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?

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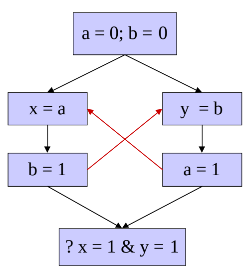
What is a memory model?

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



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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

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Some processors support Sequential Consistency

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

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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?

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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

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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?

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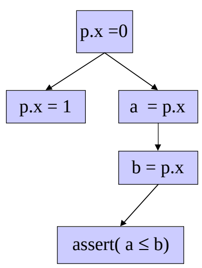
Coherent memory

- 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



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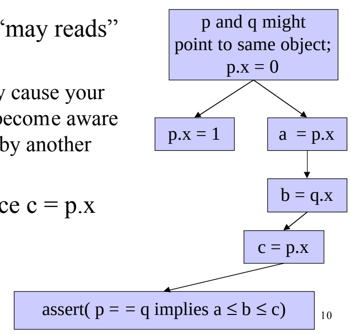
Reads kill reuse

- 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



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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

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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

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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.

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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

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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

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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".

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Weak memory models

- Initially,
  Mem[100] = 200
  Mem[200] = 17
  Mem[300] = 666

• On processor 1:	• On processor 2:
Mem[300] = 42	R1 := Mem[100]
Mem[100] = 300	R2 := Mem[R1]

R2 = ?
17, 42, 666(?)

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Not much of a surprise

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

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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(?)

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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

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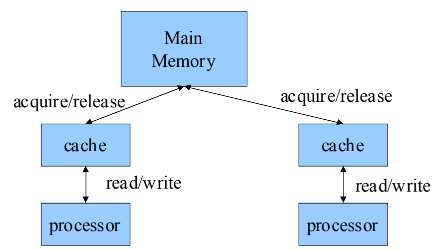
Processor weak memory models



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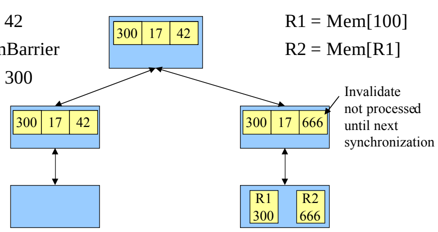
Processor weak memory models

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

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



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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

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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

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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

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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

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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

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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

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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...

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Class loading

- class Foo {
  public static Object x;
  }
- On processor 1:

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

  Foo.x.hashCode();

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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

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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

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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

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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

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Rest of the talk

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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

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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

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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

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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

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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

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Changing semantics

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

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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

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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)

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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

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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

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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

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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!

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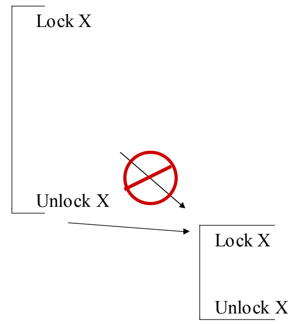
Recursive locks are no-ops



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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

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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

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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

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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

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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

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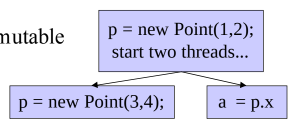
Atomic object creation

- 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



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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

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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?

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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

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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

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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;

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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

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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

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