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# Correct and Efficient Synchronization of Java <sup>TM</sup> Technology- based Threads

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# **Correct and Efficient Synchronization of Java™ Technology- based Threads**

**Doug Lea and William Pugh**

<http://gee.cs.oswego.edu>

<http://www.cs.umd.edu/~pugh>

# Audience

- Assume you are familiar with basics of Java™ technology-based threads (“Java threads”)
  - Creating, starting and joining threads
  - Synchronization
  - `wait` and `notifyAll`
- Will talk about things that surprised a lot of experts
  - Including us, James Gosling, Guy Steele, ... (others discovered many of these)



# 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
  - Has subtle implications
    - That forbid standard compiler optimizations
  - All existing JVMs violate the specification
    - Some parts should be violated



# Safety Issues in Multithreaded Systems

- Many intuitive assumptions do not hold
- Some widely used idioms are not safe
  - Double-check idiom
  - Checking non-volatile flag for thread termination
- Can't use testing to check for errors
  - Some anomalies will occur only on some platforms
    - e.g., multiprocessors



# 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



# What To Do Today?

- Guidelines we will provide should work under both existing and future thread specs
- Don't try to read the official specs
- Avoid corner cases of the thread spec
  - Not needed for efficient and reliable programs



# Three Aspects of 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



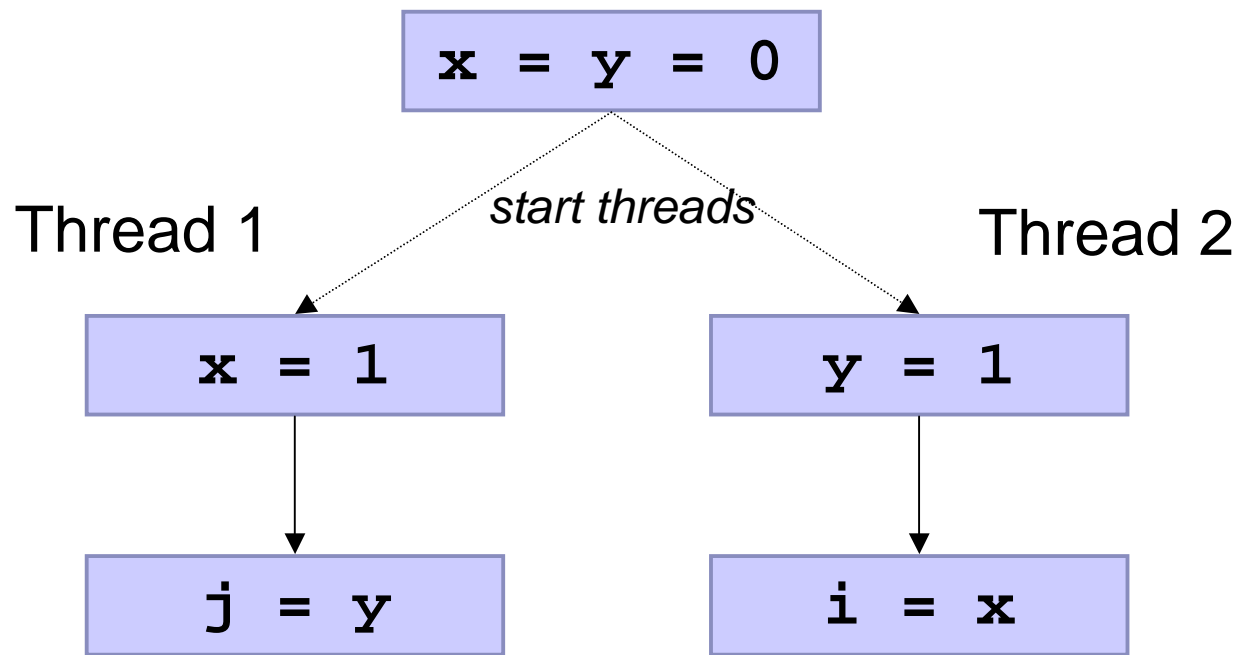


# Don't Be Too Clever

- People worry about the cost of synchronization
  - Try to devise schemes to communicate between threads
    - Without using synchronization
- Very difficult to do correctly
  - Inter-thread communication without synchronization is not intuitive

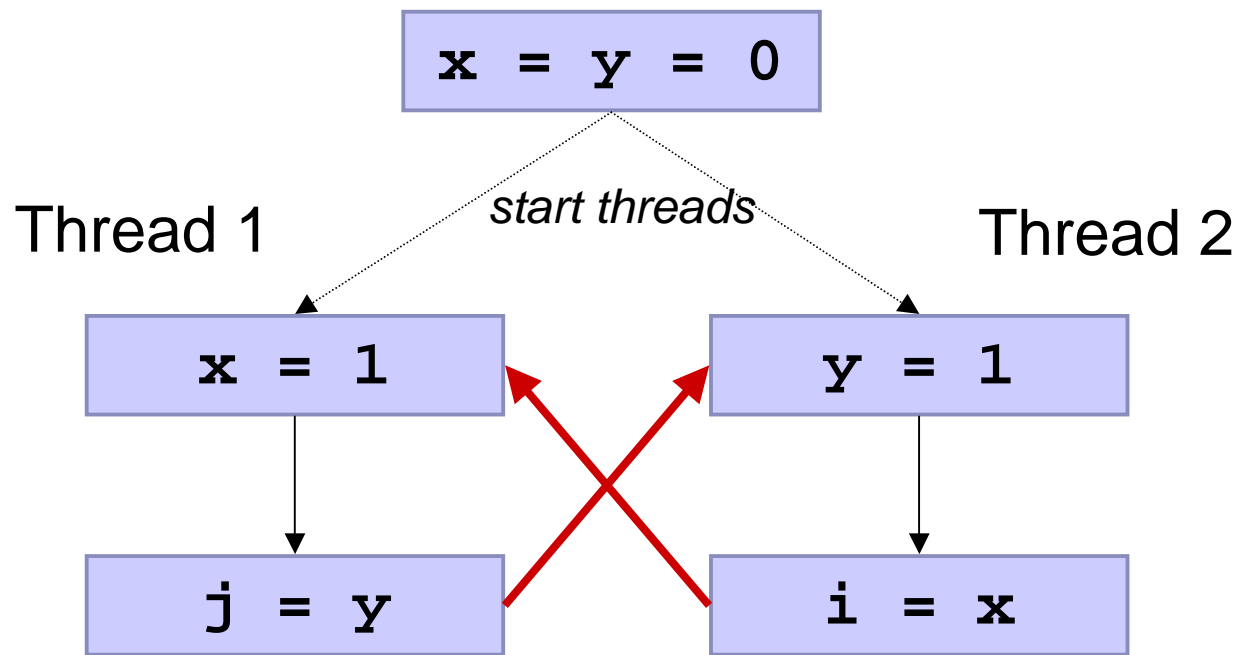


# Quiz Time



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

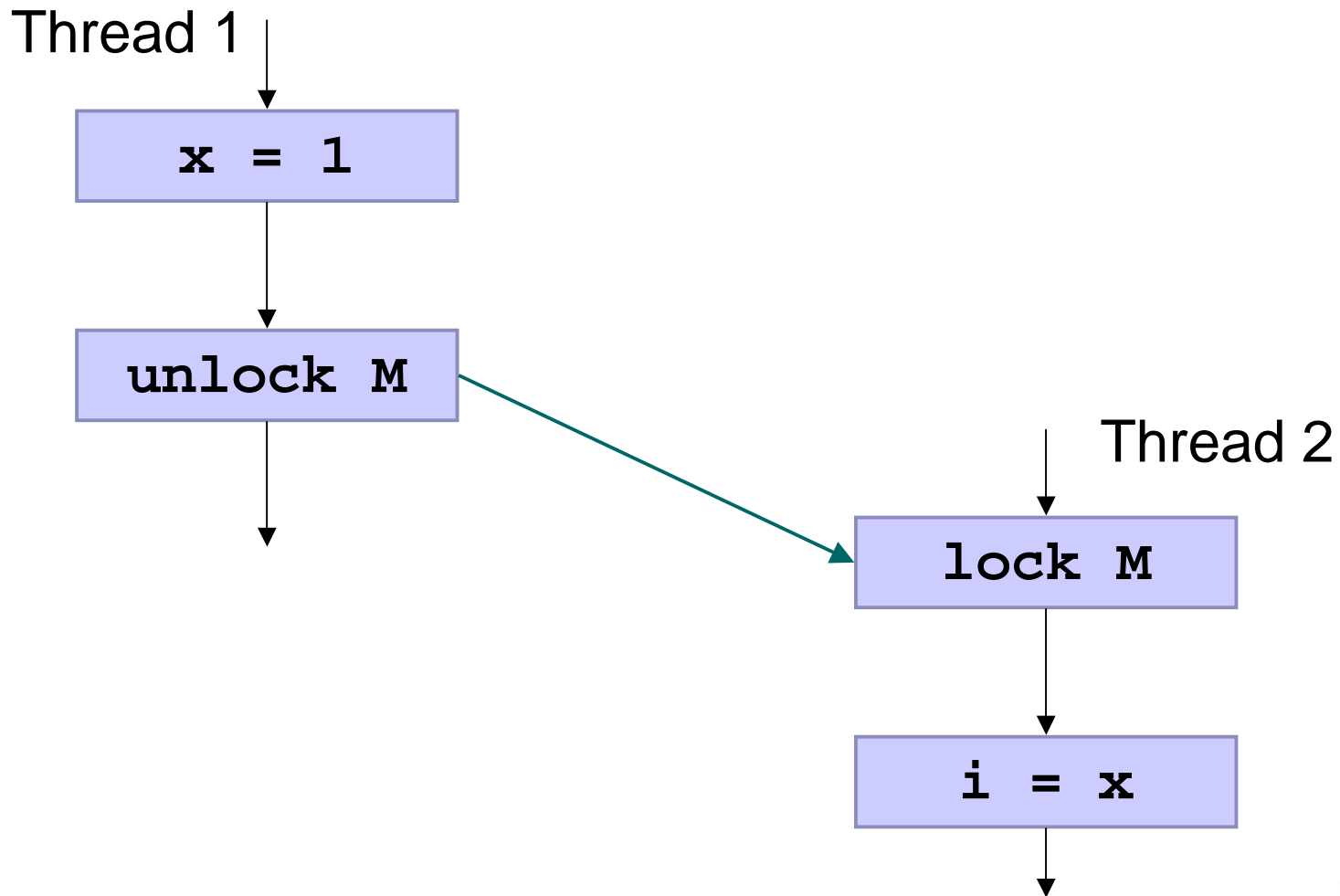


# Synchronization Actions (*approximately*)

```
// block until obtain lock
synchronized(anObject) {
    // get main memory value of field1 and field2
    int x = anObject.field1;
    int y = anObject.field2;
    anObject.field3 = x+y;
    // commit value of field3 to main memory
}
// release lock
moreCode();
```



# When Are Actions Visible to Other Threads?



# What Does Volatile Mean?

- C/C++ spec
  - *There is no implementation independent meaning of volatile*
- Situation a little better with Java technology
  - Volatile reads/writes guaranteed to go directly to main memory
    - Can't be cached in registers or local memory



# Using Volatile

- Volatile used to guarantee visibility of writes
  - `stop` *must* be declared volatile
  - Otherwise, compiler could keep in register

```
class Animator implements Runnable {  
    private volatile boolean stop = false;  
    public void stop() { stop = true; }  
    public void run() {  
        while (!stop)  
            oneStep();  
    }  
    private void oneStep() { /*...*/ }  
}
```





# Using Volatile to Guard Other Fields Doesn't Work

- Do not use - Does not work

```
class Future {  
    private volatile boolean ready = false;  
    private Object data = null;  
    public Object get() {  
        if (!ready) return null;  
        return data;  
    }  
    // only one thread may ever call put  
    public void put(Object o) {  
        data = o;  
        ready = true;  
    }  
}
```



# Nobody Implements Volatile Correctly

- Existing JVM requires sequential consistency for volatile variables
  - In quiz example, if x and y are volatile
  - Should be impossible to see  $i = 0$  and  $j = 0$
  - Haven't found any JVMs that enforce it
- Reads/writes of volatile longs/doubles
  - Guaranteed to be atomic (see old or new value, not a mixture)
- Some JVMs ignore volatile flag



# Volatile Compliance

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

# Why Use Volatile?

- Since the semantics are implemented inconsistently
- Future-proof your code
  - Prohibit optimizations compilers might do in the future
- Works well for flags
  - More complicated uses are tricky
- Revising the thread spec...
  - Test compliance
  - Strengthen to make easier to use

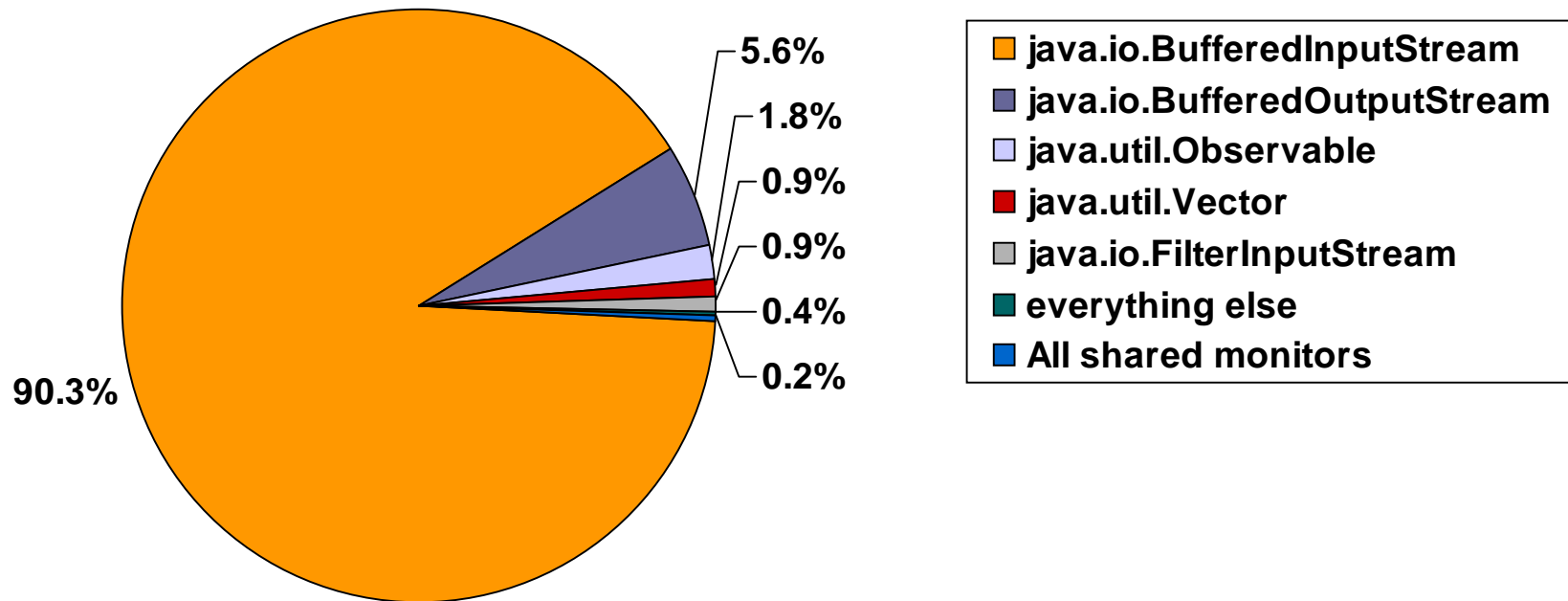


# Cost of Synchronization

- Few good public multithreaded benchmarks
  - See us if you want to help
- Volano Benchmark
  - Most widely used server benchmark
  - Multithreaded chat room server
  - Client performs 4.8M synchronizations
    - 8K useful (0.2%)
  - Server 43M synchronizations
    - 1.7M useful (4%)



# Synchronization in VolanoMark Client



*7,684 synchronizations on shared monitors*  
*4,828,130 thread local synchronizations*

# Cost of Synchronization in VolanoMark

- Removed synchronization of
  - `java.io.BufferedInputStream`
  - `java.io.BufferedOutputStream`
- Performance (2 processor Ultra 60)
  - Larger is better
  - HotSpot (1.3 beta)
    - Original: 4788
    - Altered: 4923 (+3%)
  - Exact VM (1.2.2)
    - Original: 6649
    - Altered: 6874 (+3%)



# Most Synchronization is on Thread Local Objects

- Synchronization on thread local object
  - Is useless
  - Current spec says it isn't quite a no-op
    - But very hard to use usefully
  - Revised spec will likely make it a no-op
- Largely arises from using synchronized classes
  - In places where not required





# Synchronize When Needed

- Places where threads interact
  - Need synchronization
  - Need careful thought
  - Need documentation
  - Cost of required synchronization not significant
    - For most applications
    - No need to get tricky
- Elsewhere, using a synchronized class can be expensive



# Synchronized Classes

- Some classes are synchronized
  - Vector, Hashtable, Stack
  - Most Input/Output Streams
- Contrast with 1.2 Collection classes
  - By default, not synchronized
  - Can request synchronized version
- Using synchronized classes
  - Often doesn't suffice for concurrent interaction



# Synchronized Collections Aren't Always Enough

- Transactions (DO NOT USE)

```
ID getID(String name) {  
    ID x = (ID) h.get(name);  
    if (x == null) {  
        x = new ID();  
        h.put(name, x);  
    }  
    return x; }
```

- Iterators
  - Can't modify collection while another thread is iterating through it



# Concurrent Interactions

- Often need entire transactions to be atomic
  - Reading and updating a Map
  - Writing a record to an OutputStream
- OutputStreams are synchronized
  - Can have multiple threads trying to write to the same OutputStream
  - Output from each thread is nondeterministically interleaved
  - Essentially useless

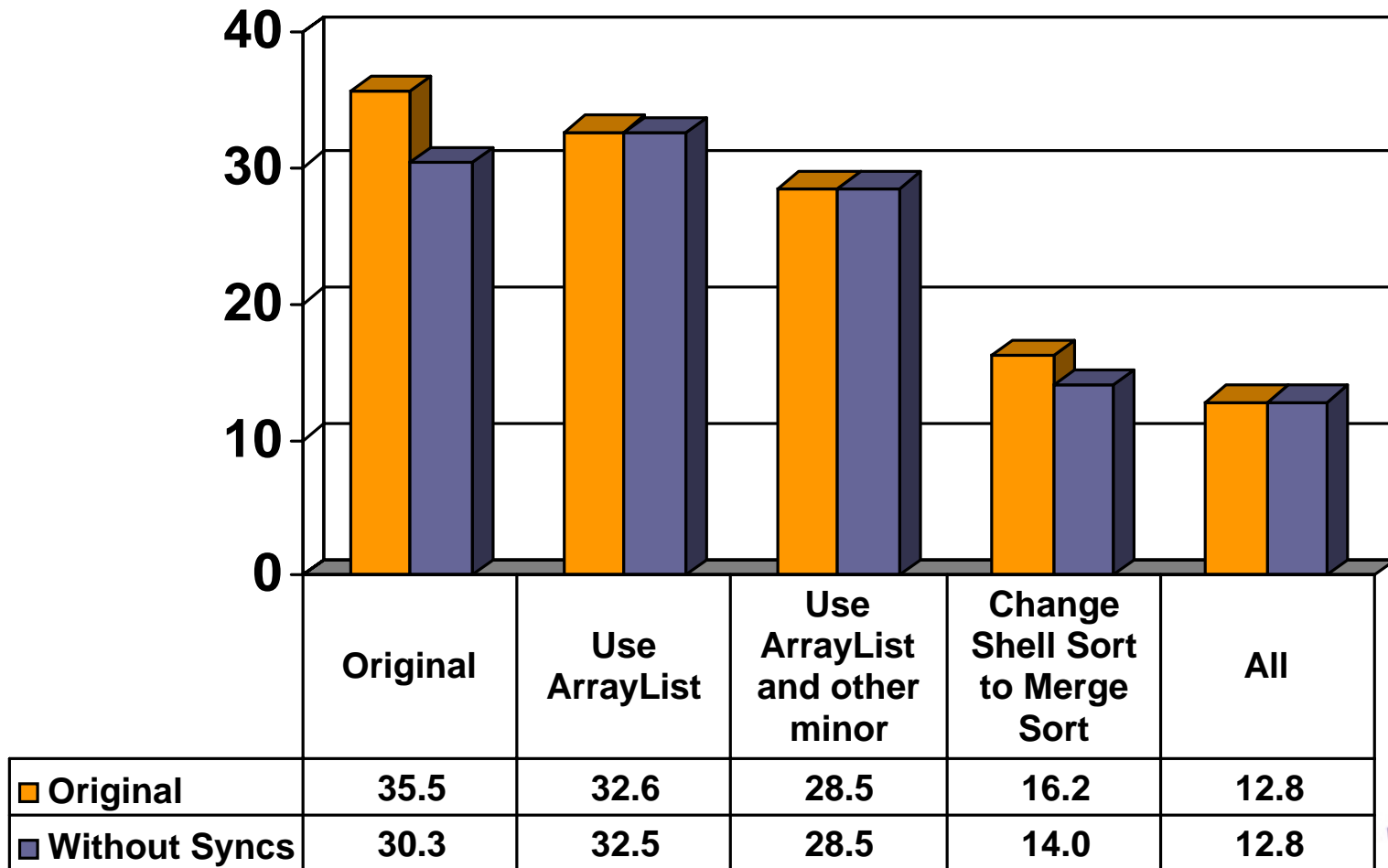


# Cost of Synchronization in SpecJVM DB Benchmark

- Program in the Spec JVM benchmark
- Does lots of synchronization
  - > 53,000,000 syncs
    - 99.9% comes from use of Vector
  - Benchmark is single threaded, all of it is useless
- Tried
  - Remove synchronizations
  - Switching to ArrayList
  - Improving the algorithm



# Execution Time of Spec JVM \_209\_db, Hotspot Server



# Lessons

- Synchronization cost can be substantial
  - 10-20% for DB benchmark
  - Consider replacing all uses of Vector, Hashtable and Stack
- Use profiling
- Use better algorithms!
  - Cost of stupidity higher than cost of synchronization
  - Used built-in merge sort rather than hand-coded shell sort



# Designing Fast Code

- Make it right before you make it fast
- Avoid synchronization
  - Avoid sharing across threads
  - Don't lock already-protected objects
  - Use immutable fields and objects
  - Use volatile
- Avoid contention
  - Reduce lock scopes
  - Reduce lock durations





# Isolation in Java™ Foundation Classes (JFC)/Swing

- JFC/Swing relies entirely on ***Isolation***
  - AWT thread owns all Swing components
    - No other thread may access them
  - Eliminates need for locking
    - Still need care during initialization
    - Can be fragile
      - Every programmer must obey rules
  - Rules are usually easy to follow
  - Most Swing components accessed in handlers triggered within AWT thread



# Accessing Isolated Objects

- Need safe inter-thread communication
  - Swing uses via runnable Event objects
    - Created by some other thread
    - Serviced by AWT thread

```
SwingUtilities.invokeLater(new Runnable() {  
    public void run() {  
        statusMessage.setText("Running");  
    }  
});
```



# GetX/SetX Access Methods

- Not synchronizing access methods
  - `int thermometer.getTemperature()`  
(doesn't work for references)
- Synchronizing access methods
  - `account.getTotalBalance()`
- Omitting access methods
  - `queue` doesn't need `getSize()`



# Things That Don't Work

- Double-Check Idiom
  - Also, unsynchronized reads/writes of refs
- Non-volatile flags
- Depending on sleep for visibility



# Initialization Check - v1 - OK

Basic version:

```
class Service {  
    Parser parser = null;  
    public synchronized void command() {  
        if (parser == null)  
            parser = new Parser(...);  
        doCommand(parser.parse(...));  
    }  
    // ...  
}
```



# Initialization checks - v2 - OK

Isolate check:

```
class ServiceV2 {  
    Parser parser = null;  
    synchronized Parser getParser() {  
        if (parser == null)  
            parser = new Parser();  
        return parser;  
    }  
    public void command(...) {  
        doCommand(getParser().parse(...));  
    }  
}
```



# Single-check - DO NOT USE

Try to do it without synchronization:

```
class ServiceV3 { // DO NOT USE
    Parser parser = null;
    Parser getParser() {
        if (parser == null)
            parser = new Parser();
        return parser;
    }
}
```



# Double-check - DO NOT USE

Try to minimize likelihood of synch:

```
class ServiceV4 { // DO NOT USE
    Parser parser = null;
    Parser getParser() {
        if (parser == null)
            synchronized(this) {
                if (parser == null)
                    parser = new Parser();
            }
        return parser;
    }
}
```





# Problems with Double-check

- Can reorder
  - Initialization of Parser object
  - Store into parser field
- ...Among other reasons
  - See JMM web page for gory details
- Can go wrong on uniprocessors
  - e.g., Symantic JIT
- Using volatile doesn't help
  - Under current JMM



# Alternatives to Double-Check

- Use synchronization
- Double check OK for primitive values
  - `hashCode` caching  
(still technically a data race)
- For static singletons
  - Put in separate class
  - First use of a class forces class initialization
  - Later uses guaranteed to see class initialization
  - No explicit check needed



# Rare Heavy New Objects

- Sometimes, need singleton that is expensive to create

```
static final Font HELVETICA  
    = new FONT("Helvetica",Font.PLAIN, 24);
```

```
Font getFont() {  
    if (!chinese)  
        return HELVETICA;  
    else  
        return new ChineseFont();  
}
```



# Using Static Singletons

```
static final Font HELVETICA  
    = new Font("Helvetica",Font.PLAIN,24);
```

```
static class CFSingleton{  
    static final Font CHINESE  
        = new ChineseFont(...);  
}
```

```
Font getFont() {  
    if (!chinese)  
        return HELVETICA;  
    else  
        return CFSingleton.CHINESE;  
}
```



# Unsynchronized Reads/Writes of References

- Beware of unsynchronized getX/setX methods that return a reference
  - Same problems as double check
  - Doesn't help to synchronize **only** setX

```
private Color color;  
void setColor(int rgb) {  
    color = new Color(rgb);  
}  
Color getColor() {  
    return color;  
}
```



# Thread Termination in Sun's Demo Applets

```
Thread blinker = null;
public void start() {
    blinker = new Thread(this);
    blinker.start();
}

public void stop() {
    blinker = null;
}

public void run() {
    Thread me = Thread.currentThread();
    while (blinker == me) {
        try {Thread.currentThread().sleep(delay);}
        catch (InterruptedException e) {}
        repaint();
    }
}
```

unsynchronized access to blinker field

confusing but not wrong: sleep is a static method



# Problems

- Don't assume another thread will see your writes
  - Just because you did them
- Calling sleep doesn't guarantee you see changes made while you slept
  - Nothing to force thread that called stop to push change out of registers/cache



# Wrap-up

- Cost of synchronization operations can be significant
  - But cost of *needed* synchronization rarely is
- Thread interaction needs careful thought
  - But not too clever
- Need for synchronization...





# Wrapup - Synchronization

- Communication between threads
  - Requires both threads to synchronize
    - Or communication through volatile fields
- Synchronizing everything
  - Is rarely necessary
  - Can be expensive (3%-20% overhead)
  - May lead to deadlock
  - May not provide enough synchronization
    - e.g., transactions





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