b=true;
 else {s3;return;}
}
if(b) wait(cv);
while(true){
atomic{
 s2;
 if(!e){s3;return;}
}
wait(cv);
}
```

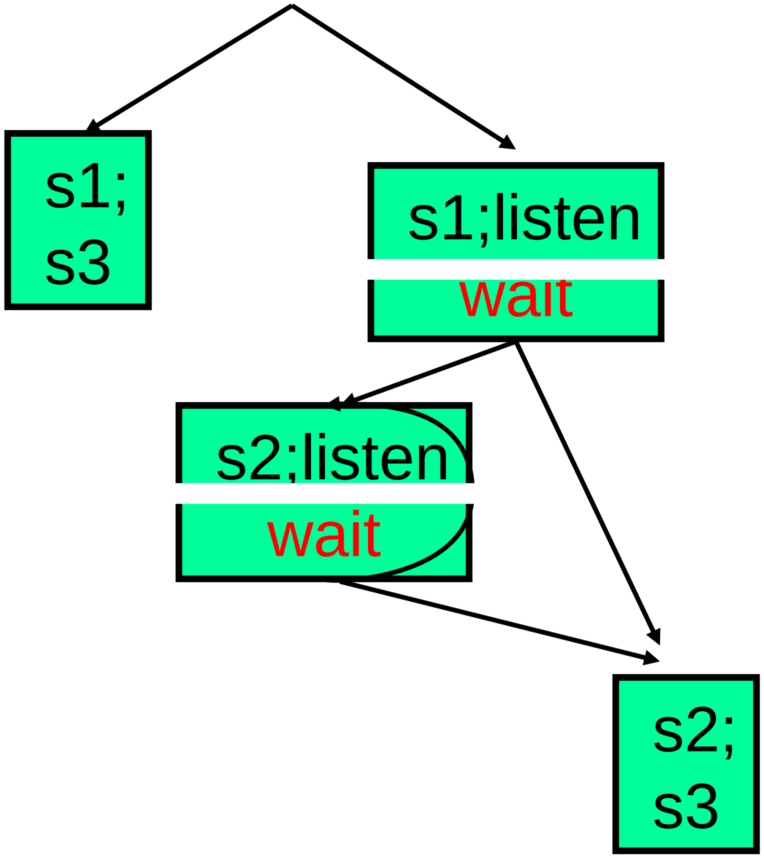


Cannot wait after atomic: you can miss the signal!

Solution: listen!

```
b=false;
atomic {
 s1;
 if(e) {
  ch=listen(cv);
  b=true;
 }
 else {s3;return;}

}
if(b) wait(ch);
/* … similar for
the loop */
```



You wait on a *channel* and can *listen* before blocking

(signal chooses any channel)

The interfaces

With locks:

```
condvar new_condvar();
void    wait(lock,condvar);
void    signal(condvar);
```

With atomic:

```
condvar new_condvar();
channel listen(condvar);
void    wait(channel);
void    signal(condvar);
```

A 20-line implemention uses only atomic and lists of mutable booleans

back

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Closed nesting

One transaction inside another has no effect!

```
void f() { … atomic { … g() … } }
void g() { … h() … }
void h() { … atomic { … } }
```

- AtomCaml literally treats nested atomic “as a no-op”
  - Abort to outermost (a legal interpretation)
- Abort to innermost (“partial rollback”) could avoid some recomputation via extra bookkeeping [Intel, PLDI06]
  - Recall in reality there is parallelism
- Claim: This is not an observable issue, “just” an implementation question.

Open nesting

An open (**open { s; }**) is a total cheat/back-door

- Its effects happen even if the transaction aborts
- So can do them "right away"

Arguments against:

- It's not a transaction anymore!
- Now caller knows nothing about effect of "wrapping call in atomic"

Arguments for:

- Can be correct at application level and more efficient
  - (e.g., caching, unique-name generation)
- Useful for building a VM (or O/S) w/ only atomic [Atomos, PLDI06]

A compromise?

- Most people agree the code in the open should never access memory the “outer transaction” has modified.
- So could detect this conflict and raise a run-time error.
- But… this detection must not have false positives from false sharing
  - E.g., a different part of the cache line

Parallel nesting

- Simple semantics: A fork inside an atomic is delayed until the commit
  - Compatible with “no scheduling guarantees”
- But then all critical sections must run sequentially
  - Not good for many-core
- Semantically, could start the threads, let them see transaction state, kill them on abort
  - Now nested transactions very interesting!
  - It all works out [Moss, early 80s]
  - Implementation more complicated (what threads should see what effects of what transactions)
    - Must maintain/discern fork/transaction trees

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Why orelse?

- Sequential composition of transactions is easy:

```
void f() { atomic { … } }
void g() { atomic { … } }
void h() { atomic { f(); g(); } }
```

- But what about alternate composition
- Example: “get something from either of two buffers, failing only if both are empty”

```
void get(buf){
 atomic{if(empty(buf))abort; else …}}
void get2(buf1,buf2) { ??? }
```

orelse

- Only “solution” so far is to break abstraction
  - The greatest sin in programming
- Better:
  - **atomic{get(buf1);}orelse{get(buf2);}**
  - Semantics: On abort, try alternative, if it also aborts, the whole thing aborts
- Eerily similar to something Flatt just showed you?

Memory-Ordering issues

- As Dwarkadas and Cartwright have told you, sequential consistency is often not provided by hardware or a language implementation
  - For a compiler, can prevent “basic” optimizations like dead-code elimination
- Locking: Acquires and releases of the same lock must be ordered (“happens before”)
- Transactions: There are no locks!
  - No great solution known (“accesses same memory” prohibits changing memory accesses)
  - Ongoing work with Pugh & Manson

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Basic design

no change to parser and type-checker

- **`atomic`** a first-class function
- Argument evaluated without interleaving

```
external atomic : (unit->α)->α = "atomic"
```

Advantages:

- Elegant
- Simplifies implementation (next time)
- “Same old” functional-language sermon?
- Not actually useful to programmers?

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