Revising the Java Thread/Memory Model

See

http://www.cs.umd.edu/~pugh/java/memoryModel

for more information

Audience

- This will be an advanced talk
- Helpful if
  - you've been aware of the discussion,
  - have implemented a JVM,
  - know what sequential consistency is, and that most processors don't support it, or
  - have read Doug Lea's book
- The easy version of this talk is Thursday, 1:30, Hall C.

Java Thread Specification

- Chapter 17 of the Java Language Spec
  - Chapter 8 of the Virtual Machine Spec
- Very, very hard to understand
  - not even the authors understood it
  - doubtful that anyone entirely understands it
  - has subtle implications
    - that forbid standard compiler optimizations
  - all existing JVMs violate the specification
    - some parts should be violated

Revising the Thread Spec

- Work is underway to consider revising the Java Thread Spec
  - http://www.cs.umd.edu/~pugh/java/memoryModel
- Goals
  - Clear and easy to understand
  - Foster reliable multithreaded code
  - Allow for high performance JVMs
- Will effect JVMs
  - and badly written existing code
    - including parts of Sun's JDK

When's the JSR?

- Very hard and technical problems need to be solved
  - formal specification is difficult
  - not appropriate for JSR process
- Once we get technically solid proposals
  - we will start JSR process
  - aiming to start this fall
- Will miss Merlin cutoff
- Workshop at OOPSLA

Proposed Changes

- Make it clear
- Allow standard compiler optimizations
- Remove corner cases of synchronization
  - enable additional compiler optimizations
- Strengthen volatile
  - make easier to use
- Strengthen final
  - Enable compiler optimizations
  - Fix security concerns

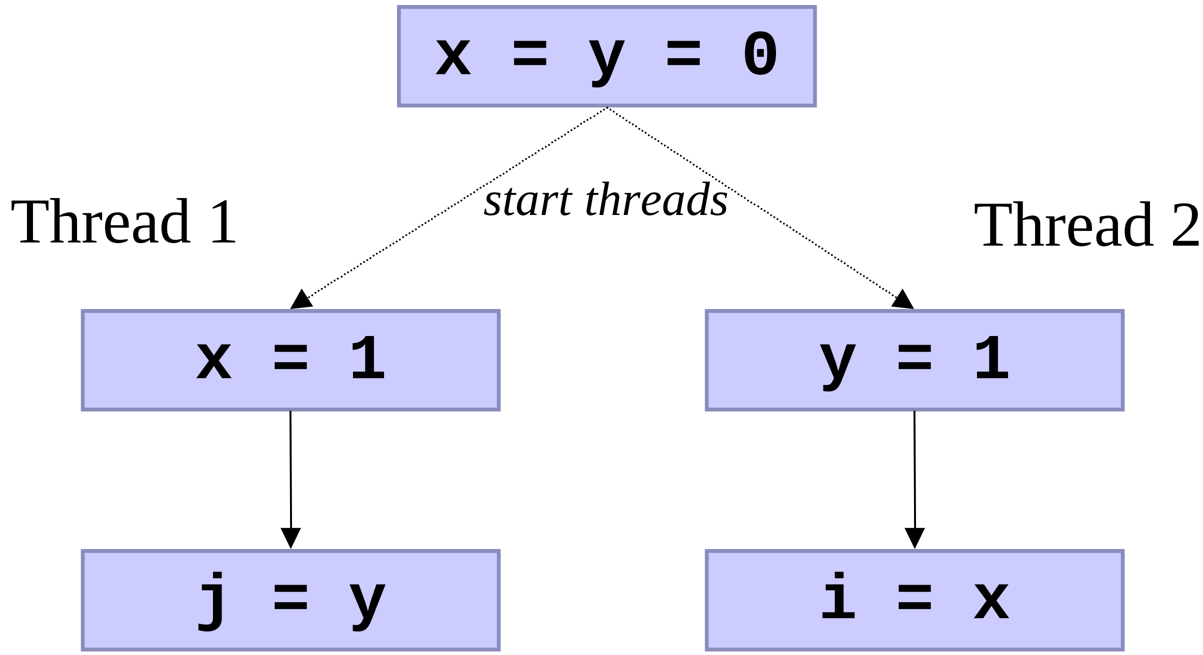
VM Safety

- Type safety
- Not-out-of-thin-air safety
  - (except for longs and doubles)
- No new VM exceptions
- Only thing lack of synchronization can do is produce surprising values for getfields/getstatics/array loads

VM Safety implications

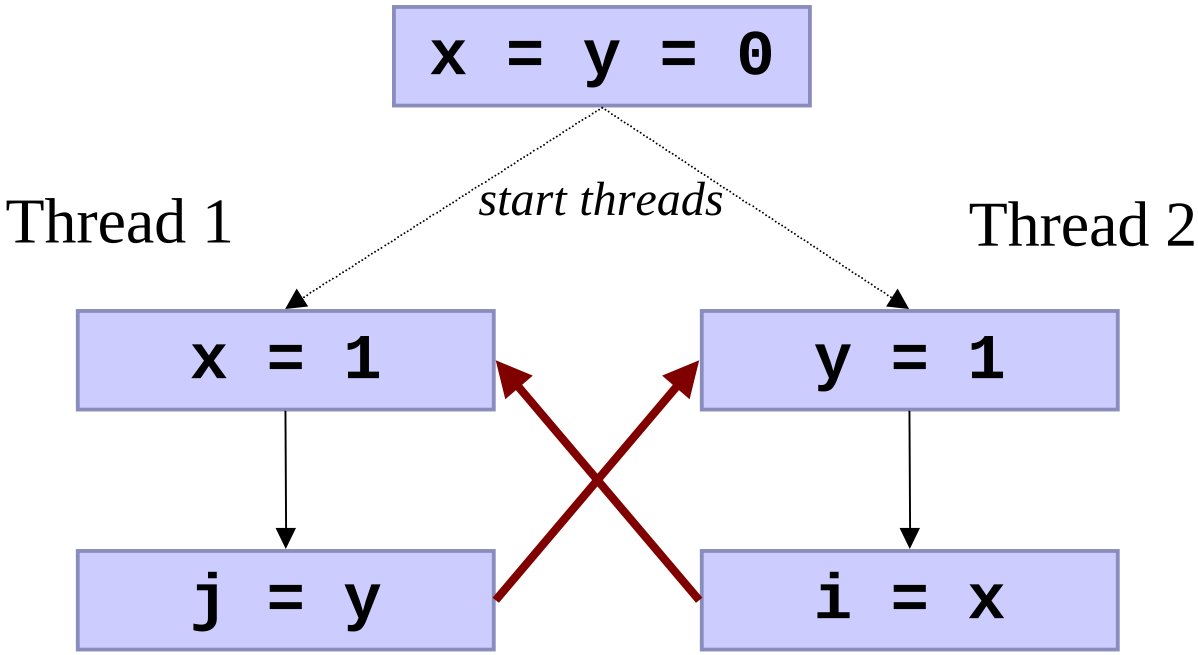
- Problems on SMPs with weak memory models
- Could see uninitialized objects created by another thread
  - need to initialize memory during GC
  - worry about seeing null vptr
  - worry about seeing zero array length
- Class loading and initialization issues

Weird Behavior of Improperly Synchronized Code



Can this result in i = 0 and j = 0?

Answer: Yes!



How can i = 0 and j = 0?

How Can This Happen?

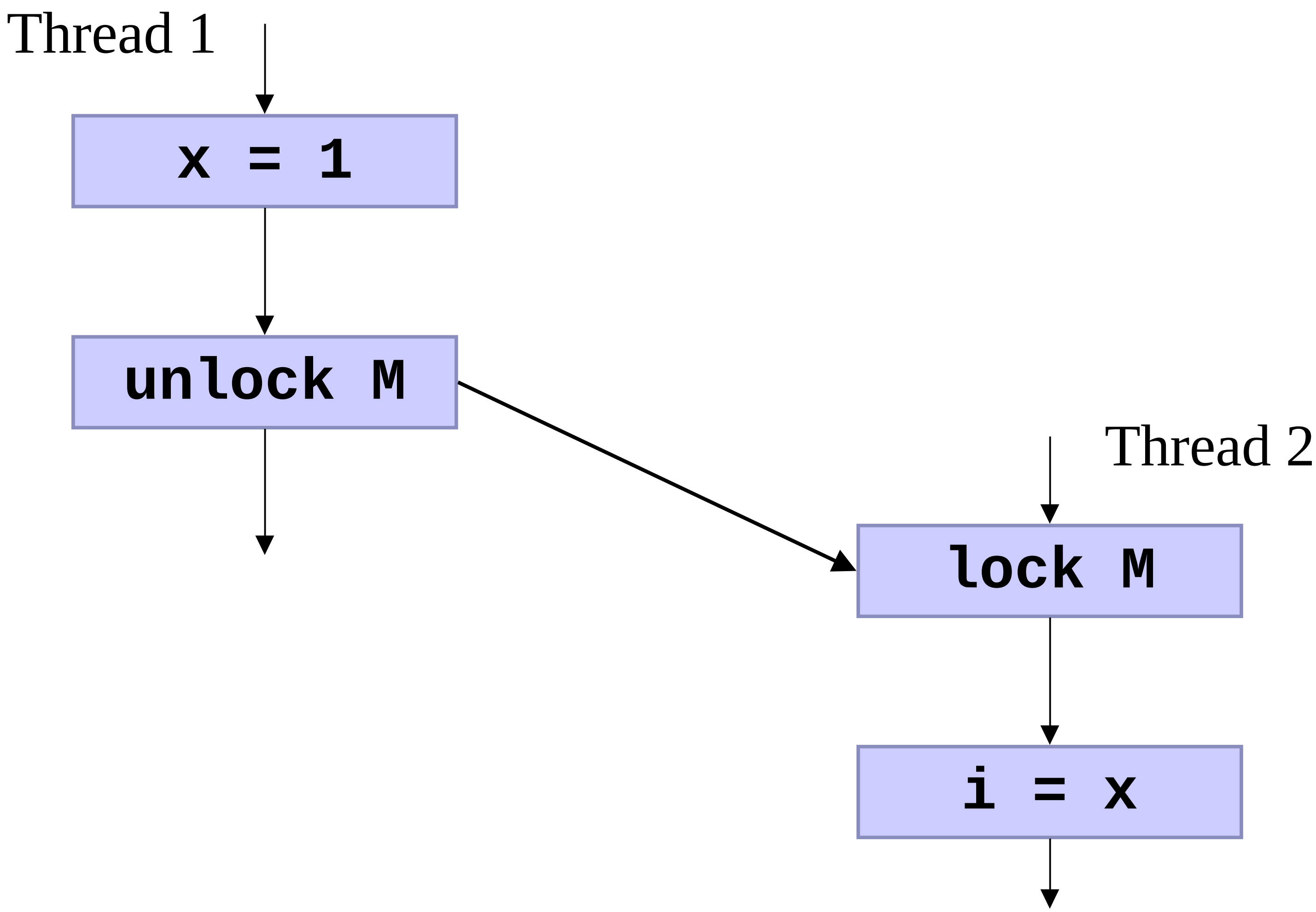
- Compiler can reorder statements
  - or keep values in registers
- Processor can reorder them
- On multi-processor, values not synchronized in global memory

- Must use synchronization to enforce visibility and ordering
  - as well as mutual exclusion

Synchronization

- Synchronization on thread local objects
  - e.g., synchronized(new Object()) {}
  - is not a no-op under current semantics
  - but it isn’t a memory barrier
- Proposal: make it a no-op
  - and allow other compiler optimizations
- Programming model is release consistency

When Are Actions Visible to Other Threads?



New Optimizations Allowed

- Turning synchronizations into no-ops
  - locks on objects that aren't ever locked by any other threads
  - reentrant locks
  - enclosed locks
- Lock coarsening
  - merging two calls to synchronized methods on same object
    - need to be careful about starvation issues

Double-check - DO NOT USE

Doesn't work under either existing or proposed semantics

```
class Service { // DO NOT USE
  Parser parser = null;
  Parser getParser() {
    if (parser == null)
      synchronized(this) {
        if (parser == null)
          parser = new Parser();
      }
    return parser;
  }}
```

Existing Semantics of Volatile

- No compiler optimizations
  - Can’t hoist read out of loop
  - reads/writes go directly to memory
- Reads/writes of volatile are sequentially consistent
  - can not be reordered
  - but access to volatile and non-volatile variables can be reordered
- Reads/writes of long/doubles are atomic

Existing Volatile Compliance

- Very poor
  - some JVMs completely ignore volatile
- No one enforces sequential consistency
- Atomic longs/doubles isn't enforced on most

- New compliance tests will likely be rolled out soon

Volatile Compliance

	No Compiler Optimizations	Sequential Consistency	Atomic Longs/Doubles
Solaris JDK 1.2.2 EVM	Pass	Fail	Pass
Solaris JDK 1.3.0 beta Hotspot Client	Fail	Fail	Fail
Windows JDK 1.3.0 Hotspot Client	Fail	Fail	Fail
Solaris JDK 1.3.0 beta Hotspot Server	Pass	Fail	Fail
Windows JDK 1.3.0 Hotspot Server	Pass	Fail	Fail
Windows IBM JDK 1.1.8	Pass	Fail	Fail

Need for volatile

```
int answer = 0;
boolean ready = false;
```

start threads

```
answer = 42;
ready = true;
```

```
if (ready)
  System.out.println(answer);
```

Can print 0

Need for volatile

```
volatile int answer = 0;
volatile boolean ready = false;
```

start threads

```
answer = 42;
ready = true;
```

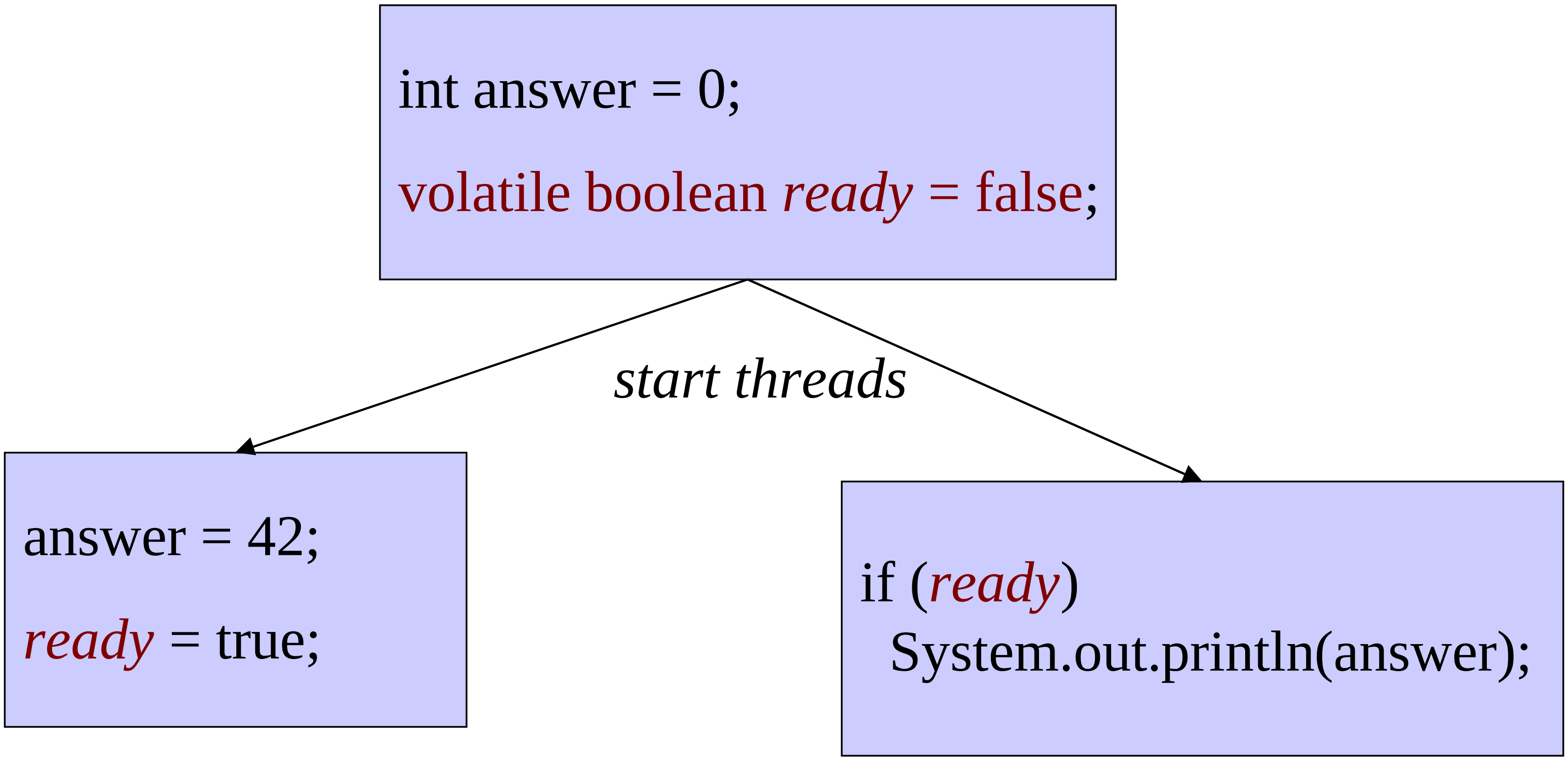
```
if (ready)
  System.out.println(answer);
```

Must *not* print 0

Proposed New Semantics for Volatile

- Write to a volatile acts as a release
- Read of a volatile acts as an acquire
- If a thread reads a volatile
  - all writes done by any other thread,
  - before earlier writes to the same volatile,
  - are guaranteed to be visible

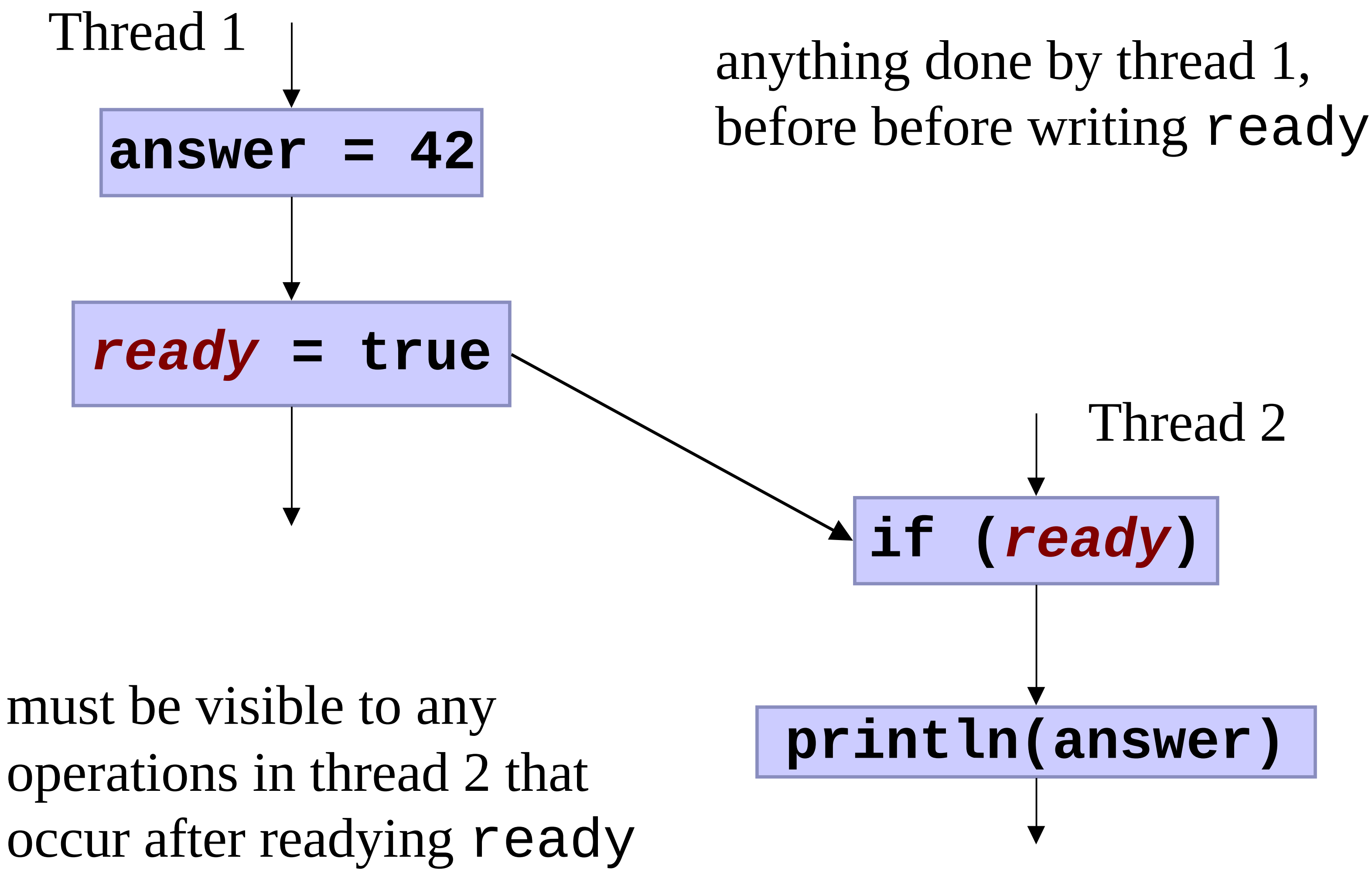
New semantics for volatile



Existing semantics: can print 0

Proposed semantics: must not print 0

When Are Actions Visible to Other Threads?



Naïve Implementation of Volatile

- On SMP with weak memory model (Alpha)
  - Membar before & after each volatile write
  - Membar after each volatile read
- On SMP with TSO (e.g. Sparc)
  - Membar after each volatile write
- On IA-64
  - use ld.acq and st.rel for volatile fields
  - also, memory barrier after each volatile write

Implementation Cost of Proposed Change in Semantics

- Naïve implementation handles new semantics
  - unclear if only enforcing only existing semantics would incur fewer memory barriers
- New semantics will prohibit some compiler optimizations
  - reading a volatile will force all values cached in registers to be reloaded

Volatile Summary

- These semantics make volatile rather heavy weight
  - may not be cheaper than synchronization
- Few programmers will use all these features
  - Do we really need sequential consistency, on top of acquire/release semantics?
- But it is simple and easy to understand
  - more likely to be used correctly

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, rather than in all uses of String

Strings aren't immutable

just because thread 2 sees new value for **`Global.s`** doesn't mean it sees all writes done by thread 1 before store to **`Global.s`**

thread 1

```
String foo
  = new String(sb)
```

```
Global.s = foo
```

```
String t = Global.s
```

```
ok = t.equals("/tmp")
```

thread 2

Compiler, processor or memory system can reorder these writes

Symantic JIT will do it

Why aren’t Strings immutable?

- A String object is initialized to have default values for its 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
  - synchronization would 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

Final = Immutable?

- Existing Java memory model doesn’t mention final
  - no special semantics
- Would be nice if compiler could treat final fields as constant
  - Don’t have to reload at memory barrier
  - Don’t have to reload over unknown function call

Existing semantics require that final fields need to be reloaded at synchronization points

```
class A extends Thread
  {
    final int x;
    A() {

  synchronized(this) {
        start();
        sleep(10);
        }
      x = 42;
      };
```

```
public void run() {
    int i,j;
    i = x;
    synchronized(this) {
        j = x;
        }
    System.out.println(i+j);
    }
}
```

Must *not* print 0

Proposed Semantics for Final

- Read of a final field always sees the value set in constructor
  - If,
    - a final field is read before set
      - (by the constructing thread)
    - or, a reference to the object becomes visible to another thread before object is constructed
    - semantics are ugly
- Can assume final fields never change
- Makes string immutable?

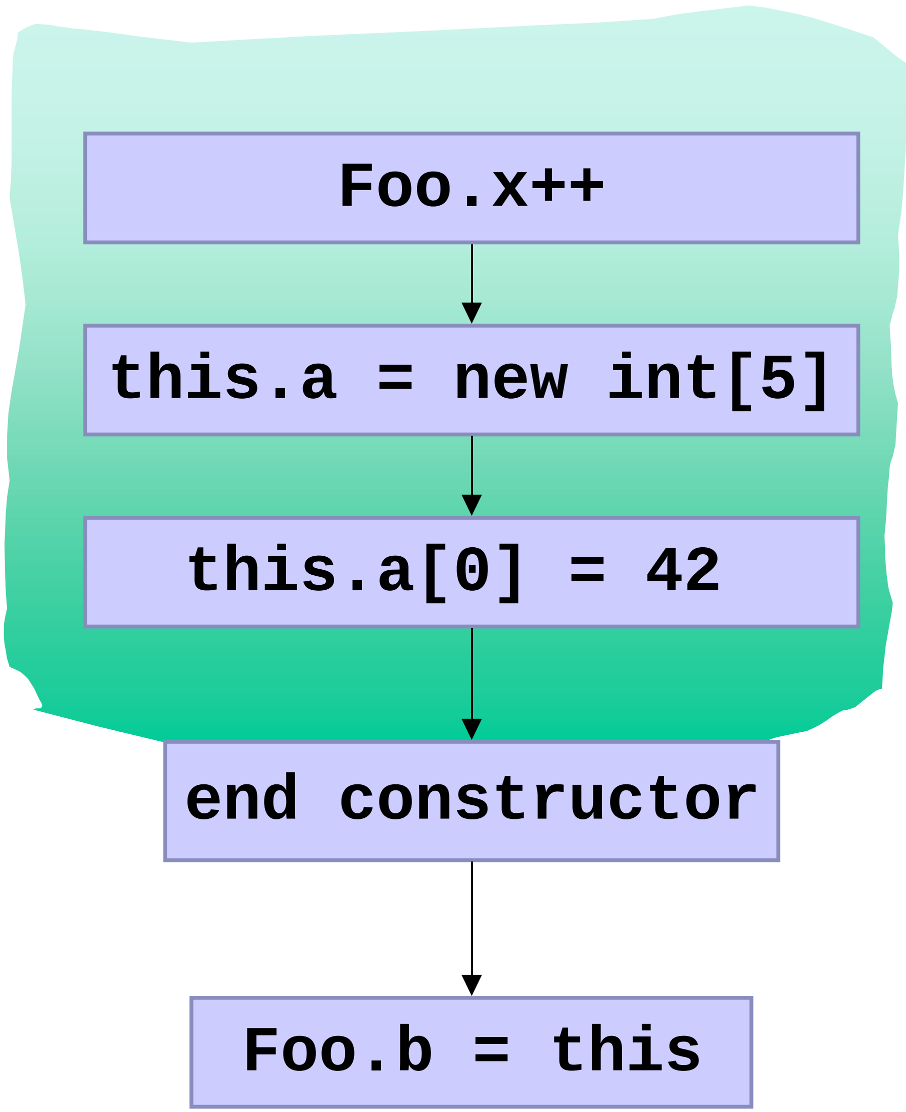
Problems

- JNI code can change final fields
  - setIn, setOut, setErr
  - **Propose to remove this ability**
  - (reflection appears to be safe)
- Objects that escape their constructor before final fields are set
  - Base class “registers” object, derived class has final fields
- Doesn’t suffice to make strings immutable

Doesn’t make Strings immutable

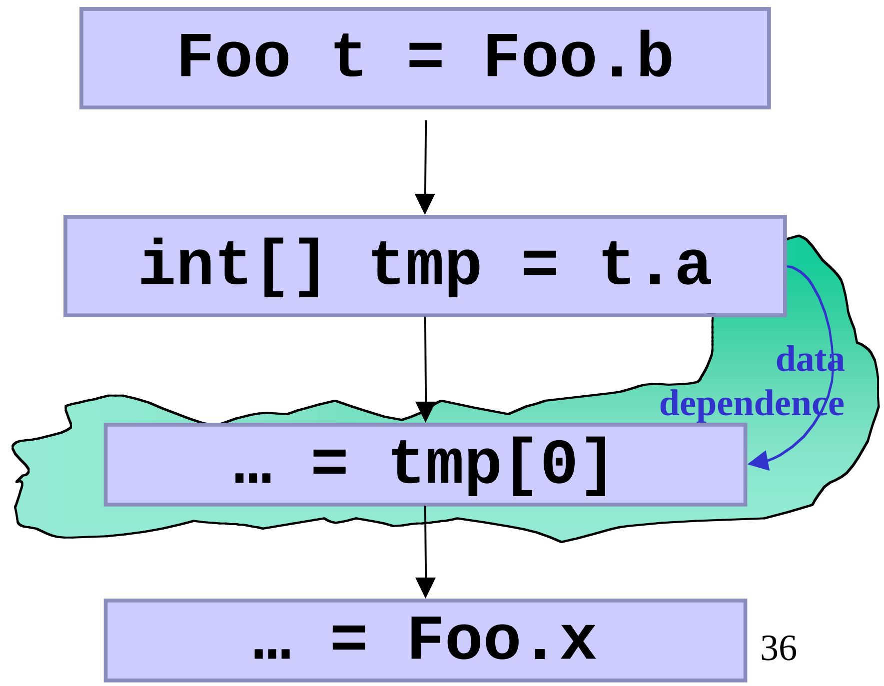
- No way for elements of an array to be final
- For Strings, have to see final values for elements of character array
- So…
  - Read of final field is treated as a weak acquire
    - matching a release done when object is constructed
  - weak in that it only effects things dependent on value read
  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

Visibility enforced by final field a

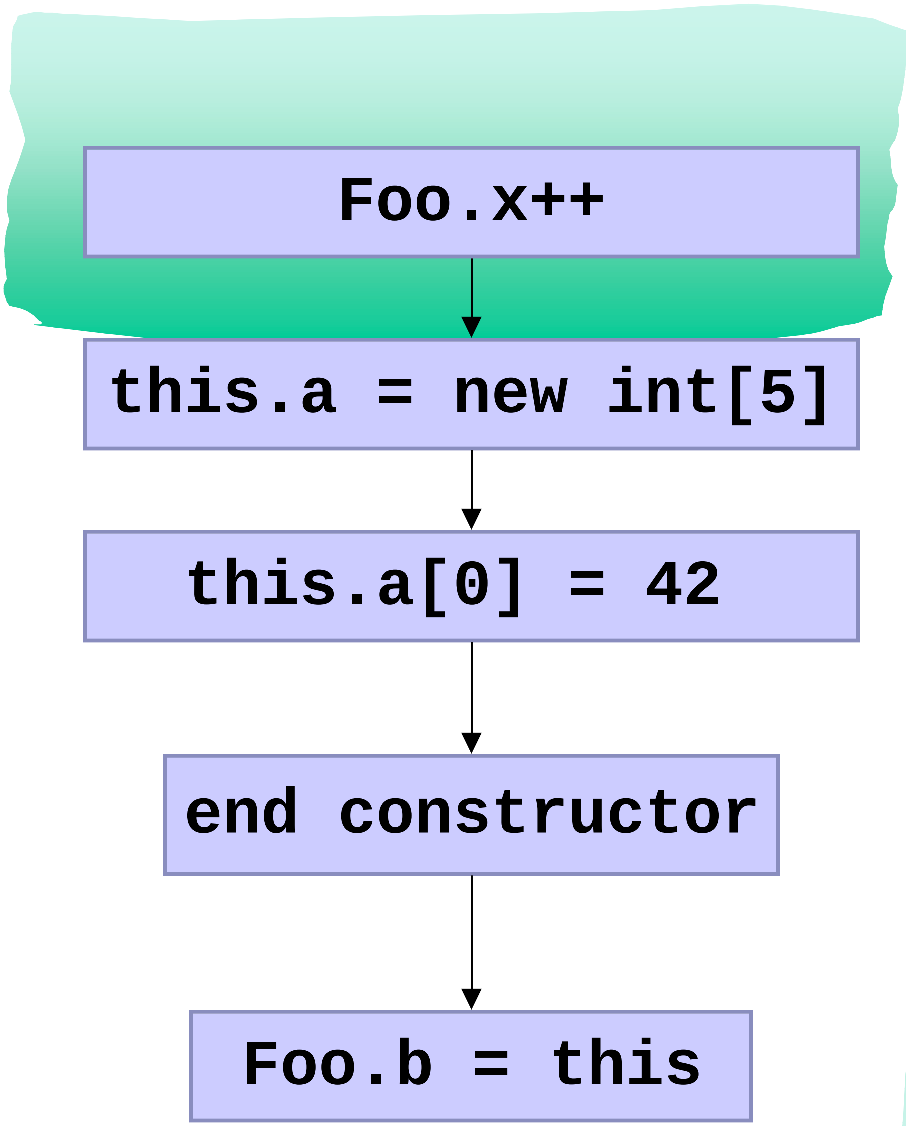


All actions done before completion of constructor

must be visible to any action that is data dependent on the read of a final field set in that constructor

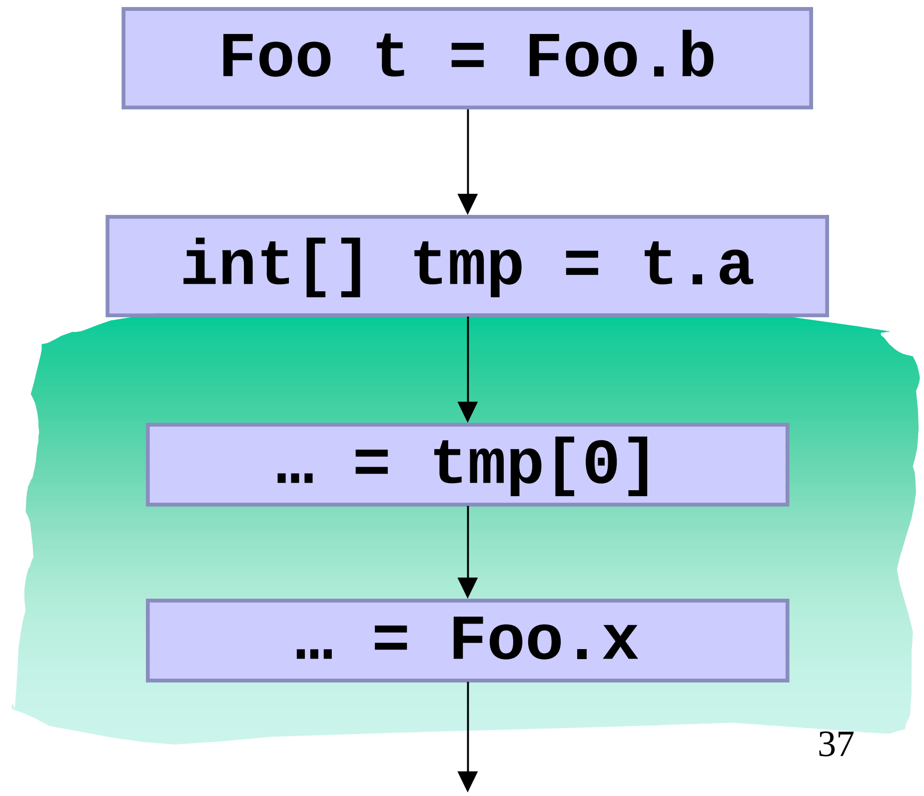


Contrast with volatile

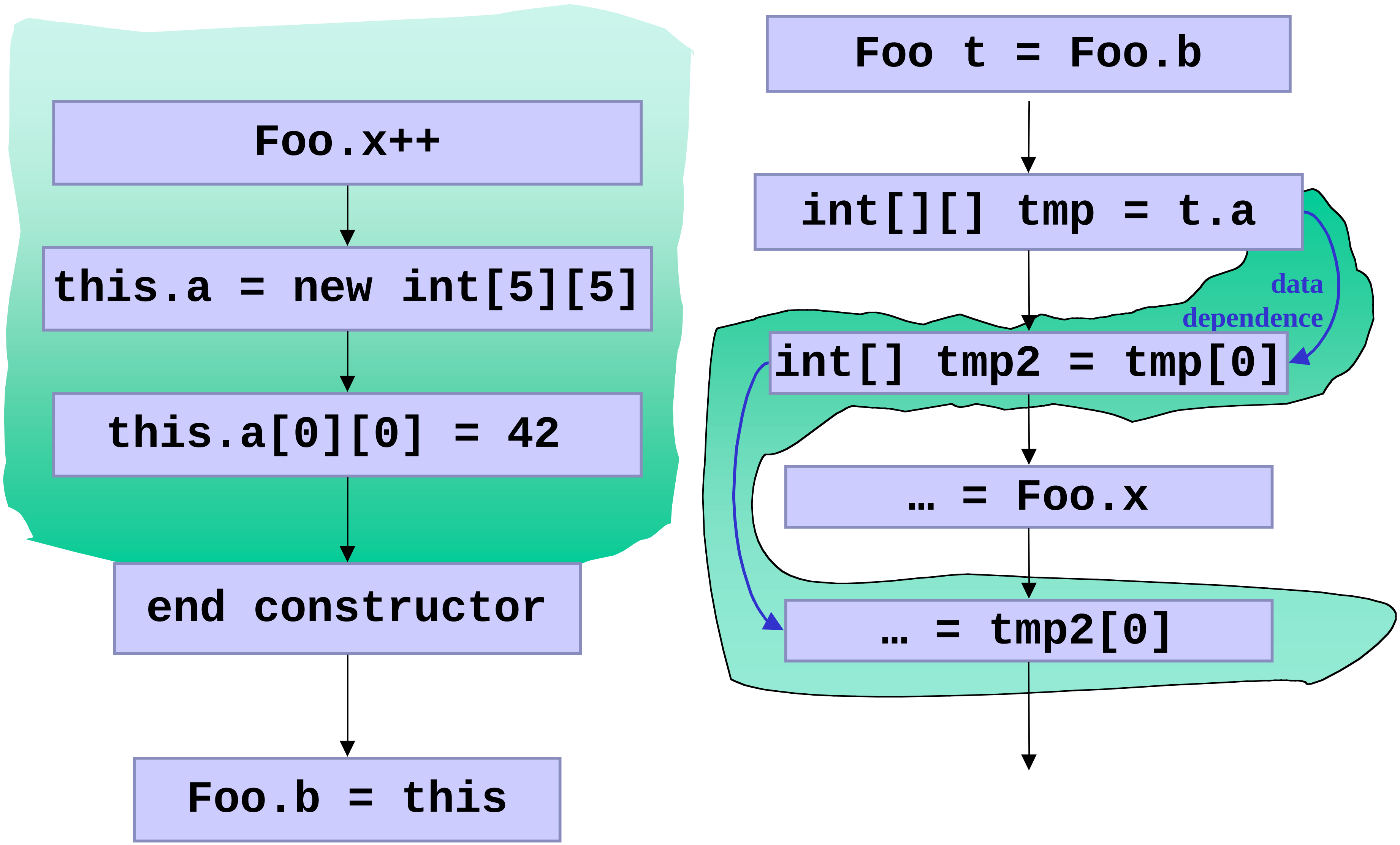


Actions done before assignment to volatile field

must be visible to any action after the read



Data dependence is transitive



Thread Communication

- All forms of inter-thread communication force writes to be visible
  - interrupt
  - start/join
  - isAlive
- Sleep and yield have no effect on visibility
  - will cause problems for broken programs
  - but difficult/impossible to specify semantics of visibility for sleep

finalization

- Loosing the last reference to an object is an asynchronous signal to another thread to run the finalizer
  - which writes, done before loosing the last ref
  - are visible to the finalizer?
- Proposal: only writes to the object being finalized
  - need synchronization to see other writes
- Unsynchronized finalizers are dubious