The Why, What, and How of Software Transactions for More Reliable Concurrency

Dan Grossman
University of Washington

17 November 2006

Atomic

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

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

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

lock acquire/release

(behave as if)
no interleaved computation;
no unfair starvation

Why now?

You are 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

Transactions should be a hot area, and it is…

A big deal

Software-transactions research broad…

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

… and coming together
  TRANSACT (at PLDI06)

Viewpoints

Software transactions good for:

- Software engineering (avoid races & deadlocks)
- Performance (optimistic "no conflict" without locks)

Research should be guiding:

- New hardware with transactional support
- Inevitable software support
  - Legacy/transition
  - Semantic mismatch between a PL and an ISA
  - May be fast enough

Today

Issues in language design and semantics

1. Transactions for software evolution
2. Transactions for strong isolation [Nov06]*
3. The need for a memory model [MSPC06a]**

Software-implementation techniques

1. On one core [ICFP05]
2. Without changing the virtual machine [MSPC06b]
3. Static optimizations for strong isolation [Nov06]*

* Joint work with Intel PSL

** Joint work with Manson and Pugh

Atomic

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

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

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

lock acquire/release

(behave as if)
no interleaved computation;
no unfair starvation

Code evolution

Having chosen “self-locking” today, hard to add a correct transfer method tomorrow

```
void deposit(…)  { synchronized(this) { … }}
void withdraw(…) { synchronized(this) { … }}
int  balance(…)  { synchronized(this) { … }}
void transfer(Acct from, int amt) {
  synchronized(this) {
   //race
   if(from.balance()>=amt && amt < maxXfer) {
     from.withdraw(amt);
     this.deposit(amt);
   }
  }
}
```

Code evolution

Having chosen "self-locking" today, hard to add a correct transfer method tomorrow

```
void deposit(…)  { synchronized(this) { … }}
void withdraw(…) { synchronized(this) { … }}
int  balance(…)  { synchronized(this) { … }}
void transfer(Acct from, int amt) {
  synchronized(this) {
  synchronized(from) { //deadlock (still)
   if(from.balance()>=amt && amt < maxXfer) {
     from.withdraw(amt);
     this.deposit(amt);
   }
  }}
}
```

Code evolution

Having chosen "self-locking" today, hard to add a correct transfer method tomorrow

```
void deposit(…)  { atomic { … }}
void withdraw(…) { atomic { … }}
int  balance(…)  { atomic { … }}
void transfer(Acct from, int amt) {

   //race
   if(from.balance()>=amt && amt < maxXfer) {
      from.withdraw(amt);
      this.deposit(amt);
   }

}
```

Code evolution

Having chosen “self-locking” today, hard to add a correct transfer method tomorrow

```
void deposit(…)  { atomic { … }}
void withdraw(…) { atomic { … }}
int  balance(…)  { atomic { … }}

void transfer(Acct from, int amt) {
  atomic {
    //correct (for any field maxXfer)
    if(from.balance()>=amt && amt < maxXfer){
      from.withdraw(amt);
      this.deposit(amt);
    }
  }
}
```

Lesson

Locks do not compose; transactions do

Today

Issues in language design and semantics

1. Transactions for software evolution
2. Transactions for strong isolation [Nov06]*
3. The need for a memory model [MSPC06a]**

Software-implementation techniques

1. On one core [ICFP05]
2. Without changing the virtual machine [MSPC06b]
3. Static optimizations for strong isolation [Nov06]*

* Joint work with Intel PSL

** Joint work with Manson and Pugh

“Weak” atomicity

Common belief:

- “Weak” means nontransactional code can interpose reads/writes with transactions
- Same bugs arise with lock-based code
- Strict *segregation* of transactional vs. non-transactional data sufficient to avoid races

```
initially y==0
```

```
atomic {
  y = 1;
  x = 3;
  y = x;
}
```

```
x = 2;
print(y); //1? 2?
```

Joint work with Intel PSL

Segregation

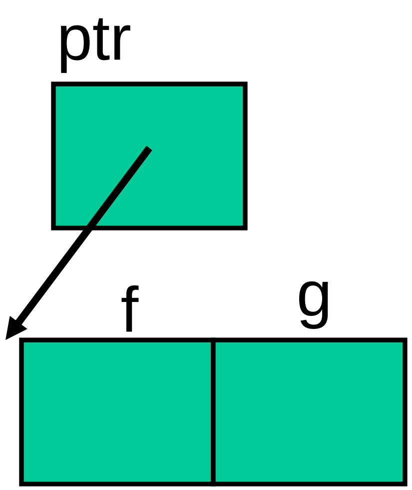
Segregation is not necessary in lock-based code

- Even under relaxed memory models

```
initially ptr.f == ptr.g
```

```
sync(lk) {
  r = ptr;
  ptr = new C();
}
r.f == r.g;//true
```

```
sync(lk) {
  ++ptr.f;
  ++ptr.g;
}
```



(Example from [Rajwar/Larus]
and [Hudson et al])

Joint work with Intel PSL

“Weak” atomicity redux

“Weak” really means nontransactional code bypasses the transaction mechanism…

Weak STMs violate isolation on example:

- Eager-updates (one update visible before abort)
- Lazy-updates (one update visible after commit)

Imposes correctness burdens on programmers that locks do not

Joint work with Intel PSL

Lesson

"Weak" is worse than most think; it can require segregation where locks do not

Corollary: "Strong" has easier semantics

– especially for a safe language

Joint work with Intel PSL

Today

Issues in language design and semantics

1. Transactions for software evolution
2. Transactions for strong isolation [Nov06]*
3. The need for a memory model [MSPC06a]**

Software-implementation techniques

1. On one core [ICFP05]
2. Without changing the virtual machine [MSPC06b]
3. Static optimizations for strong isolation [Nov06]*

* Joint work with Intel PSL

** Joint work with Manson and Pugh

Relaxed memory models

Modern languages don't provide sequential consistency

1. Lack of hardware support
2. Prevents otherwise sensible & ubiquitous compiler transformations (e.g., copy propagation)

So safe languages need two complicated definitions

1. What is "properly synchronized"?
2. What can compiler and hardware do with "bad code"?

(Unsafe languages need (1))

A flavor of simplistic ideas and the consequences…

Joint work with Manson,Pugh

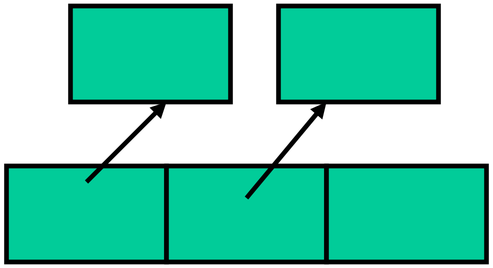
Simplistic ideas

"Properly synchronized" → All thread-shared mutable memory accessed in transactions

Consequence: *Data-handoff* code deemed "bad"

```
//Producer
tmp1=new C();
tmp1.x=42;
atomic {
 q.put(tmp1);
}
```

```
//Consumer
atomic {
 tmp2=q.get();
}
tmp2.x++;
```



Joint work with Manson,Pugh

Simplistic ideas

There exists a total "happens-before" order among all transactions

Consequence: atomic has barrier semantics, making dubious code correct

```
initially x==y==0
```

```
x = 1;

y = 1;
```

```
r = y;

s = x;
assert(s>=r);//invalid
```

Joint work with Manson,Pugh

Simplistic ideas

There exists a total "happens-before" order among all transactions

Consequence: atomic has barrier semantics, making dubious code correct and real implementations wrong

```
initially x==y==0
```

```
x = 1;
atomic { }
y = 1;
```

```
r = y;
atomic { }
s = x;
assert(s>=r);//valid?
```

Joint work with Manson,Pugh

Simplistic ideas

There exists a total "happens-before" order among transactions with conflicting memory accesses

Consequence: "memory access" now in the language definition; dead-code elim must be careful

```
initially x==y==0
```

```
x = 1;
atomic {z=1;}
y = 1;
```

```
r = y;
atomic {tmp=0*z;}
s = x;
assert(s>=r);//valid?
```

Joint work with Manson,Pugh

Lesson

It is not clear when transactions are ordered, but languages need memory models

Corollary: This could/should delay adoption of transactions in well-specified languages

Shameless provocation:

architectures need memory models too! (Please?!)

Joint work with Manson,Pugh

Today

Issues in language design and semantics

1. Transactions for software evolution
2. Transactions for strong isolation [Nov06]*
3. The need for a memory model [MSPC06a]**

Software-implementation techniques

1. On one core [ICFP05]
2. Without changing the virtual machine [MSPC06b]
3. Static optimizations for strong isolation [Nov06]*

* Joint work with Intel PSL

** Joint work with Manson and Pugh

Interleaved execution

The “uniprocessor (and then some)” assumption:

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

Important special case:

- Uniprocessors still exist
- Multicore may assign one core to an app
- Many concurrent apps don’t need a multiprocessor (e.g., a document editor)
- Many language implementations assume it (e.g., OCaml, DrScheme)

Implementing atomic

Key pieces:

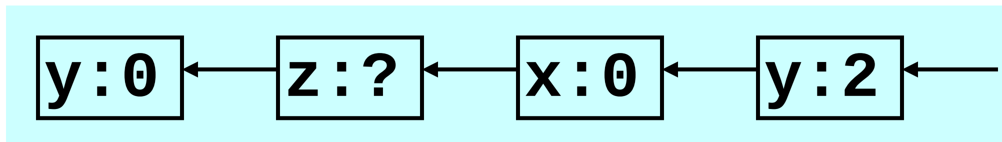
- Execution of an atomic block logs writes
- If scheduler pre-empts a thread in atomic, rollback the thread
- Duplicate code so non-atomic code is not slowed by logging
- Smooth interaction with GC

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:

- build LIFO log of old values:



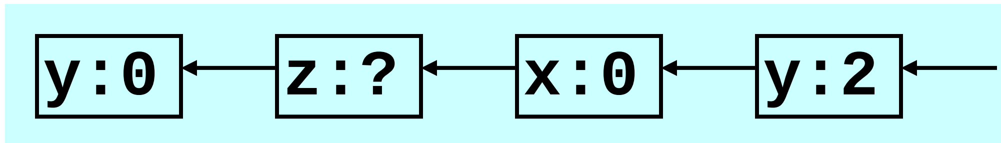
Rollback on pre-emption:

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

On exit from atomic:

- drop log

Logging efficiency



Keep the log small:

- Don’t log reads (key uniprocessor advantage)
- Need not log memory allocated after atomic entered
  - Particularly *initialization writes*
- Need not log an address more than once
  - To keep logging fast, switch from array to hashtable after “many” (50) log entries

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();
  }
}
```

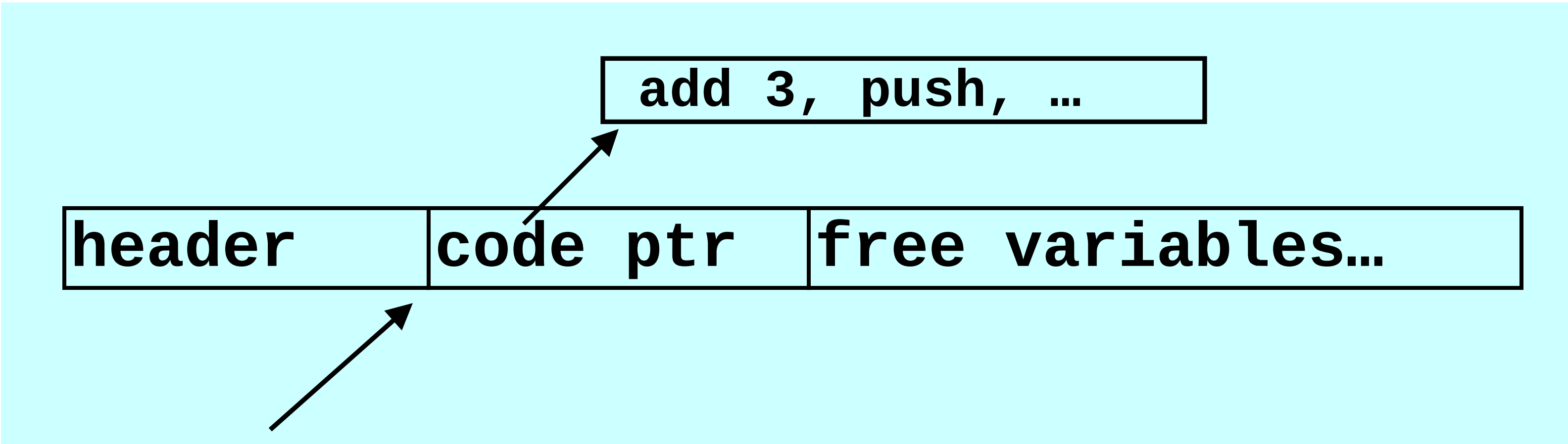
Duplicate code so callees know to log or not:

- For each function **`f`**, compile **`f_atomic`** and **`f_normal`**
- Atomic blocks and atomic functions call atomic functions
- Function pointers compile to pair of code pointers

Representing closures/objects

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

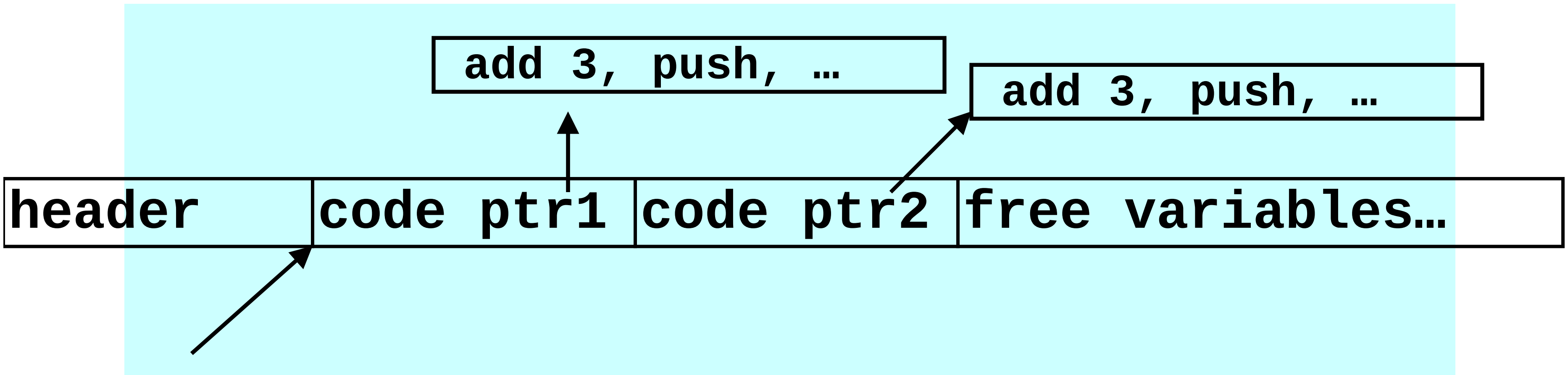
OCaml:



Representing closures/objects

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

One approach: bigger closures

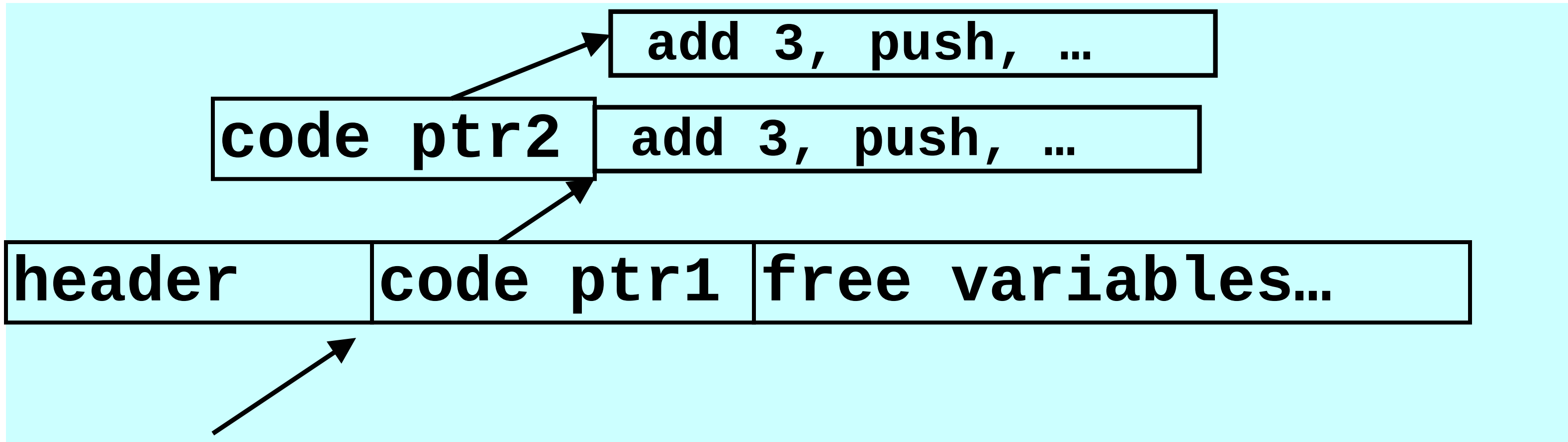


Note: atomic is first-class, so it is just one of these too!

Representing closures/objects

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

Alternate approach: slower calls in **`atomic`**



Note: Same overhead as OO dynamic dispatch

Interaction with GC

What if GC occurs mid-transaction?

- The log is a root (in case of rollback)
- Moving objects is fine
  - Rollback produces *equivalent* state
  - Naïve hardware solutions may log/rollback GC!

What about rolling back the allocator?

- Don't bother: after rollback, objects allocated in transaction are unreachable
  - Naïve hardware solutions may log/rollback initialization writes!

Evaluation

Strong atomicity for Caml at little cost

– Already assumes a uniprocessor

– See the paper for "in the noise" performance

- Mutable data overhead

	not in atomic	in atomic
read	none	none
write	none	log (2 more writes)

- Rare rollback

Lesson

Implementing (strong) atomicity in software for a uniprocessor is so efficient it deserves special-casing

Note: Don't run other multicore services on a uni either

Today

Issues in language design and semantics

1. Transactions for software evolution
2. Transactions for strong isolation [Nov06]*
3. The need for a memory model [MSPC06a]**

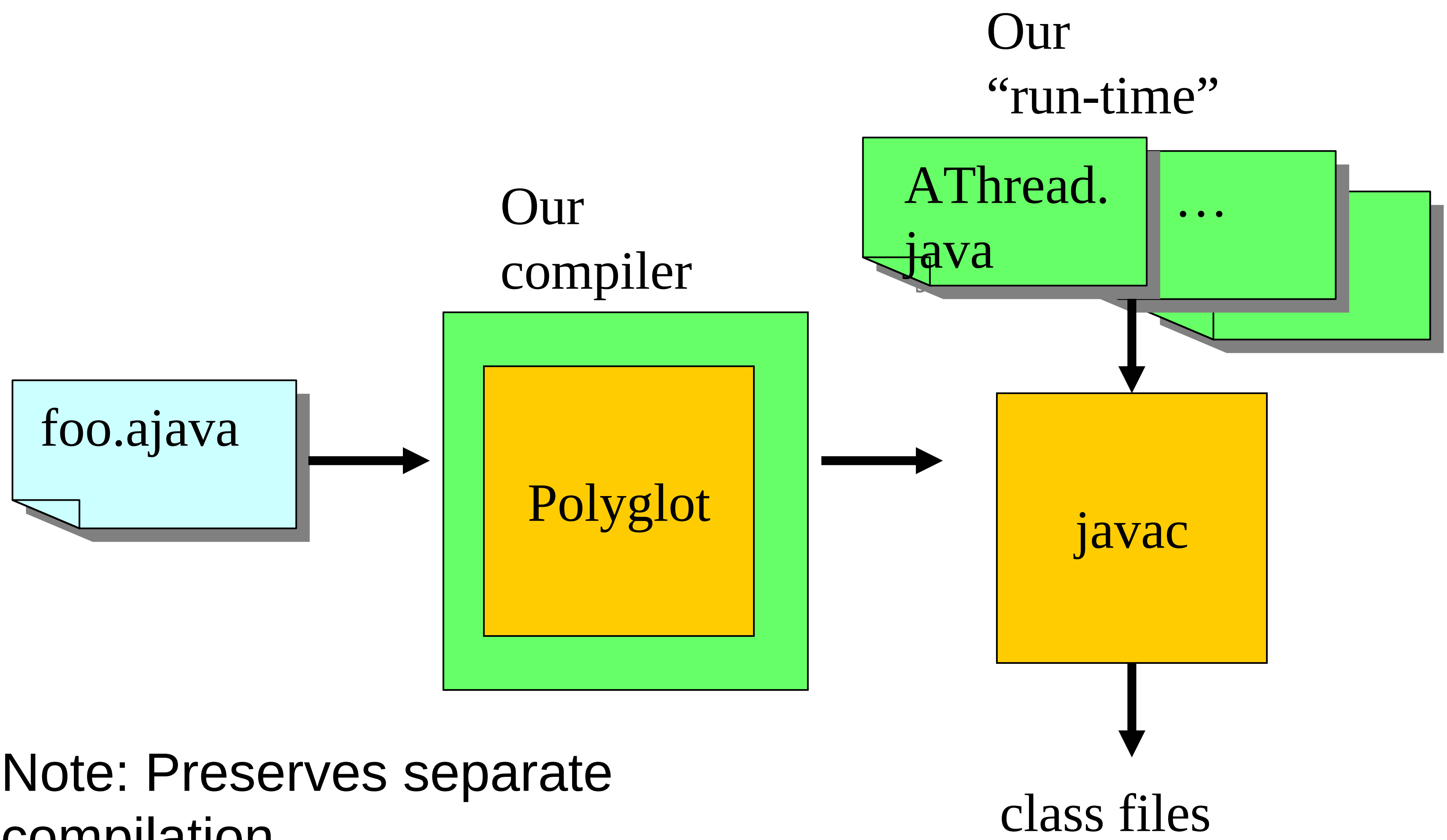
Software-implementation techniques

1. On one core [ICFP05]
2. Without changing the virtual machine [MSPC06b]
3. Static optimizations for strong isolation [Nov06]*

* Joint work with Intel PSL

** Joint work with Manson and Pugh

System Architecture



Note: Preserves separate compilation

Key pieces

- A field read/write first *acquires ownership* of object
  - In transaction, a write also *logs the old value*
  - No synchronization if already own object
- *Polling* for releasing ownership
  - Transactions rollback before releasing
- Some Java cleverness for efficient logging
- Lots of details for other Java features

Acquiring ownership

All objects have an **owner** field

```
class AObject extends Object {
  Thread owner; //who owns the object
  void acq(){…} //owner=caller (blocking)
}
```

Field accesses become method calls

- Read/write barriers that acquire ownership
  - Then do the read or write
  - In transaction, log between acquire and write
- Calls simplify/centralize code (JIT will inline)

Read-barrier

```
//field in class C
D x;
```

```
D x;
static D get_x(C o){
  o.acq();
  return o.x;
}
//also two setters
```

```
//some field-read
   e.x
```

```
C.get_x(e)
```

Important fast-path

If thread already owns an object, no synchronization

```
void acq(){
 if(owner==currentThread()) return;
 …
}
```

- Does *not* require sequential consistency
- With “owner=currentThread()” in constructor, thread-local objects *never* incur synchronization

Else add object to owner’s “to release” set and wait

  - Synchronization on owner field and “to release” set
  - Also fanciness if owner is dead or blocked

Releasing ownership

- Must "periodically" check "to release" set
  - If in transaction, first rollback
    - Retry later (backoff to avoid livelock)
  - Set owners to **`null`**
- Source-level "periodically"
  - Insert call to **`check()`** on loops and non-leaf calls
  - Trade-off synchronization and responsiveness:

```
int count = 1000; //thread-local
void check(){
 if(--count >= 0) return;
 count=1000; really_check();
}
```

But what about…?

Modern, safe languages are big…

See paper & tech. report for:

constructors, primitive types, static fields,
class initializers, arrays, native calls,
exceptions, condition variables, library classes,
…

Lesson

Transactions for high-level programming languages do not need low-level implementations

But good performance does tend to need parallel readers, which is future work. ☹

Today

Issues in language design and semantics

1. Transactions for software evolution
2. Transactions for strong isolation [Nov06]*
3. The need for a memory model [MSPC06a]**

Software-implementation techniques

1. On one core [ICFP05]
2. Without changing the virtual machine [MSPC06b]
3. Static optimizations for strong isolation [Nov06]*

* Joint work with Intel PSL

** Joint work with Manson and Pugh

Strong performance problem

Recall uniprocessor overhead:

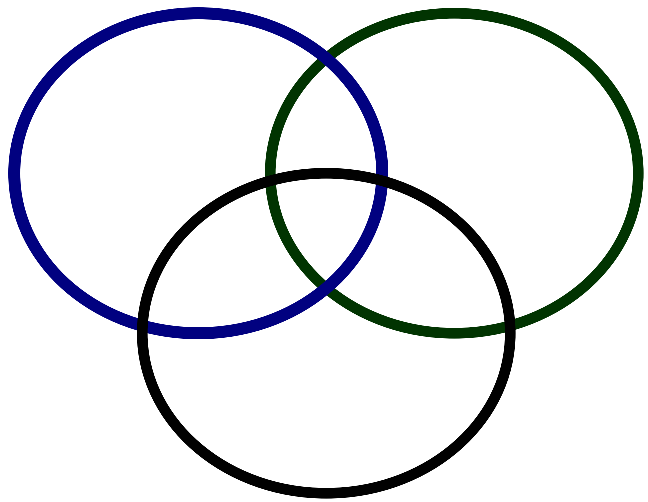
	not in atomic	in atomic
read	none	none
write	none	some

With parallelism:

	not in atomic	in atomic
read	none iff weak	some
write	none iff weak	some

Joint work with Intel PSL

Optimizing away barriers



New: static analysis for not-accessed-in-transaction …

Joint work with Intel PSL

Not-accessed-in-transaction

Revisit overhead of not-in-atomic for strong atomicity, given information about how data is used in atomic

	not in atomic			in atomic
	no atomic access	no atomic write	atomic write	
read	none	none	some	some
write	none	some	some	some

Yet another client of pointer-analysis

Joint work with Intel PSL

Analysis details

- Whole-program, context-insensitive, flow-insensitive
  - Scalable, but needs whole program
- Can be done before method duplication
  - Keep lazy code generation without losing precision
- Given pointer information, just two more passes
  1. How is an "abstract object" accessed transactionally?
  2. What "abstract objects" might a non-transactional access use?

Joint work with Intel PSL

Static counts

Not the point, but good evidence

- Usually better than thread-local analysis

App	Access	Total	Barrier removed by NAIT or TL	NAIT only	TL only
SpecJVM98	Read	12671	12671	8796	0
	Write	9885	9885	7961	0
Tsp	Read	106	93	89	0
	Write	36	17	16	0
JBB	Read	804	798	364	24
	Write	621	575	131	344

Joint work with Intel PSL

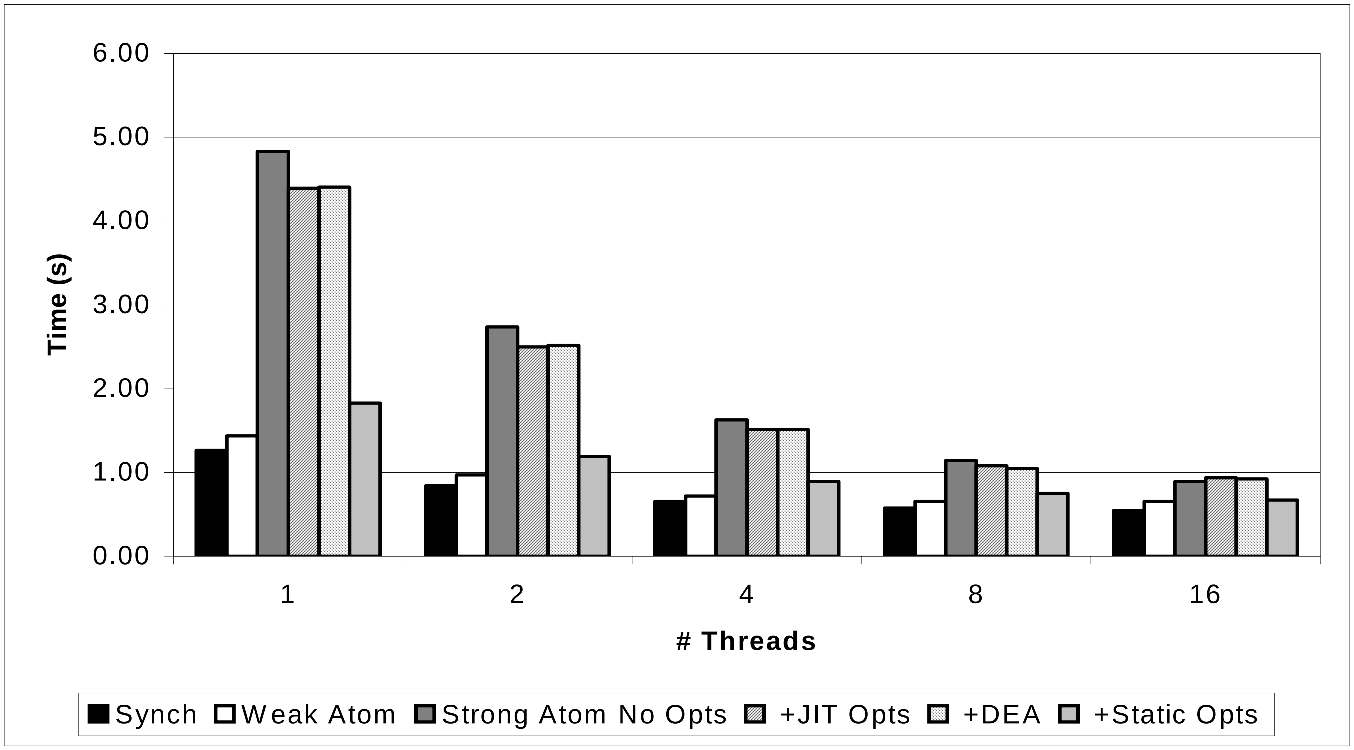
Experimental Setup

High-performance strong STM from Intel PSL

- StarJIT
  - IR and optimizations for transactions and isolation barriers
  - Inlined isolation barriers
- ORP
  - Transactional method cloning
  - Run-time optimizations for strong isolation
- McRT
  - Run-time for weak and strong STM

Joint work with Intel PSL

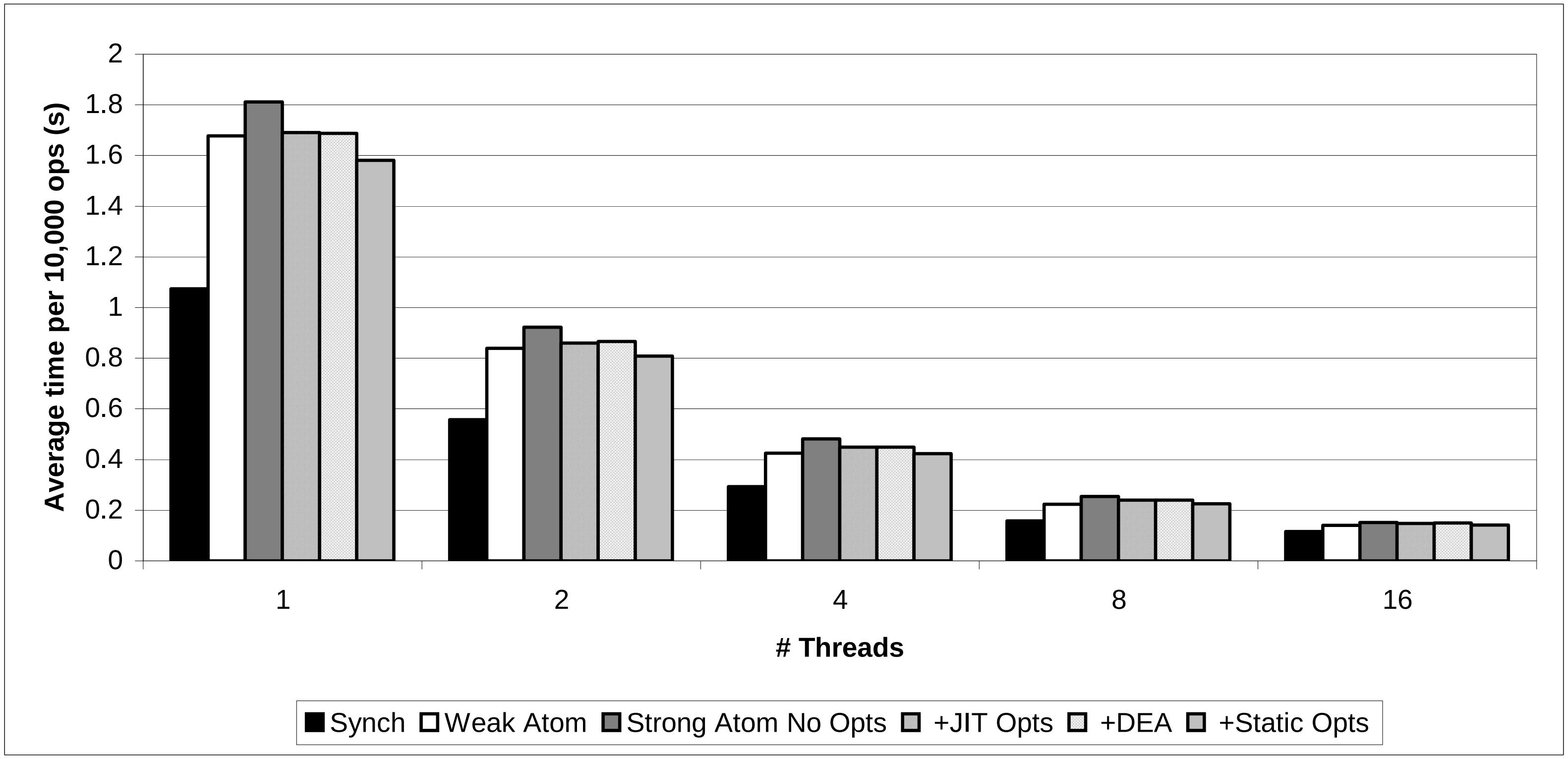
Benchmarks



Tsp

Joint work with Intel PSL

Benchmarks



JBB

Joint work with Intel PSL

Lesson

The cost of strong isolation is in nontransactional barriers and compiler optimizations help a lot

Lessons

1. Locks do not compose; transactions do
2. “Weak” is worse than most think; can require segregation where locks do not
3. Unclear when transactions are ordered, but languages need memory models

---

4. Strong atomicity in software for a uniprocessor is so efficient it deserves special-casing
5. Transactions for high-level programming languages do not need low-level implementations
6. The cost of strong isolation is in nontransactional barriers and compiler optimizations help a lot

Related work

Work at UW complements other pieces of the puzzle…

- Efficient transaction "engines" in hw, sw, hybrid
- Semantics of closed, open, parallel nesting
- Irrevocable actions (e.g., I/O)
  - We provide and use a pragmatic transaction-aware foreign-function interface [ICFP05]

Credit

Uniprocessor: Michael Ringenburg

Source-to-source: Benjamin Hindman

Barrier-removal: Steven Balensiefer, Kate Moore

Memory-model issues: Jeremy Manson, Bill Pugh

High-performance strong STM: Tatiana Shpeisman, Vijay Menon, Ali-Reza Adl-Tabatabai, Richard Hudson, Bratin Saha

wasp.cs.washington.edu