The Semantics of Multithreaded Java

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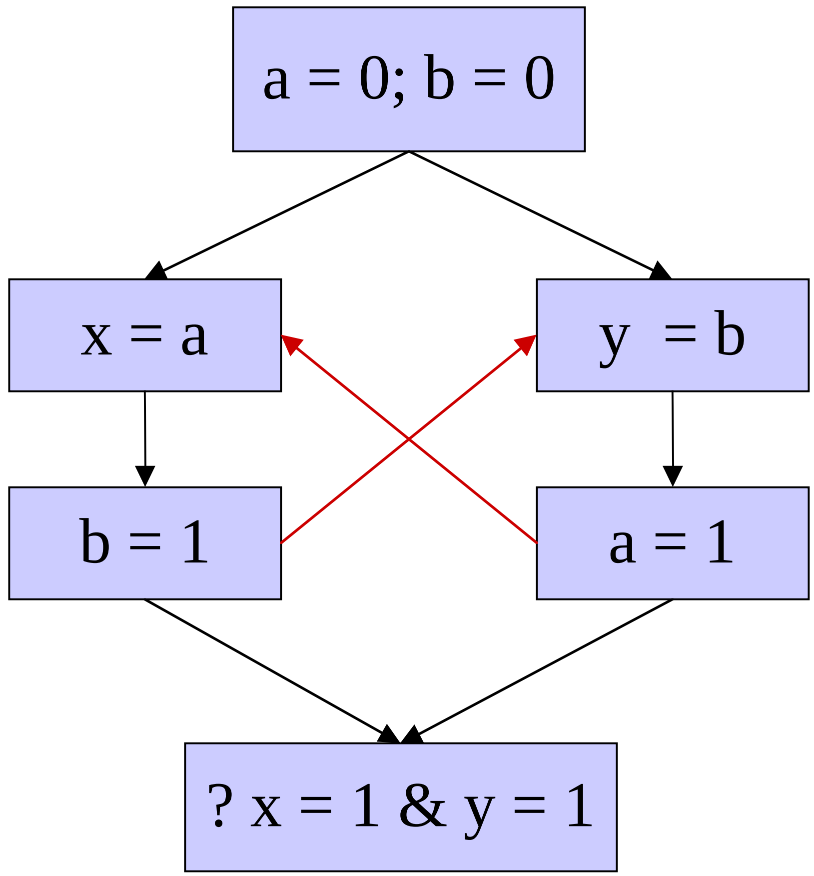
Overview

- Memory Models, and the JMM in particular
- Memory models involve the compiler
  - an example: Coherence
- Need to make safety guarantees
  - even for improperly synchronized code
- Integration of MM and language
  - what does volatile mean?

What is a memory model?

- If two threads have a data race, what behaviors are allowed?
- Sequential consistency
  - interleave memory operations consistent with original ordering in each thread



MM's can interfere with optimization

- In each thread, no ordering constraint between actions in that thread
- Compiler could decide to reorder
- Processor architecture might perform out of order
- Sequential consistency prohibits almost all reordering of memory operations
  – unless you can prove accessed by single thread

Some processors support Sequential Consistency

- But most compilers violate it
- Interesting experiment
  - disable all optimization that could violate sequential consistency
  - examine effect on performance

Do programmers care about the details of MM's?

- If you are writing synchronization primitives
  - You care deeply about the memory model your processor supports
- But if you have synchronized everything properly
  - do you really care?
  - but *do* you have everything synchronized properly?

The Java Memory Model

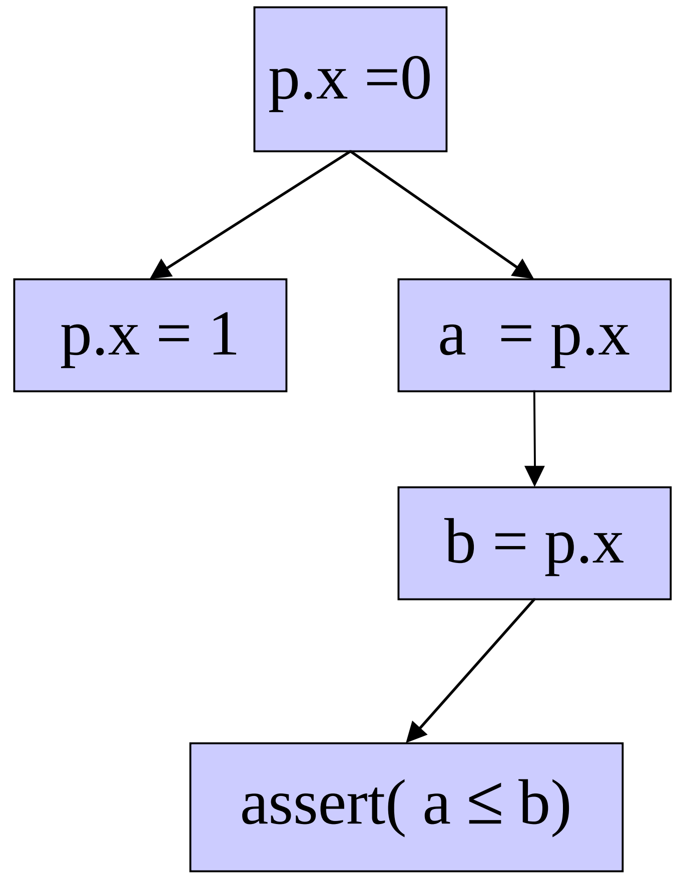
- Chapter 17 of the Java Language Specification (and Chap 8 of the VM Spec)
- Describes how threads interact via locks and read/writes to memory
- Done in a style foreign to other work on memory models
- Very hard to understand
  - At first I thought I was just dense
  - Eventually I figured out that no one understands it

The Java Memory Model is dead

- Was intended to have Coherence
  - For each memory location in isolation, SC
  - Unanticipated impact on compiler
- I found a hairball
  - imposes constraints no one intended
  - makes system unusable
- Proof by invocation of Guy Steele
- It will be replaced, not patched
  - but with what?

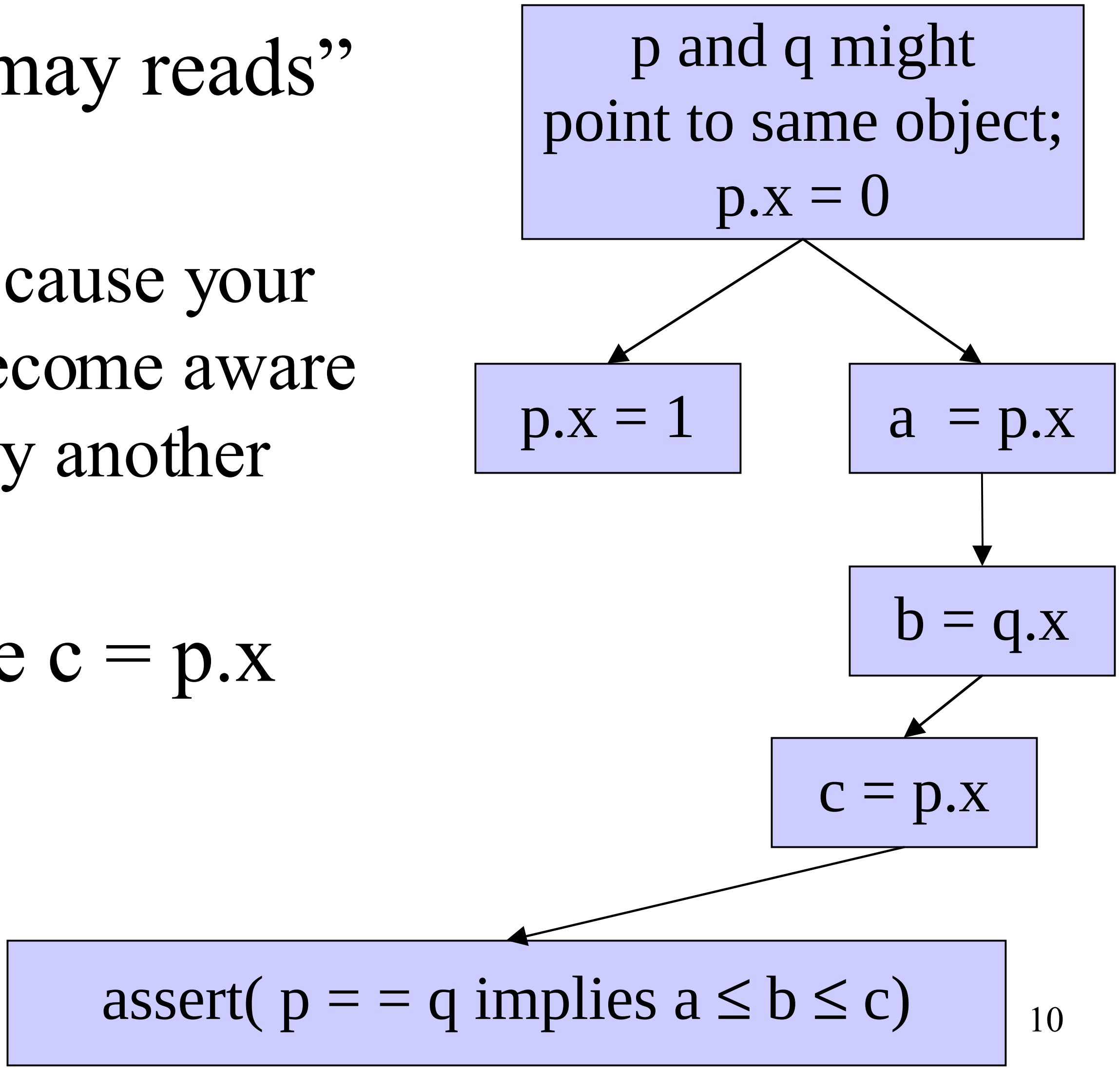
Coherent memory

- Once you see an update by another thread
  - can't forget that you've seen the update
- Cannot reorder two reads of the same memory location



Reads kill reuse

- Must treat "may reads" as kills
  - a read may cause your thread to become aware of a write by another thread
- Can't replace c = p.x with c = a



Most JVM’s violate Coherence

- Every JVM I’ve tested that eliminates redundant loads violates Coherence:
  - Sun’s Classic Wintel JVM
  - Sun’s Hotspot Wintel JVM
  - IBM’s 1.1.7b Wintel JVM
  - Sun’s production Sparc Solaris JVM
  - Microsoft’s JVM
- Bug # 4242244 in Javasoft’s bug parade
  - JVM’s don’t match spec

Impact on Compiler Optimizations?

- Preliminary work by Dan Scales, DecWRL
- Made reads kill, have side effects
- Better is probably possible, but will require work
- Reads have side effects but can be done speculatively
  - change intermediate representation

compress	1.18		mpegaudio	1.44
jess	1.03		richards	0.98
cst	1.01		mtrt	1.02
db	1.04		jack	1.06
si	1.03		tsgp	1.36
javac	0.99		tmix	1.11

OK, what do we want

- Not going to change Java threading model
  - even if people don't like it
- Have to keep in mind that most Java programmers haven't taken an OS course
  - Can't hold them to high standards
- Incorrectly synchronized programs must have a (safe) meaning
  - can't allow a cracker to use improperly synchronized code to attack a system.

Rest of the talk

- ⇒ **Goals for new memory model**
- Weak memory models
  – what can go wrong
- Safety Guarantees
- Changing semantics
- Immutable objects / Atomic object creation
- Future

Goals for new Memory Model

- Preserve existing and/or necessary safety guarantees
  - even in the presence of data races
- Have a clear specification we can reason about
- Allow efficient immutable classes
- New MM should not break "reasonable" existing code

Goals for new MM (continued)

- In code that doesn't involve locks or volatile variables, use as much as possible of the standard compiler optimization techniques
- Data-race-free programs should be guaranteed sequentially consistent results
  - Constraints not necessary to ensure SC for data-race-free programs should be imposed with "care and deliberation".

Rest of the talk

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- **⇒ Weak memory models**
  - **what can go wrong**
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Weak memory models

- Initially,

  Mem[100] = 200
  Mem[200] = 17
  Mem[300] = 666

- On processor 1:

  Mem[300] = 42
  Mem[100] = 300

- On processor 2:

  R1 := Mem[100]
  R2 := Mem[R1]

  R2 = ?

  17, 42, 666(?)

Not much of a surprise

- Compiler could reorder write instructions
- Processor might reorder write instructions
- Put in a memory barrier...

Weak memory models

- Initially,

  Mem[100] = 200
  Mem[200] = 17
  Mem[300] = 666

- On processor 1:

  Mem[300] = 42
  MemBarrier
  Mem[100] = 300

- On processor 2:

  R1 := Mem[100]
  R2 := Mem[R1]

  ?

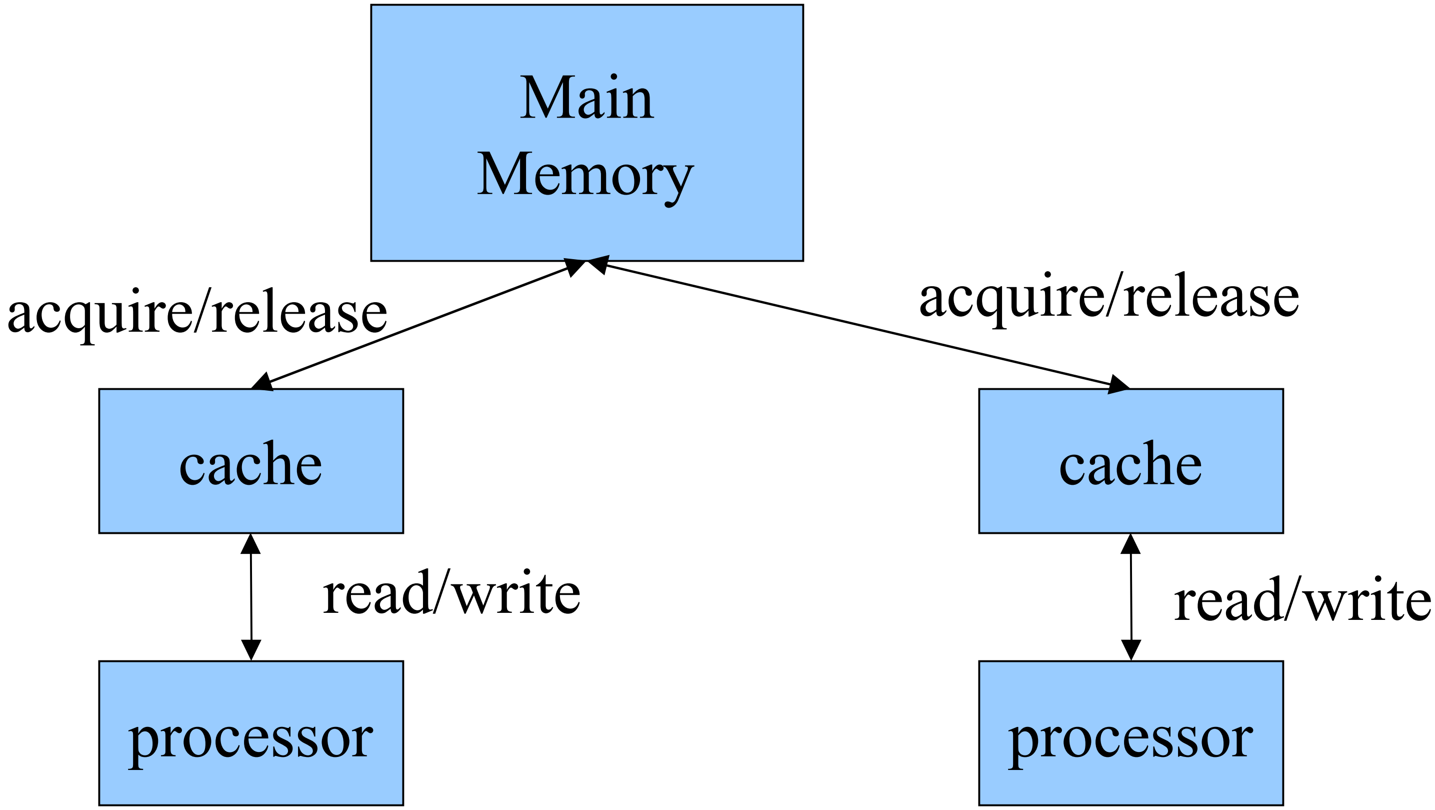
  R2 = ?

  17, 42, 666(?)

More of a surprise

- The data dependence does *not* prevents reordering of instructions on processor 2
- How could this happen?
- Spec says it can happen (Alpha, IA-64, …)
- Can it happen in reality?
  - Value prediction
  - Cache memories

Processor weak memory models



Processor weak memory models

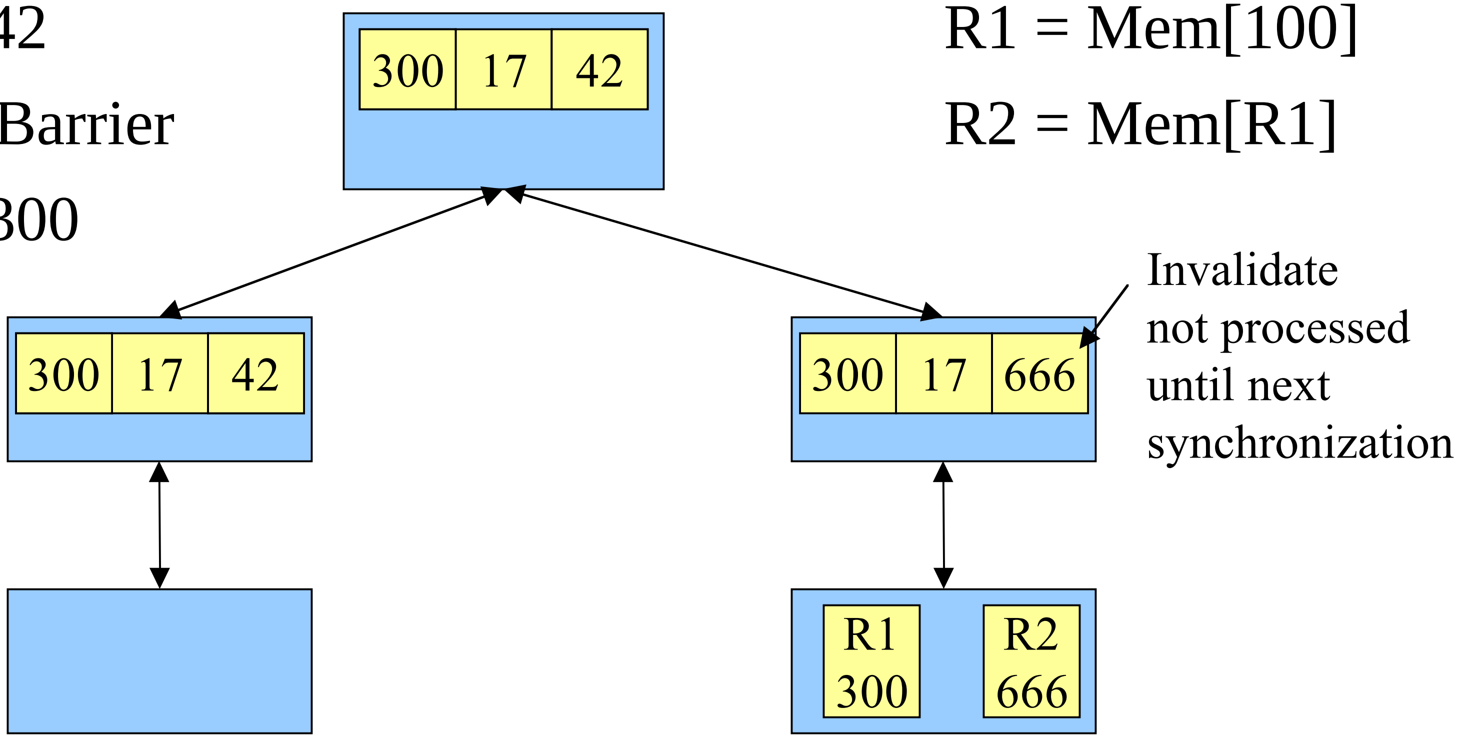
Mem[300] = 42

Release/MemBarrier

Mem[100] = 300

R1 = Mem[100]

R2 = Mem[R1]



What machines can it happen on?

- Only on shared memory multiprocessors
- Sun's TSO (Total store order), PSO (Partial store order) and RMO (Relaxed Memory Order) all strong enough to prevent it
  - Sun Sparc's all run in TSO order
    - because too much of Sun's code breaks under any looser model
  - MAJC runs under RMO
    - although some details still up in the air

It does go wrong on some machines

- Multiprocessor Dec Alphas and Intel IA-64 machines
  - at least according to the spec
  - not clear if any current implementations would allow it to happen
- Intel IA-32?
  - not sure; probably allowed by spec
  - not clear if current implements allow it

Same issues, but for object initialization

- Thread 1
  - initialize an object at address X,
  - Make Foo.x reference the object at address X
- Thread 2
  - reads Foo.x, gets X
  - reads field of object at address X, sees pre-initialization value

This is bad!

- If we see an uninitialized value, we might see something that isn't typesafe
  - seeing a random integer isn't so great either
- We could put a memory barrier after object initialization
  - but that isn't enough (as before)
  - need a memory barrier for reading processor

A simple fix

- Allocate objects out of zeroed memory
  - Zero memory during garbage collection
  - All processors know that the memory was initially zero.
- If we see a pre-initialized ptr, we see null
  - zero for numerics, false for boolean
- Matches Java semantics
  - Fields set to default value (null/false/zero) before constructor is executed

Not sufficient

- This fix isn't sufficient
  - for several reasons
- Consider reading the vtbl ptr of an object
  - points to the virtual function table and class data for object
- If we saw null, virtual method dispatch would generate a segmentation fault for VM
- instanceof and checkedCast could also go wrong

What else can go wrong

- Can see 0 for any world in object header
  - implementation dependent as to what is stored in header
- Can see 0 for array length
  - can throw invalid IndexOutOfBoundsException
- Class loading...

Class loading

- class Foo {
```
public static Object x;
}
```
- class Bar {
```
public int hashCode()
    { … };
}
```
- On processor 1:
```
// First use of Bar
// loads class Bar
tmp = new Bar();
Foo.x = tmp;
```
- On processor 2:
```
Foo.x.hashCode();
```

Now what can go wrong

- Nothing in code executed by processor 2 to indicate that it might be executing code from a new class
- Any field in Bar's vtbl or class data could be zero
  - while others could be valid
- Parts of native code for Bar could be zero

Global memory barriers

- Class loading requires global memory barrier
  - each processor must do a memory barrier
  - but initiated by only one processor
- May need to synchronize instruction as well as data caches
- Not cheap/easy to do on many systems

Code generation/specialization

- Generating native code also requires global memory barrier
- In system like HotSpot
  - new code is generated as profile data is collected
  - not just the first time a method is executed

OK, so safety is hard

- Hopefully, I’ve convinced you that many safety issues, often taken for granted, are difficult on a SMP with a weak memory model
- Need to formalize the safety issues we will guarantee

Rest of the talk

- Goals for new memory model
- Weak memory models
  - what can go wrong
- $\Rightarrow$ **Safety Guarantees**
- Changing semantics
- Immutable objects / Atomic object creation
- Future

Safety Guarantees

- For reads of fields and arrays
  - type safety
  - not-out-of-thin-air safety
- VM safety - despite lack of synchronization
  - All operations other than reading a field or array are as usual
    - can't crash/violate VM
    - No new exceptions
    - array length is always correct

Implementing type safety

- Allocate objects out of memory that everyone agrees has been zeroed
  - since memory was zeroed, every processor must have done a memory barrier

Implementing VM safety

- Global memory barrier after class loading and code generation
  - work to make this efficient
- Null vtbl - two solutions
  - check if null; if so, mem barrier and reload
  - Handle SIGSEGV and recover
- Zero array length
  - check if 0; if so, mem bar and reload
    - for bounds check, only check once out of bounds exception is detected

Class loading safety

- Current spec says that before executing getstatic, putstatic, invokestatic or new on a class, you must load the class or verify that another class has loaded it
  - Add: if you verify that another class has loaded it, you must do an acquire so as to see all writes by the thread that initialized it
  - Add invokevirtual, invokespecial, getfield, putfield

Implementing class loading safety

- You don’t really want to check that a class has been loaded before each invokevirtual
- Loading/initializing a class “prepares” it
- Whenever you do a global memory barrier, “prepared” classes become “distributed”
- Before doing a new on a “prepared” class, you must do a global memory barrier

Rest of the talk

- Goals for new memory model
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  - what can go wrong
- Safety Guarantees
- ⇒ **Changing semantics**
- Immutable objects / Atomic object creation
- Future

Changing semantics

- volatile
  - tighten to make more uses valid
- final
  - change to enable optimizations
- useless locks
  - change to enable optimizations

Changing the semantics of volatile

- C++ spec:
  - *There is no implementation independent meaning for volatile*
- Existing Java spec
  - Actions on volatile variables are SC
    - but actions on normal variables and volatile variables can be reordered
- Change semantics of volatile so that
  - read of volatile is treated as acquire
  - write of volatile is treated as release

Example of new use of volatile

- Double-check idiom
  // used (incorrectly) in many places

```
if (helper == null)  // helper is volatile
  synchronized(this) {
     if (helper == null) {
            helper = new Helper();
     }}
```

- Would also be fixed by atomic object creation (see later)

Example of new use of volatile

- Advanced Double-check idiom

```
if (!initialized)  // initialized is volatile
  synchronized(this) {
    if (!initialized) {
          a = new A();
          b = new B();
          b.update(...);
          initialized = true;
    }}
```

- Not handled by atomic object creation

Changing the semantics of final

- Under current semantics, a memory barrier effects final fields
  - forces them to be reloaded from memory
- Change semantics to allow them to remain in registers
  - also across unknown method calls
- Ugly if objects escapes constructor before final fields initialized

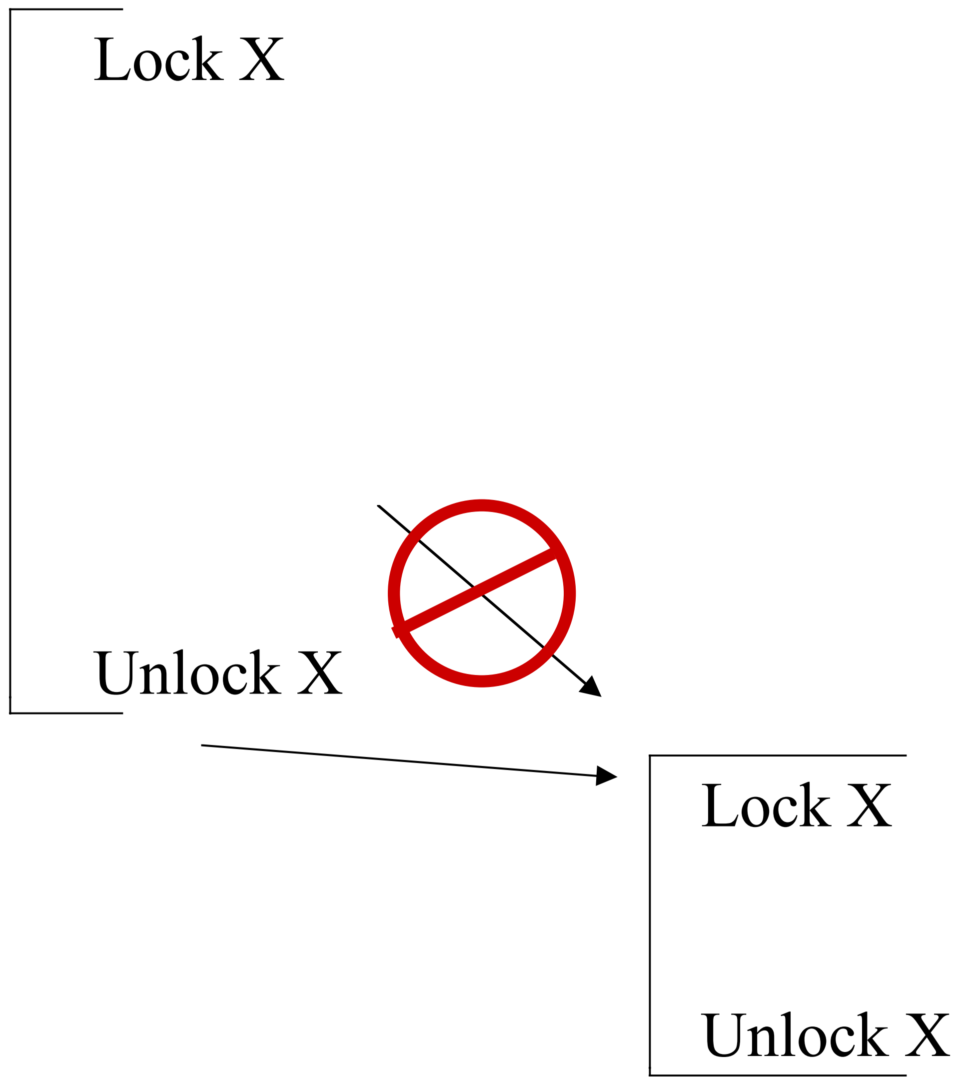
Changing the semantics of useless locks

- Right now, a lock/unlock is always treated as a memory barrier
- Even if the lock/unlock is done on an object not visible to other threads
  - synchronized (new Object()) {} is a memory barrier
- Even if it is a recursive lock
  - e.g., when a synchronized method calls another synchronized method

What MM semantics allow this?

- Lazy Release Consistency?
- Information only needs to flow
  - from Thread 1 to Thread 2 if
  - Thread 1 does a release on X
  - Thread 2 does an acquire on the same X
- Useful in software DSM systems
  - not too useful in hardware DSM systems
- Very useful for compilers!

Recursive locks are no-ops



Compilers and Lazy Release Consistency

- Locks/unlocks on thread local objects are no-ops
  - under old semantics, memory barrier required
- Java monitors are recursive
  - recursive locks/unlocks become no-ops
    - under old semantics, memory barrier required

Rest of the talk

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- Changing semantics
- **⇒ Immutable objects / Atomic object creation**
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Immutable Objects

- Many Java classes represent immutable objects
  - e.g., String
- Creates many serious security holes if Strings are not truly immutable
  - probably other classes as well
  - should do this in String implementation

Why aren’t Strings immutable?

- A String object is initialized to have default values for it’s fields
- Then the fields are set in the constructor
- Thread 1 could create a String object
- pass it to Thread 2
- which calls a sensitive routine
- which sees the fields change from their default values to their final values

Making String immutable

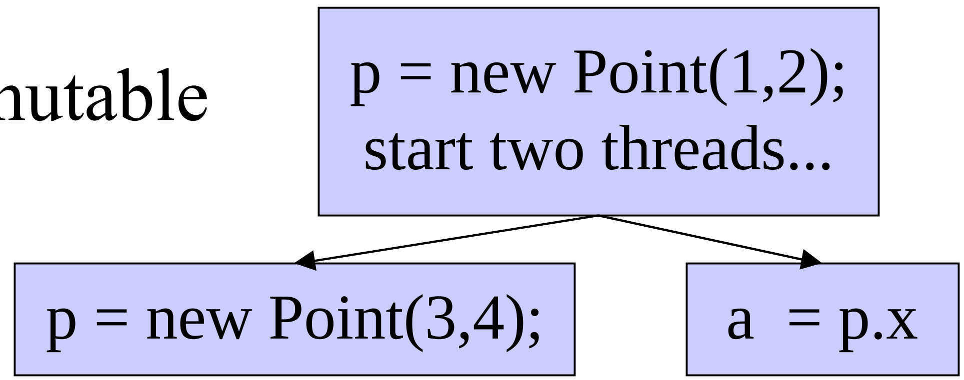
- Could make String methods synchronized
  - most programmers don't think methods for immutable objects need to be synchronized
  - slow down String methods on all platforms
    - only needs to be synchronized on SMP's with weak memory models
    - doesn't need synchronization on SPARC or MAJC(?) SMP's

What we need

- Some way of making a class truly immutable
- With minimal (zero?) performance impact on systems where nothings needs to be done
- Not too ugly

Atomic object creation

- Many naïve programmers assume object creation is atomic
  - Subsumes truly immutable objects
- They are wrong
- In this code, `a` could get the value 1, 3 or 0
- No way to make a constructor synchronized
  - wouldn't work anyway



Should object creation be atomic?

- Advocated by Sun
  - no impact on SPARC/MAJC
- Simple approach would require memory barriers in front of each getfield
  - Factor of 3 slowdown on 2 processor Alpha
    - Numbers by Sanjay Ghemawat, DEC SRC
- Simple optimization improves this
  - Factor of 1.87 slowdown on 2 processor Alpha

A solution?

- Guarantee that reads of final fields see the final value, not the initial default value
  - assuming object doesn’t escape before final fields set
- Also fits well with new semantics of final
- Might be much cheaper than full atomic object creation
- Better programming style than assuming atomic object creation?

Not as simple as that

- No way for elements of an array to be final
- For Strings, have to see final values for elements of character array
- So…
  - Read of final field is treated as a weak acquire
    - matching a release done when object is constructed
  - weak in that it only effects things dependent on value read
    - no compiler impact

Implementing these semantics

- Start with the idea of doing a memory barrier before each getfield of a final field
  - 1666 of 9018 fields in rt.jar are final
  - 2292 could be final
- Only do the memory barrier if object is young
  - Objects are no longer young once a global memory barrier occurs after their construction

Checking for young objects

- Several ways it could be done
  - Here is one
- Put young objects in addresses with sign bit off
- Put old objects and stack allocated objects in addresses with sign bit on
- Conditional memory barrier:

```
if (addr < 0) MemBar;
```

Guidelines for Compiler Writers

- Don't assume that
  - if you drop a value cached in a register,
  - you can reload the value and get the same value
  - even though you don't see any possible writes
- Memory barriers induced by acquire/release
  - moving something past a barrier isn't symmetric

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Future

- The Java Memory Model will be completely replaced
- Trying to get lots of feedback
  - mailing list, web page
  - road shows
  - BOF at OOPSLA
- Unclear how endgame will be played
  - All Java licensee's get a voice

Where next?

- Java Memory model mailing list
  – http://www.cs.umd.edu/~pugh/java/memoryModel
  – Lots of discussion going on
- Won't get changed for next rev of JLS
- Some people at Sun want to avoid a JSR
  – but if changes have a substantial impact on some Java licencees, probably unavoidable