The Java Memory Model

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Outline

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Overview

- ▶ Java memory model—revised as part of Java 5.0 (JSR-133).
- ▶ Guarantees sequential consistency for data-race free programs
- ▶ Requires that the behavior of incorrectly synchronized programs be bounded by a well-defined notion of causality.

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Motivations

- ▶ Original Java Memory Model (JMM) not well specified and difficult to understand. Semantics of final fields and volatile unclear.

- ▶ Maintain safety and security guarantees in the face of incorrectly or incompletely synchronized programs.

- ▶ Balance flexibility for code transformations and optimizations with lucidity for programmers writing concurrent code.

Definitions

Memory Model

- ▶ Correspondence between each load instruction and the store instruction that supplies the value retrieved by the load.
- ▶ Interesting mainly for multi-threaded programs. Reorderings in single-threaded programs maintain "as if sequential" semantics.
- ▶ Partially determines legal JVM and compiler implementations.

Incorrectly Synchronized (Data Race)

- ▶ Thread A writes to a variable.
- ▶ Thread B reads that same variable.
- ▶ The write and read are not ordered by synchronization.

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Definitions Cotd.

Happens-Before Order

- ▶ Transitive closure of program order and synchronizes-with order.

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Synchronization

Atomicity

▶ Locking to obtain mutual exclusion.

Visibility

▶ Ensuring that changes to object fields made in one thread are seen in other threads.

Ordering

▶ Ensuring that you aren't surprised by the order in which statements are executed.

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Problems Addressed

Several serious problems existed in the old memory model.

- ▶ Difficult to understand ⇒ widely violated.
- ▶ Did not allow reorderings that took place in every JVM.
- ▶ Final fields could appear to change value without synchronization (default value → final value).
- ▶ Allowed volatile writes to be reordered with nonvolatile reads and writes which was counter-intuitive for most developers.

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Volatile Example

```
class VolatileExample {
  int x = 0;
  volatile boolean v = false;
  public void writer() {
    x = 42;
    v = true;
  }

  public void reader() {
    if (v == true) {
      //uses x - now guaranteed to see 42.
    }
  }
}
```

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Double-Checked Locking

```
// double-checked-locking - don't do this!

private static Something instance = null;

public Something getInstance() {
  if (instance == null) {
    synchronized (this) {
      if (instance == null)
        instance = new Something();
    }
  }
  return instance;
}
```

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Double-Checked Locking Cont'd

Looks clever, but doesn't work!

▶ Writes that initialize the Something object and the write to the instance field can be done or perceived out of order

▶ Thread could see non-null reference to instance but default values for fields of the Something object.

Make instance volatile

▶ Brief synchronization not very expensive anymore.

▶ Stronger volatile semantics increases cost of volatile almost to cost of synchronization.

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Out of Thin Air
Causality
Well-Behaved Executions
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Java Memory Model

Essentially provides two things:

- ▶ For data-race-free programs, guarantees sequential consistency.
- ▶ Requires the behavior of incorrectly synchronized programs be bounded by a well defined notion of causality.

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Sequential Consistency

Each thread(CPU) executes instructions in order.

Each thread(CPU) sees **all** operations in **some** total order.

$$
\begin{array}{c}
\text{Initially, x == y == 0} \\
\begin{array}{c|c}
\text{Thread 1} & \text{Thread 2} \\
\hline
1: \text{r2} = \text{x}; & 3: \text{r1} = \text{y} \\
2: \text{y} = 1; & 4: \text{x} = 2
\end{array}
\end{array}
$$

r2 == 2, r1 == 1 violates sequential consistency.

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Out-of-Thin-Air Guarantees

Initially, x == y == 0

Thread 1	Thread 2
r1 = x;	r2 = y;
y = r1;	x = r2;

Incorrectly synchronized, but we want
to disallow r1 == r2 == 42.

An Out Of Thin Air Result

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Write Speculation

Previous strategy of leaving semantics for incorrectly synchronized programs unspecified inconsistent with Java's security and safety guarantees.

Thread 1 could speculatively write 42 to y, creating a logical chain that is self-justifying.

Security violation - create a reference "out-of-thin-ar" to an object that should not be accessible.

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Causality

Need to incorporate causality into memory model to avoid circular reasoning.

Notion of "cause" tricky—cannot employ data and control dependence

Before compiler transformation

After compiler transformation

Initially, a = 0, b = 1

Initially, a = 0, b = 1

Thread 1	Thread 2
1: r1 = a;	5: r3 = b;
2: r2 = a;	6: a = r3;
3: if (r1 == r2)	
4: b = 2;	

Is r1 == r2 == r3 == 2 possible?

Thread 1	Thread 2
4: b = 2;	5: r3 = b;
1: r1 = a;	6: a = r3;
2: r2 = r1;	
3: if (true) ;	

r1 == r2 == r3 == 2 is sequentially consistent

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Iterative Justification

Model builds a justified execution iteratively

▶ Using a sequentially consistent execution is too relaxed in some subtle cases.

▶ Well-behaved execution—a read that is not yet committed must return the value of a write that is ordered before it by happens-before.

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Well-Behaved Executions

Given a well-behaved execution:

▶ may commit any uncommitted writes that occur in it

▶ may commit any uncommitted reads that occur but require
that the read return the value of a previously committed write
in both the justifying execution and the execution being
justified.

Occurrence of a committed action and its value does not depend
on an uncommitted data race.

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Optimizations

Formally prove legality of various reorderings and transformations:

▶ Synchronization on thread local objects can be removed

▶ Redundant nested synchronization can be removed

▶ Volatile fields of thread local objects can be treated as normal fields

Also prove if an execution of a correctly synchronized program is legal under the Java memory model, it is sequentially consistent.

Conclusion

Java Memory Model:

▶ Addressed problems with previous model

▶ Guarantees sequential consistency for correctly synchronized programs

▶ Bounds behavior of incorrectly synchronized programs by a well-defined notion of causality