Strong Atomicity for Today's Programming Languages

Dan Grossman
University of Washington

10 October 2005

Atomic

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

```
void deposit(int x){
synchronized(this){
  int tmp = balance;
  tmp += x;
  balance = tmp;
}}
```

semantics:
lock acquire/release

```
void deposit(int x){
atomic {
  int tmp = balance;
  tmp += x;
  balance = tmp;
}}
```

semantics:
(behave as if)
no interleaved execution

No fancy hardware, code restrictions, deadlock, or unfair scheduling (e.g., disabling interrupts)

Target

Applications that use threads to:

- mask I/O latency
- provide GUI responsiveness
- handle multiple requests
- structure code with multiple control stacks
- …

Not:

- *high-performance scientific computing*
- *backbone routers*
- *…*

Overview

- The case for atomic
- Previous approaches to atomic
- AtomCaml
  - Logging-and-rollback
  - *Uniprocessor implementation*
  - Programming experience
- AtomJava
  - Logging-and-rollback
  - *Source-to-source implementation* (unchanged JVM)
- Condition variables via atomic (time permitting)

Locks in high-level languages

Java a reasonable proxy for state-of-the-art

```
synchronized e { s }
```

Related features:

- Reentrant locks (no self-deadlock)
- Syntactic sugar for acquiring **`this`** for method call
- Condition variables (release lock while waiting)
- …

Java 1.5 features:

- Semaphores
- Atomic *variables* (compare-and-swap, etc.)
- Non-lexical locking

Common bugs

- Races
  - Unsynchronized access to shared data
  - Higher-level races: multiple objects inconsistent
- Deadlocks (cycle of threads waiting on locks)

Example [JDK1.4, version 1.70, Flanagan/Qadeer PLDI2003]

```
synchronized append(StringBuffer sb) {
 int len = sb.length();
 if(this.count + len > this.value.length)
   this.expand(…);
 sb.getChars(0,len,this.value,this.count);
 …
}
// length and getChars are synchronized
```

Detecting locking errors

- Data-race detectors
  - Dynamic (e.g., what locks held when)
  - Static (e.g., type systems for what locks to hold)
  - *Little work on higher-level races*
- Deadlock detectors
  - Static (e.g., program-wide partial-order on locks)
- Atomicity checkers
  - Static (treat "atomic" as a type annotation)

Can catch bugs, but the tough programming model remains!

[Savage97, Cheng98, von Praun01, Choi02, Flanagan,Abadi,Freund,Qadeer99-05, Boyapati01-02,Grossman03, …]

Atomic

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

```
void deposit(int x){
synchronized(this){
  int tmp = balance;
  tmp += x;
  balance = tmp;
}}
```

semantics:
lock acquire/release

```
void deposit(int x){
atomic {
  int tmp = balance;
  tmp += x;
  balance = tmp;
}}
```

semantics:
(behave as if)
no interleaved execution

No fancy hardware, code restrictions, deadlock, or unfair scheduling (e.g., disabling interrupts)

6.5 ways atomic is better

1. Atomic makes deadlock less common

```
transfer(Acct that,
              int x){
synchronized(this){
synchronized(that){
  this.withdraw(x);
  that.deposit(x);
}}}
```

- Deadlock with parallel “untransfer”
- Trivial deadlock if locks not re-entrant
- 1 lock at a time $\Rightarrow$ race with “total funds available”

6.5 ways atomic is better

2. 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?

6.5 ways atomic is better

3. 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

6.5 ways atomic is better

4. Atomic makes abstractions thread-safe without committing to serialization

```
class Set { // synchronization unknown
 void insert(int x) {…}
 bool member(int x) {…}
 int  size  ()      {…}
}
```

To wrap this with synchronization:

Grab the same lock before any call. But:

- Unnecessary: no operations run in parallel (even if **`member`** and **`size`** could)
- Insufficient: implementation may have races

6.5 ways atomic is better

5. Atomic is usually what programmers want
   [Flanagan, Qadeer, Freund]

- Many **`synchronized`** Java methods are actually atomic
- Of those that aren't, many races are application-level bugs
- **`synchronized`** is an implementation detail
  - does not belong in interfaces (atomic does)

```
interface I { /* thread-safe? */ int m(); }
class A { synchronized int m(){ «race» }}
class B { int m() { return 3; }}
```

6.5 ways atomic is better

6. Atomic can efficiently implement locks

```
class SpinLock {
  bool b = false;
  void acquire() {
    while(true) {
      while(b) /*spin*/;
      atomic {
       if(b) continue;
       b = true;
       return; }
    }
  }
  void release() {
   b = false;
  }
}
```

- Cute O/S homework problem
- In practice, implement locks like you always have?
- Atomic and locks peacefully co-exist
  - Use both if you want

6.5 ways atomic is better

6.5 Concurrent programs have the granularity problem:

- Too little synchronization:
  non-determinism, races, bugs
- Too much synchronization:
  poor performance, sequentialization

Example: Should a chaining hashtable have one lock per table, per bucket, or per entry?

`atomic` doesn't solve the problem, but makes it easier to mix coarse- and fine-grained operations

Overview

- The case for atomic
- Previous approaches to atomic
- AtomCaml
  - Logging-and-rollback
  - *Uniprocessor implementation*
  - Programming experience
- AtomJava
  - Logging-and-rollback
  - *Source-to-source implementation* (unchanged JVM)
- Condition variables via atomic

A classic idea

- Transactions in databases and distributed systems
  - Different trade-offs and flexibilities
  - Limited (not a general-purpose language)
- Hoare-style monitors and conditional critical regions
- Restartable atomic sequences to implement locks
  - Implements locks w/o hardware support [Bershad]
- Atomicity for individual persistent objects [ARGUS]
- Rollback for various recoverability needs
- Disable interrupts

STMs

- Software Transactional Memory
  - Compute using private version of memory
  - Commit via sophisticated protocols (version #s, etc)
- Java [OOPSLA03]:
  - Guard expressions: **`atomic(e){s}`**
  - Weak guarantee: *only atomic w.r.t. other atomics!*
- Haskell [PPoPP05]:
  - Composition: “if s1 aborts, try s2”
  - Strong guarantee via purely functional language
- C#:
  - Just a library
  - Thread-shared data has many restrictions, must be created by factories, …

[Herlihy, Harris, Fraser, Marlow, Peyton-Jones,…]

Warning:

Next slide criticizes the work of the audience.

Why?

Provoke good conversation (later?)

Strong belief:

Long-term solutions will be hw + sw, but we're still learning the pure hw and pure sw solutions

HTMs

Hardware Transactional Memory

- extend ISA with “**`xstart`**” and “**`xend`**”
- cache for logging-and-rollback
- contention similar to cache-coherence (pay once!)
- long-running transactions lock the bus [ASPLOS04] or use hardware to log in RAM [HPCA05]

I am skeptical (and biased):

- need a software answer too (legacy chips, etc.)
- logs things that need not be logged
  - immutable fields
  - a garbage collection triggered in atomic
- ISA’s semantics won’t match a language’s atomic
  - compilers want *building blocks*

Claim

We can realize suitable implementations of strong atomicity on today's hardware using a purely software approach to logging-and-rollback

- Alternate approach to STMs; potentially:
  - better guarantees
  - faster common case
- No need to wait for new hardware
  - A solution for today
  - Not yet clear what hardware should provide

Overview

- The case for atomic
- Previous approaches to atomic
- AtomCaml
  - Logging-and-rollback
  - *Uniprocessor implementation*
  - Programming experience
- AtomJava
  - Logging-and-rollback
  - *Source-to-source implementation* (unchanged JVM)
- Condition variables via atomic

Interleaved execution

The “uniprocessor” assumption:

Threads communicating via shared memory don't execute in “true parallel”

More general than uniprocessor: threads on different processors can pass messages

An important special case:

- Many language implementations make this assumption
- Many concurrent apps don’t need a multiprocessor (e.g., a document editor)
- Uniprocessors are dead? Where’s the funeral?

Implementing atomic

Key pieces:

- Execution of an atomic block logs writes
- If scheduler pre-empts a thread in atomic, rollback the thread
- Duplicate code so non-atomic code is not slowed by logging
- In an atomic block, buffer output and log input
  - Necessary for rollback but may be inconvenient
  - A general native-code API

Note: Similar idea for RTSJ by Manson et al. [Purdue TR 05]

Logging example

```
int x=0, y=0;
void f() {
  int z = y+1;
  x = z;
}
void g() {
  y = x+1;
}
void h() {
  atomic {
    y = 2;
    f();
    g();
  }
}
```

- Executing atomic block in **h** builds a LIFO log of old values:

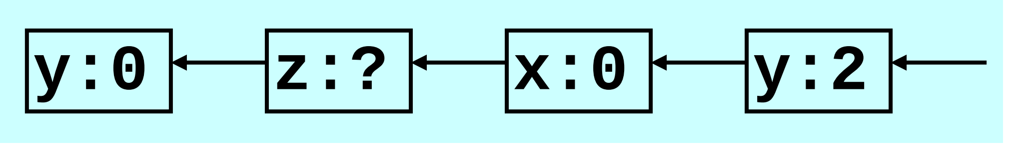
`y:0` ← `z:?` ← `x:0` ← `y:2` ←

Rollback on pre-emption:

- Pop log, doing assignments
- Set program counter and stack to beginning of atomic

On exit from atomic: drop log

Logging efficiency



Keeping the log small:

- Don't log reads (key uniprocessor optimization)
- Don't log memory allocated after atomic was entered (in particular, local variables like **`z`**)
- No *need* to log an address after the first time
  - To keep logging fast, switch from an array to a hashtable only after "many" (50) log entries
  - Tell programmers non-local writes cost more

Duplicating code

```
int x=0, y=0;
void f() {
  int z = y+1;
  x = z;
}
void g() {
  y = x+1;
}
void h() {
  atomic {
    y = 2;
    f();
    g();
  }
}
```

Duplicate code so callees know to log or not:

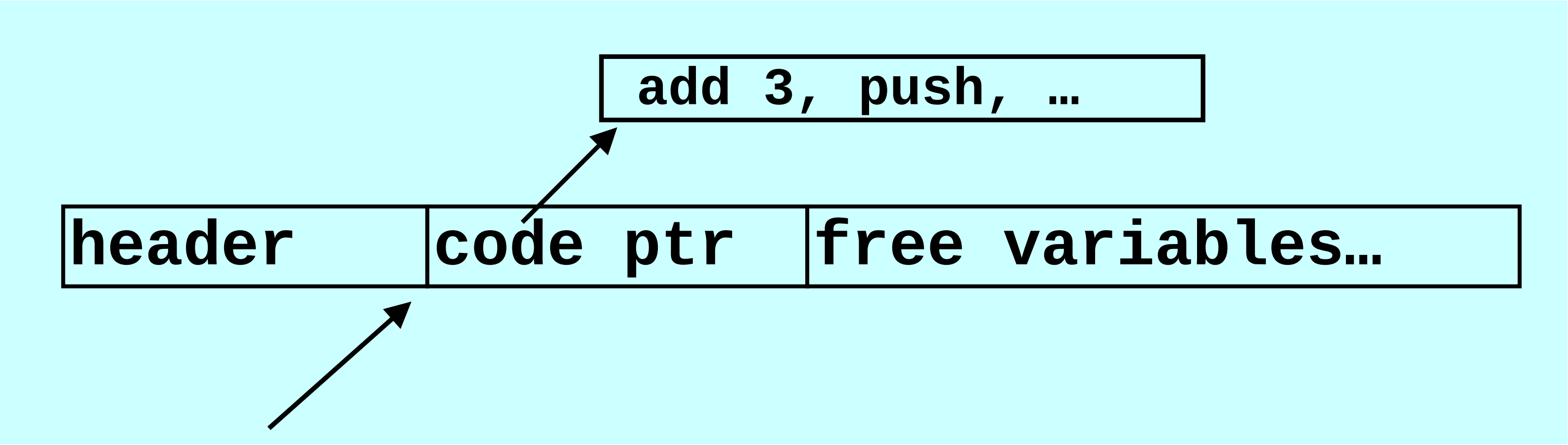
- For each function **`f`**, compile **`f_atomic`** and **`f_normal`**
- Atomic blocks and atomic functions call atomic functions
- Function pointers (e.g., vtables) compile to pair of code pointers

Cute detail: compiler erases any atomic block in **`f_atomic`**

Representing closures/objects

Representation of function-pointers/closures/objects an interesting (and pervasive) design decision

OCaml:

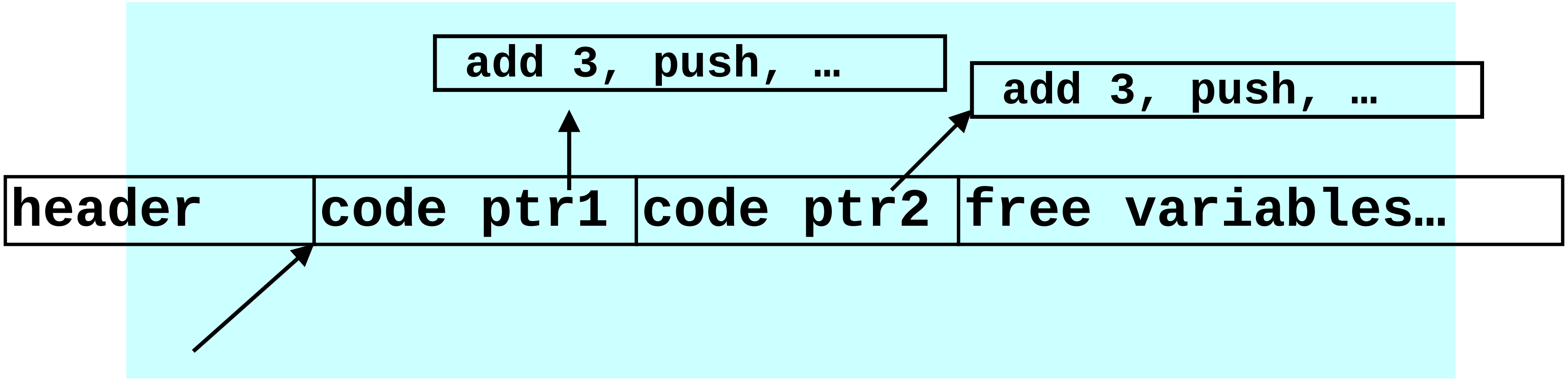


Representing closures/objects

Representation of function-pointers/closures/objects an interesting (and pervasive) design decision

AtomCaml:

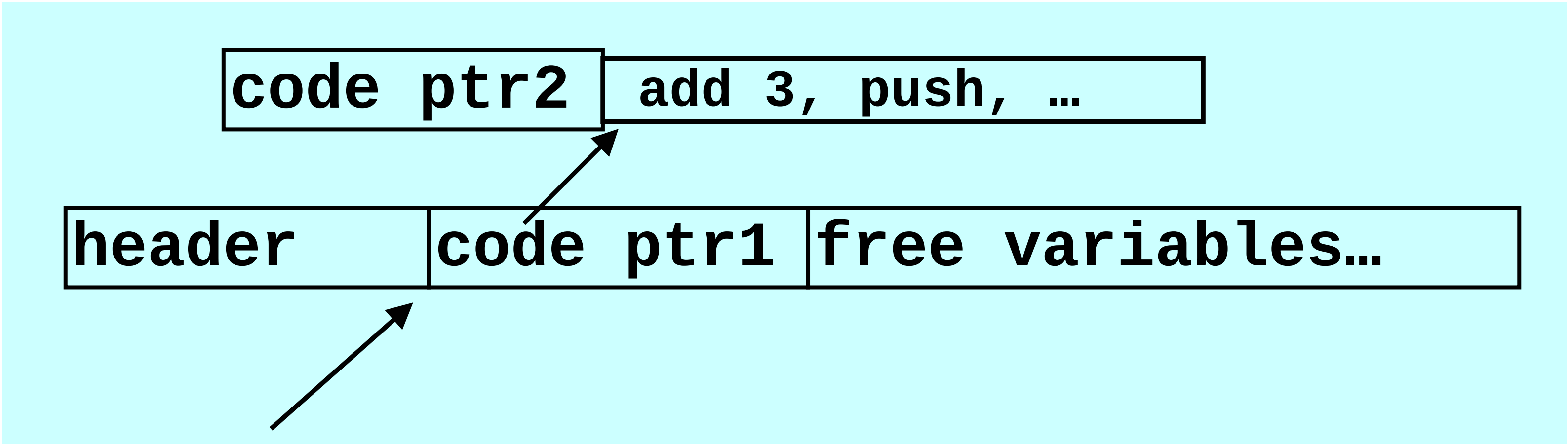
  bigger closures (and related GC changes)



Representing closures/objects

Representation of function-pointers/closures/objects an interesting (and pervasive) design decision

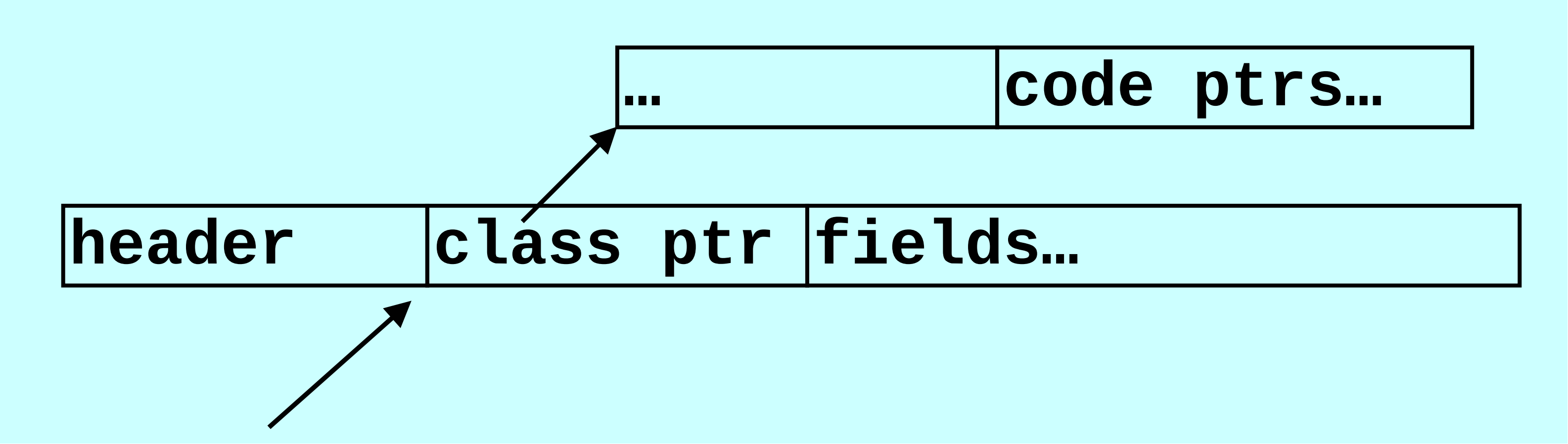
AtomCaml alternative:
    (slower calls in **`atomic`**)



Representing closures/objects

Representation of function-pointers/closures/objects an interesting (and pervasive) design decision

OO already pays the overhead atomic needs
(interfaces, multiple inheritance, … no problem)



Qualitative evaluation

- Non-atomic code executes unchanged
- Writes in atomic block are logged (2 extra writes)
- Worst case code bloat of 2x

- Thread scheduler and code generator must conspire

- Still have to deal with I/O
  - Atomic blocks probably shouldn't do much

Handling I/O

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

- But may miss subtle non-determinism:

```
void f() {
 write_file_foo(); // flushed?
 read_file_foo();
}
void g() {
  atomic {f();} // read won't see write
  f();          // read may   see write
}
```

Native mechanism

- Previous approaches: disallow native calls in **`atomic`**
  - raise an exception
  - **`atomic`** no longer meaning preserving!

- We let the C library decide:
  - Provide two functions (in-atomic, not-in-atomic)
  - in-atomic can call not-in-atomic, raise-exception, or do something else
  - in-atomic can *register* commit-actions and rollback-actions (sufficient for buffering)
  - problem: if commit-action has an error “too late”

Overview

- The case for atomic
- Previous approaches to atomic
- AtomCaml
  - Logging-and-rollback
  - *Uniprocessor implementation*
  - Programming experience
- AtomJava
  - Logging-and-rollback
  - *Source-to-source implementation* (unchanged JVM)
- Condition variables via atomic

Prototype

- AtomCaml: modified OCaml bytecode compiler
- Advantages of mostly functional language
  - Fewer writes (don't log object initialization)
  - To the front-end, **`atomic`** is just a function

```
atomic : (unit -> 'a) -> 'a
```

- Using atomic to implement locks, CML, …
- Planet active network [Hicks et al, INFOCOM99, ICFP98] "ported" from locks to **`atomic`**

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;
let rec loop () =
  if e
  then (wait cv m; s2; loop())
  else s3
in loop ();
unlock m
```

Porting Planet

- Found bugs
  - Reader-writer locks unsound due to typo
  - Clock library deadlocks if callback registers another callback
- Most lock uses trivial to change
- Condition-variable uses need only local restructuring
- 6 “native calls in atomic”
  - 2 pure (so hoist before atomic)
  - 1 a clean-up action (so move after atomic)
  - 3 we wrote new C versions that buffered
- Note: could have left some locks in but didn’t
- Synchronization performance all in the noise

Overview

- The case for atomic
- Previous approaches to atomic
- AtomCaml
  - Logging-and-rollback
  - *Uniprocessor implementation*
  - Programming experience
- AtomJava
  - Logging-and-rollback
  - *Source-to-source implementation* (unchanged JVM)
- Condition variables via atomic

A multiprocessor approach

Strategy: Use locks to implement **`atomic`**

- Each *shared* object guarded by a lock
  - Key: many objects can share a lock
- Logging and rollback to prevent deadlock

Less efficient straight-line code:

- All (even *non-atomic*) code must hold the correct lock to write or *read* a thread-shared object

But try to minimize inter-thread communication

- "Acquiring" a lock you hold needs no synchronization

Acquiring locks

Translate from AtomJava to Java:

- add getter/setter methods for each field
- code duplication and logging like in AtomCaml

- **`e.f`** becomes **`e.get_f()`**
  - acquire lock for e, then return **`e.f`**
- **`e1.f = e2`** similar (and atomic version logs)
- Every object's lock has a current-holder field
  - If the Thread "is me", continue.
  - Else ask the holder to release the lock and wait

Releasing locks

- Threads *poll* to see if they hold requested locks
  - Rewrite source code to insert polling calls
  - To avoid deadlock, satisfy requests
  - If in atomic and you release a lock, rollback first
- Exponential backoff to avoid livelock
- For correctness, the rest is in the (many) details: arrays, primitive types, java.lang, class-loading, native calls, constructors, static fields, …

Optimizations

- Access does not need a lock if *any* of the following:
  - Data is thread-local
  - Data is immutable
  - Data is never accessed within an atomic block
  - You definitely hold the lock already
- Static and dynamic tricks to reduce polling costs
- … much, much more (make it a compiler problem!)

Only one problem… what is the object-to-lock mapping?

What locks what?

There is little chance any compiler in my lifetime will infer a decent object-to-lock mapping

- More locks = more communication
- Fewer locks = less parallelism

What locks what?

There is little chance any compiler in my lifetime will infer a decent object-to-lock mapping

- More locks = more communication
- Fewer locks = less parallelism
- Programmers can't do it well either, though we make them try

What locks what?

There is little chance any compiler in my lifetime will infer a decent object-to-lock mapping

When stuck in computer science, use 1 of the following:

a. Divide-and-conquer
b. Locality
c. Level of indirection
d. Encode computation as data
e. An abstract data-type

Locality

Hunch: Objects accessed in the same atomic block will likely be accessed in the same atomic block again

- So while holding their locks, change the object-to-lock mapping to share locks
  - Conversely, detect false contention and break sharing
- If hunch is right, future atomics acquire fewer locks
  - Less inter-thread communication
  - And many papers on heuristics and policies ☺
- Challenge is cheap profiling (future work)

Overview

- The case for atomic
- Previous approaches to atomic
- AtomCaml
  - Logging-and-rollback
  - *Uniprocessor implementation*
  - Programming experience
- AtomJava
  - Logging-and-rollback
  - *Source-to-source implementation* (unchanged JVM)
- Condition variables via atomic

Summary

- (Strong) atomic is a big win for reliable concurrency
- Key is implementation techniques and properties
  - Disabling interrupts
  - Software Transactional Memory
  - Hardware Transactional Memory
  - Uniprocessor logging-rollback
  - Multiprocessor logging-rollback

An analogy

Garbage collection is a big win for reliable memory management

- Programmers can usually ignore the implementation
- For 3 decades, perceived as “too slow”
  (and we tried hardware support)
- Manual memory management requires subtle, whole-program invariants

Is “TMs vs. rollback” like “copying vs. mark-sweep” (will the best systems be a hybrid)?

Hopefully < 30 years to find out

Acknowledgments

- Joint work with students Michael Ringenburg and Ben Hindman

- For updates and other projects:

  www.cs.washington.edu/research/progsys/wasp/

[end of presentation; auxiliary slides follow]

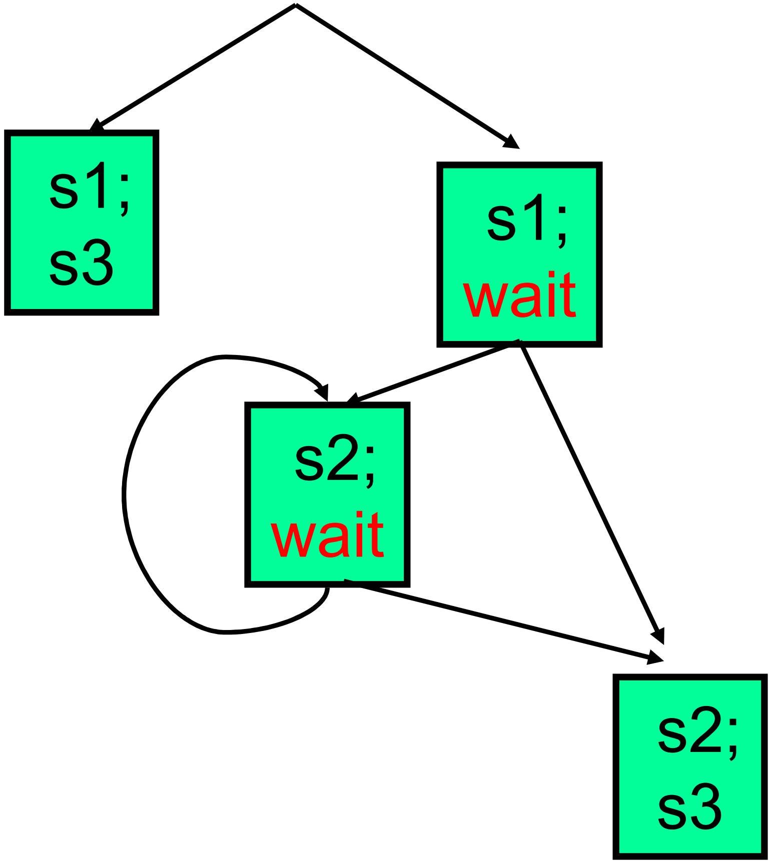
Condition variables: canonical use

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

- **`wait`** blocks until another thread *signals* **`cv`**
- signalling thread must hold **`m`**

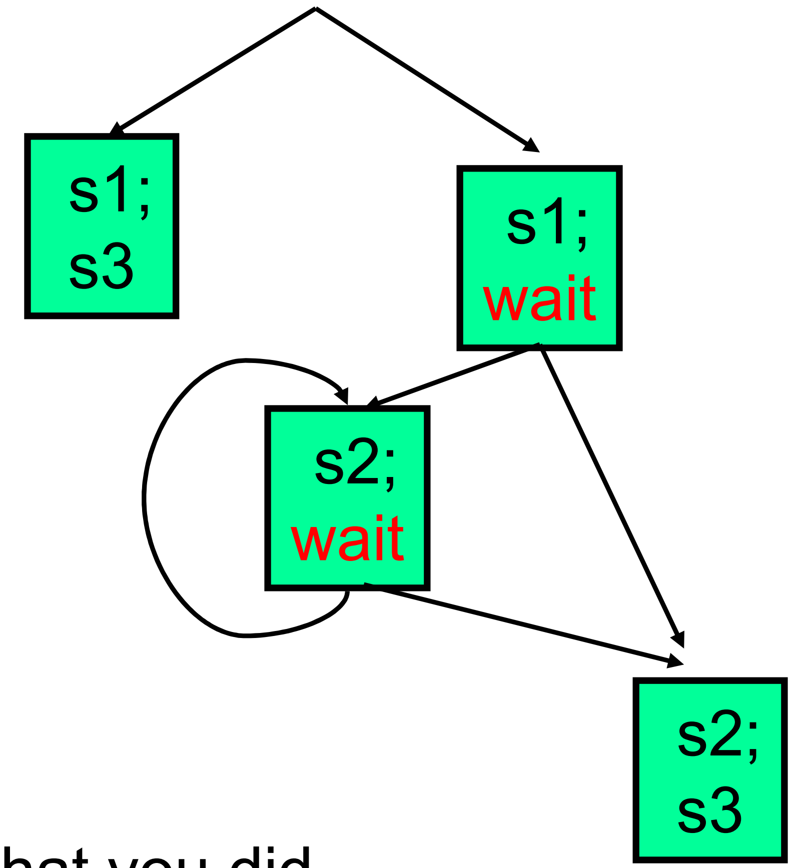
Atomic w.r.t. code holding **m**:

```
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;}
}}
```

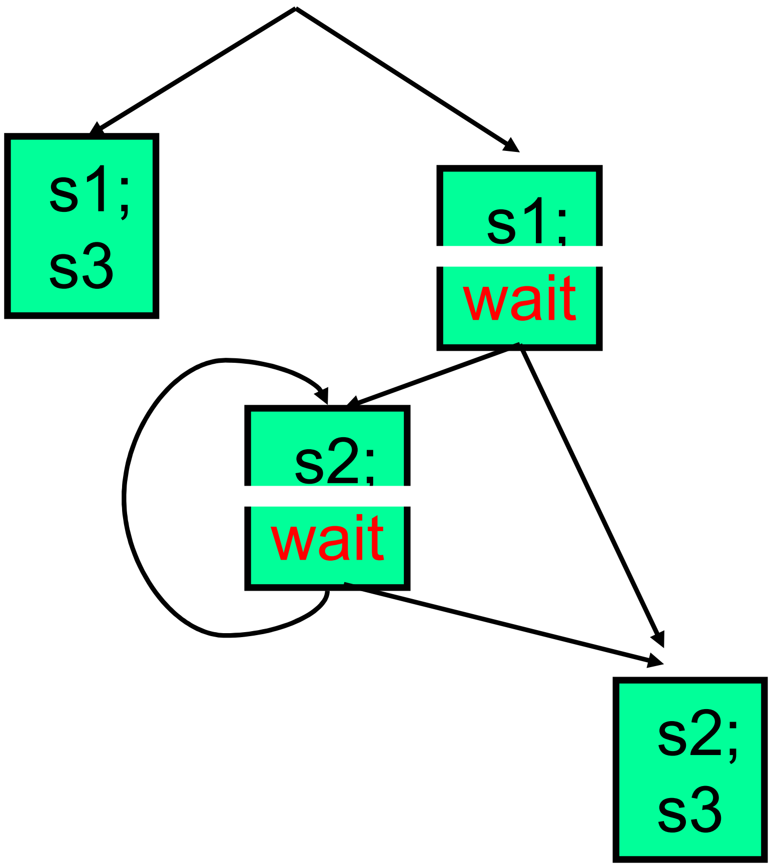


Cannot wait in atomic!

- 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);
}
```

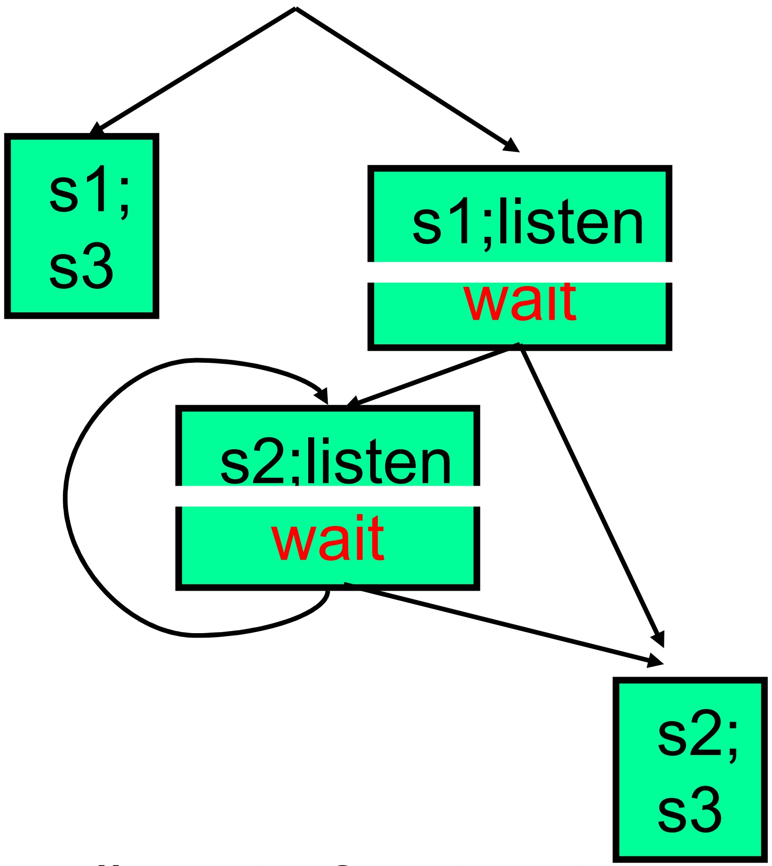


Cannot wait after atomic: you can miss the signal!

Solution: listen!

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

}
if(b) wait(ch);
…
```



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

[really, really auxiliary slides follow]

Detecting concurrency errors

Dynamic approaches

- Lock-sets: Warn if:
  - An object's accesses come from > 1 thread
  - Common locks held on accesses = empty-set
- Happens-before: Warn if an object's accesses are reorderable without
  - Changing a thread's execution
  - Changing memory-barrier order

neither sound nor complete

(happens-before more complete)

[Savage97, Cheng98, von Praun 01, Choi02]

Detecting concurrency errors

Static approaches: lock types

- Type system ensures:

  For each shared data object, there exists a lock that a thread must hold to access the object

- Polymorphism essential
  - fields holding locks, arguments as locks, …
- Lots of add-ons essential
  - read-only, thread-local, unique-pointers, …
- Deadlock avoiding partial-order possible

incomplete, sound only for single objects

[Flanagan,Abadi,Freund,Qadeer99-02, Boyapati01-02,Grossman03]

Enforcing Atomicity

- Lock-based code often enforces atomicity (or tries to)
- Building on lock types, can use Lipton's theory of movers to detect [non]atomicity in locking code
- `atomic` becomes a *checked type annotation*
- Detects StringBuffer race (but not deadlock)

- Support for an inherently difficult task
  - the *programming* model remains tough

[Flanagan,Qadeer,Freund03-05]

Condition Variables

- Idiom releasing/reacquiring a lock: Condition variable

```
lock m;
let rec loop () =
  if e1 then e3
  else (wait cv m; e2; loop())
in loop ();
unlock m;
```

- This *almost* works

```
let f() = if e1 then Some e3 else None
let rec loop x =
  match x with
    Some y -> y
  | None -> wait' cv;
              loop(atomic(fun()-> e2; f()))
in loop(atomic f)
```

Condition Variables

- This *almost* works

```
let f() = if e1 then Some e3 else None
let rec loop x =
  match x with
    Some y -> y
  | None -> wait' cv;
            loop(atomic(fun()-> e2; f()))
in loop(atomic(fun()-> f()))
```

- Unsynchronized **`wait'`** is a race:

  we could miss the **`signal`** (notify)

- Solution: split **`wait'`** into
  - "start listening" (called in **`f()`**, returns a "channel")
  - "wait on channel" (yields unless/until the signal)

Condition Variables

- This *really* works

```
type 'a attempt = Go   of 'a
                | Wait of channel
let f() = if   e1
          then Go e3
          else Wait (listen cv)
let rec loop x =
  match x with
    Go   y  -> y
  | Wait ch ->
    wait’ ch; loop(atomic(fun()->e2;f()))
in loop(atomic f)
```

- Note: These condition variables are implemented in AtomCaml on top of **atomic**
  – (in 20 lines, including broadcast)

Condition variables

```
type channel = bool ref
type condvar = channel list ref
let create () = ref []
let signal cv =
  atomic(fun()->
    match !cv with
      []     -> ()
    | hd::tl -> (cv := tl; hd := false))
let listen cv =
  atomic(fun()->
    let r = ref true in
    cv := r :: !cv;
    r)
let wait ch =
  atomic(fun()->
    if !ch then yield_r ch else ())
```

Example redux

```
int x=0, y=0;
void f() {
  int z = y+1;
  x = z;
}
void g() {
  y = x+1;
}
void h() {
  atomic {
    y = 2;
    f();
    g();
  }
}
```

- Atomic code acquires lock(s) for **x** and **y** (1 or 2 locks)
- Release locks on rollback or completion
- Avoid deadlock automatically. Possibilities:
  - Rollback on lock-unavailable
  - Scheduler detects deadlock, initiates rollback
- Only 1 problem…

Cheap Profiling

Can cheaply monitor the lock assignment

- Per shared object:
  “my current lock”
- Per lock (i.e., objects ever used for locking):
  “number of objects I lock”:
  optional: “how much recent contention on me?”
- Also: atomic log of objects accessed

Revisit STMs

- STMs or lock-based logging-rollback?
  - It’s time to try out all the basics
  - What would hybrids look like?
  - Analogy: 1960s garbage-collectors

- STM advantage: more optimistic, …

- Locks advantage: spatial locality; less wasted computation, …