JavaOne[SM]

Sun's 2001 Worldwide Java Developer Conference™

Taming Java™ Programming Language Threads (“Java Threads”)

Allen I. Holub
President
Holub Associates
www.holub.com *allen@holub.com*

What We'll Do Today

- Programming threads in the Java™ programming language is fraught with peril, but is mandatory in a realistic program
- This talk discusses traps and pitfalls, along with some solutions
- This talk focuses on material not covered in most books

Shameless Self Promotion

- Former CTO, NetReliance
- Learned threads doing real-time programming
- Talk based on my JavaWorld™ "Java Toolbox" column, now a book:
  - Taming Java™ Threads
    (Berkeley: APress, 2000; http://www.apress.com)
- Source code, etc., found at http://www.holub.com
- My Prejudices and Bias
  - I do not work for Sun
  - I have opinions and plan to express them.
    The appearance of impartiality is always just appearance
  - Java™ technology is the best thing since sliced bread
    (but bakery bread is better than sliced)

I'm Assuming That…

- I'm assuming you know:
  - The language, including inner classes
  - How to create threads using Thread and Runnable
  - synchronized, wait(), notify()
  - The methods of the Thread class
- You may still get something out of the talk if you don't have the background, but you'll have to stretch

We'll Look At

- Thread creation/destruction problems
- Platform-dependence issues
- Synchronization & Semaphores (**`synchronized`**, **`wait`**, **`notify`**, etc.)
- Memory Barriers and SMP problems
- Lots of other traps and pitfalls
- A catalog of class-based solutions
- An OO-based architectural solution

Books, Etc.

Allen Holub *Taming Java™ Threads*

- Berkeley, APress, 2000

Doug Lea *Concurrent Programming in Java™: Design Principles and Patterns*, 2nd Edition

- Reading: Addison Wesley, 2000

Scott Oaks and Henry Wong *Java™ Threads*

- Sebastopol, Calif.: O'Reilly, 1997

Bill Lewis and Daniel J. Berg
Threads Primer: A Guide to Multithreaded Programming

- Englewood Cliffs: Prentice Hall/SunSoft Press, 1996

http://developer.java.sun.com/developer/technicalArticles/Threads/

Words to Live By

All nontrivial applications for the Java™ platform are multithreaded, whether you like it or not.

It's not okay to have an unresponsive UI.

It's not okay for a server to reject requests.

Threads vs. Processes

- A Process is an address space
- A Thread is a flow of control through that address space
  - Threads share the process's memory
  - Thread context swaps are much lower overhead than process context swaps

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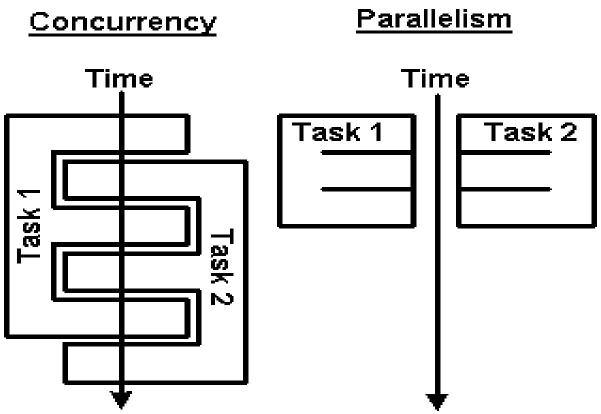
Threads vs. Processes in the Java Programming Language

- A process is a JVM™ instance
  - The Process contains the heap (everything that comes from **`new`**)
  - The heap holds all static memory
- A thread is a runtime (JVM™) state
  - The "Java Stack" (runtime stack)
  - Stored registers
  - Local variables
  - Instruction pointer
- Thread-safe code can run in a multithreaded environment
  - Must synchronize access to resources (e.g., memory) shared with other threads or be reentrant
  - Most code in books isn't thread safe

Thread Behavior Is Platform Dependent!

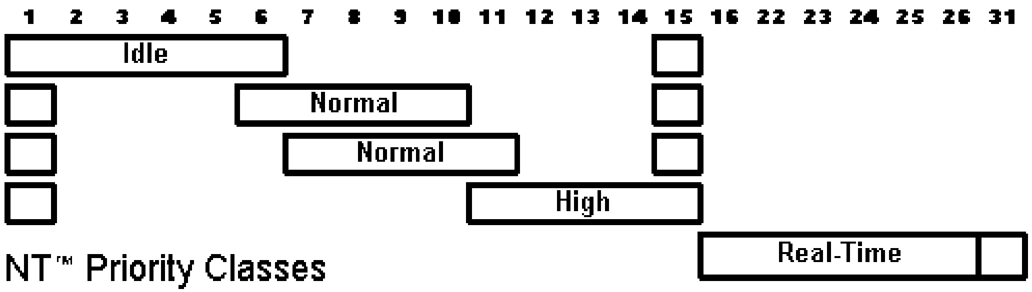
- You need to use the OS threading system to get parallelism (vs. concurrency)



- Different operating systems use different threading models (more in a moment)
- Behavior often based on timing
- Multithreaded apps can be slower than single-threaded apps (but be better organized)

Priorities

- The Java programming language has 10 levels
- The Solaris™ OS has 231 levels
- NT offers 5 (sliding) levels within 5 "priority classes"

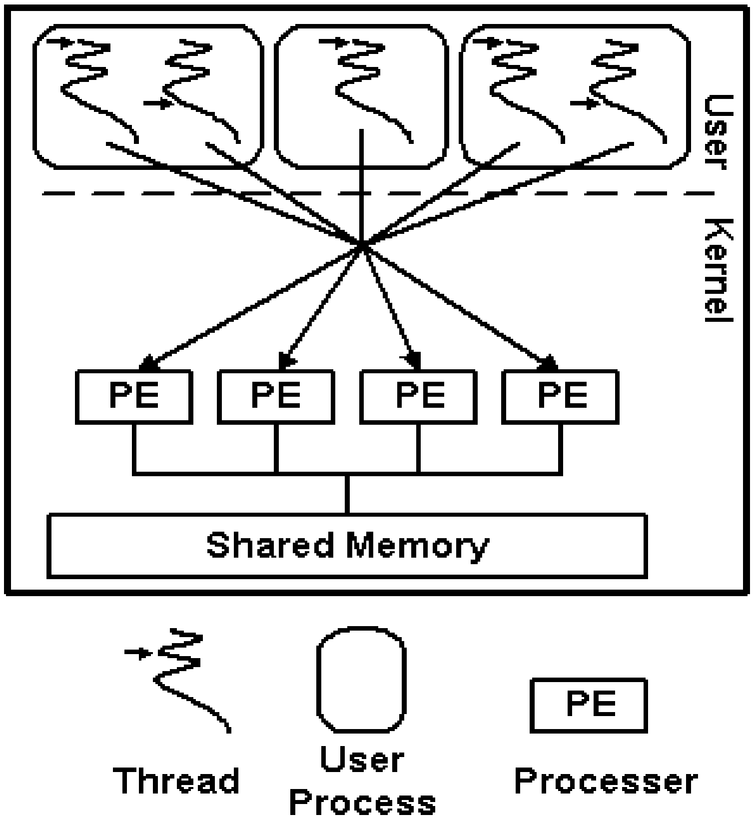


- NT priorities change by magic
  - After certain (unspecified) I/O operations priority is boosted (by an indeterminate amount) for some (unspecified) time
  - Stick to **`Thread.MAX_PRIORITY`**, **`Thread.NORM_PRIORITY`**, **`Thread.MIN_PRIORI`**

Threading Models

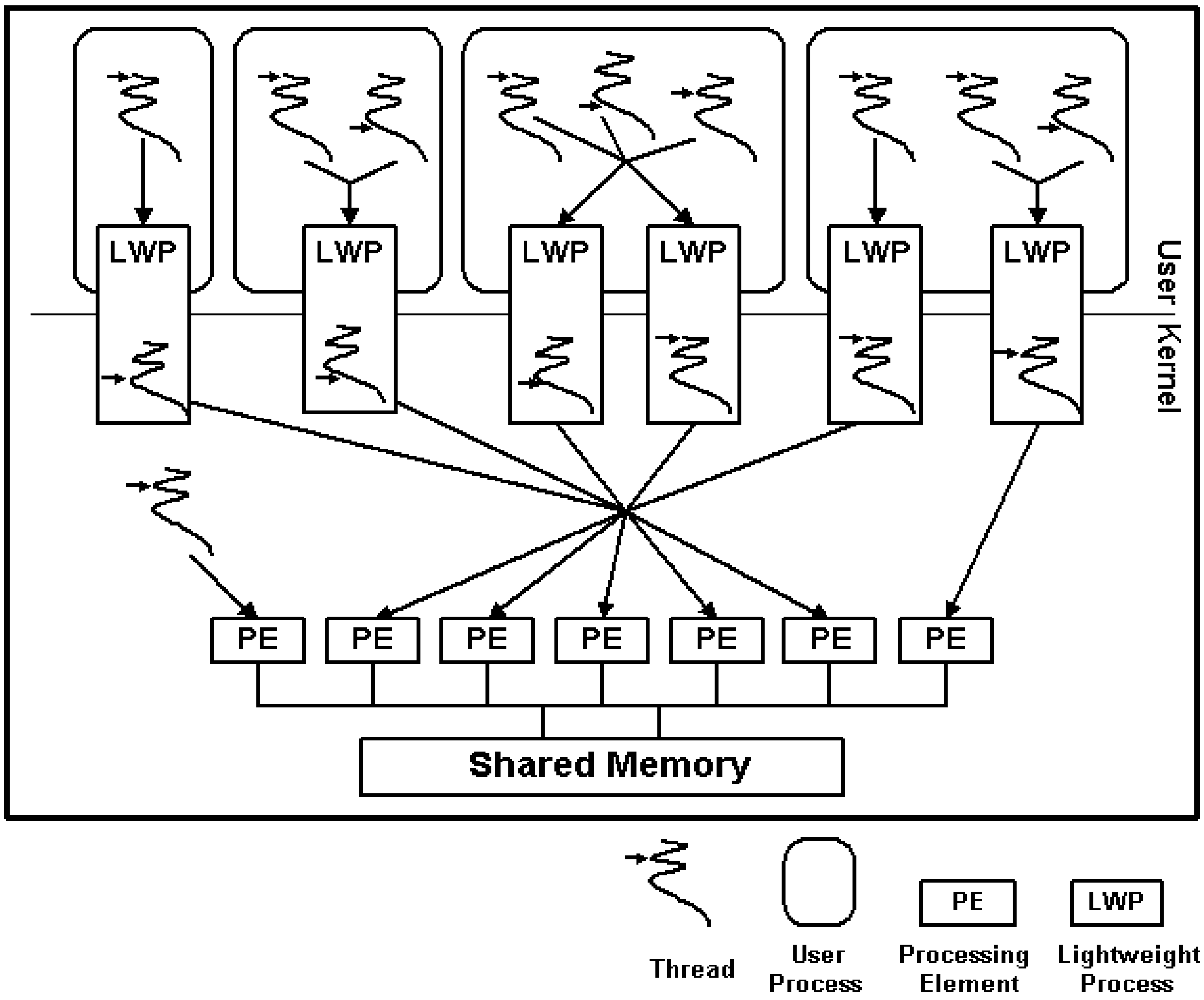
- Cooperative (Windows 3.1)
  - A Thread must voluntarily relinquish control of the CPU
  - Fast context swap, but hard to program and can't leverage multiple processors
- Preemptive (NT)
  - Control is taken away from the thread at effectively random times
  - Slower context swap, but easier to program and multiple threads can run on multiple processors
- Hybrid (Solaris OS, Posix, HPUX, Etc.)
  - Simultaneous cooperative and preemptive models are supported

NT Threading Model



(Win32 “fibers” are so poorly documented, and so buggy, they are not a real option)

Solaris™ OS Threading Model



Do Not Assume a Particular Environment

- Assume both of these rules, all the time:
  1. A thread can prevent other threads from running if it doesn't occasionally yield
     - By calling yield(), performing a blocking I/O operation, etc.
  2. Thread can be preempted at any time by another thread
     - Even by one that appears to be lower priority than the current one

Thread Creation

- Java technology's Thread class isn't (a thread)
  - It's a thread controller

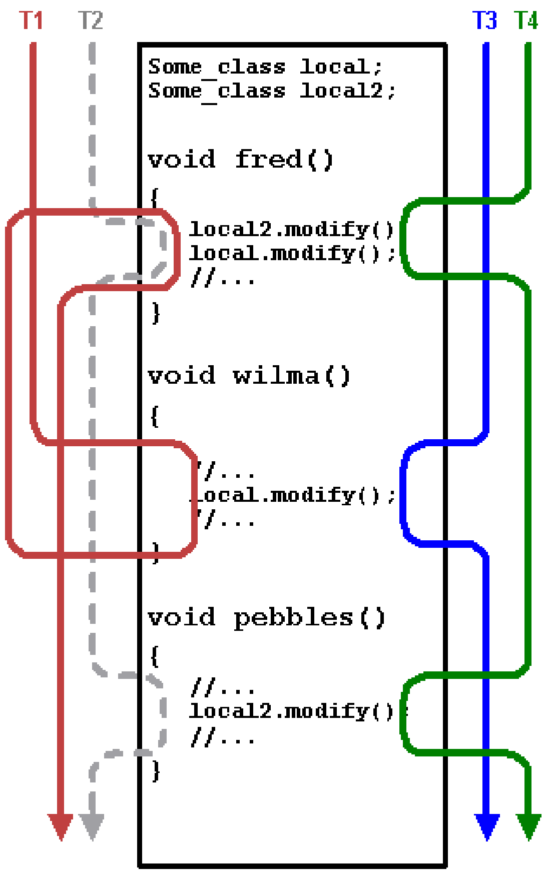
```
class Operation implements Runnable
{   public void run()
    {   // This method (and the methods it calls) are
        // the only ones that run on the thread.
    }
}

Thread thread_controller = new Thread(new Operation);
thread_controller.start();
```

Java Threads Aren't Object Oriented (1)

- Simply putting a method in a **`Thread`** derivative does not cause that method to run on the thread
  - A method runs on a thread **only** if it is called from run()(directly or indirectly)

```
class Fred extends Thread
{   public void run()
    {   // This method (and the methods it calls) are
        // the only ones that run on the thread.
    }
    public foo()
    {   // This method will not run on the thread since
        // it isn't called by run()
    }
}
```

Java Threads Aren't Object Oriented (2)



- Objects do not run on threads, methods do
- Several threads can send messages to the same object simultaneously
  - They execute the same code with the same this reference, so share the object's state

Basic Concepts: Atomic Operations (Atomicity)

- Atomic operations can't be interrupted (divided)
- Assignment to double or long is not atomic

```
long x;
```

thread 1:

```
        x = 0x0123456789abcdef
```

thread 2:

```
        x = 0;
```

possible results:

```
        0x0123456789abcdef;
        0x0123456700000000;
        0x0000000089abcdef;
        0x0000000000000000;
```

64-bit assignment is effectively implemented as:

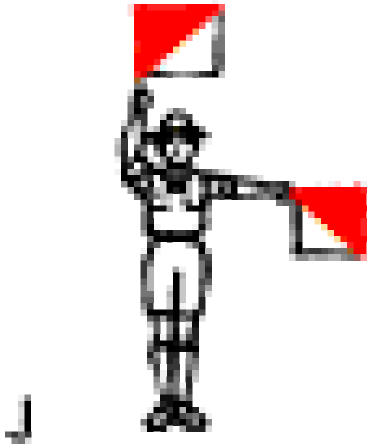
x.high = 0x01234567
x.low = 0x89abcdef;

You can be preempted between the assignment operations.

Basic Concepts: Synchronization

- Mechanisms to assure that multiple threads:
  - Start execution at the same time and run concurrently ("condition variables" or "events")
  - Do not run simultaneously when accessing the same object ("monitors")
  - Do not run simultaneously when accessing the same code ("critical sections")
- The `synchronized` keyword is essential in implementing synchronization, but is poorly designed
  - E.g., No timeout, so deadlock detection is impossible

Basic Concepts: Semaphores



- A semaphore is any object that two threads can use to synchronize with one another
  – Don't be confused by Microsoft documentation that (incorrectly) applies the word "semaphore" only to a Dijkstra counting semaphore
- Resist the temptation to use a Java native interface (JNI) call to access the underlying OS synchronization mechanisms

The Mutex (Mutual-exclusion Semaphore)

- The mutex is the key to a lock
  - Though it is sometimes called a “lock”
- Ownership is the critical concept
  - To cross a **`synchronized`** statement, a thread must have the key, otherwise it blocks (is suspended)
  - Only one thread can have the key (own the mutex) at a time
- Every Object contains an internal mutex

```
Object mutex = new Object();
synchronized( mutex )
{   // guarded code is here.
}
```

  - Array are also objects, as is the **`Class`** object

Monitors and Airplane Bathrooms

- A monitor is a body of code (not necessarily contiguous), access to which is guarded by a single mutex
  - Every object has its own monitor (and its own mutex)
- Think "airplane bathroom"
  - Only one person (thread) can be in it at a time (we hope)
  - Locking the door acquires the associated mutex— You can't leave without unlocking the door
  - Other people must line up outside the door if somebody's in there
  - Acquisition is not necessarily FIFO order

Synchronization With Individual Locks

- Enter the monitor by passing over the synchronized keyword
- Entering the monitor does not restrict access to objects used inside the monitor—it just prevents other threads from entering the monitor

```
long field;
Object lock = new Object();

synchronized(lock)
{   field = new_value
}
```

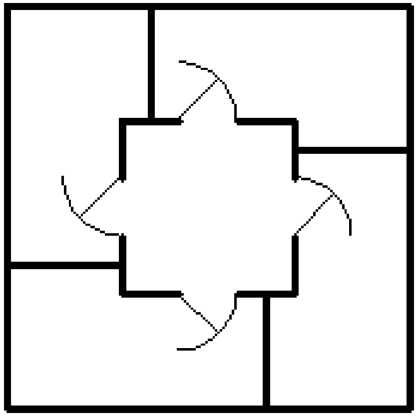
Method-level Synchronization

```
class Queue
{   public synchronized void enqueue(Object o)
    { /*…*/ }
    public synchronized Object dequeue()
    { /*…*/ }
}
```

- The monitor is associated with the object, not the code
  - Two threads can happily access the same synchronized code at the same time, provided that different objects receive the request
  - E.g., Two threads can enqueue to different queues at the same time, but they cannot simultaneously access the same queue
  - Same as **`synchronized(this)`**

He Came in the Bathroom Window

- The Bathroom can have several doors



```
class Bathroom_window
{   private double guard_this;

    public synchronized void ringo(double some_value)
    {    guard_this = some_value;
    }

    public double george()   // WRONG! Needs
    {    return guard_this;   // synchronization
    }
}
```

Constructors Can't Be `Synchronized`, So Always Have Back Doors

```
class Unpredictable
{   private final int x;
    private final int y;

    public Unpredictable(int init_x, int init_y)
    {   new Thread()
        {   public void run()
            {   System.out.println("x=" + x + " y=" + y);
            }
        }.start();

        x = init_x;
        y = init_y;
    }
}
```

- Putting the thread-creation code at the bottom doesn't help (the optimizer might move it)

Locking the Constructor's Back Door

```
class Predictable
{   private final int x;
    private final int y;

    public Predictable(int init_x, int init_y)
    {   synchronized( this )
        {   new Thread()
            {   public void run()
                {   synchronized( Predictable.this)
                    { System.out.println("x="+x+" y="+y);
                    }
                }
            }.start();

            x = init_x;
            y = init_y;
        }
    }
}
```

Synchronization Isn’t Cheap

```
class Synch
{   synchronized int locking    ( int a, int b )
                                      { return a + b;}
    int               not_locking     ( int a, int b )
                                      { return a + b;}
  static public void main(String[] arguments)
  {  double start = new Date().get Time();

      for(long i = 1000000; --i >= 0 ;)
         tester.locking(0,0);

      double end = new Date().getTime();

      double locking_time = end - start;
      // repeat for not_locking
  }
}
```

Synchronization Isn't Cheap

```
% java -verbose:gc Synch
Pass 0: Time lost: 234 ms.     121.39% increase
Pass 1: Time lost: 139 ms.     149.29% increase
Pass 2: Time lost: 156 ms.     155.52% increase
Pass 3: Time lost: 157 ms.     155.87% increase
Pass 4: Time lost: 157 ms.     155.87% increase
Pass 5: Time lost: 155 ms.     154.96% increase
Pass 6: Time lost: 156 ms.     155.52% increase
Pass 7: Time lost: 3,891 ms. 1,484.70% increase
Pass 8: Time lost: 4,407 ms. 1,668.33% increase
```

—200MHz Pentium, NT4/SP3, JDK 1.2.1, HotSpot 1.0fcs, E

- Contention in last two passes (Java Hotspot™ VM can't use atomic-bit-test-and-set)

Synchronization Isn't Cheap

But...

- The cost of stupidity is always higher than the cost of synchronization
  - Pick a fast algorithm
- Overhead can be insignificant when the synchronized method is doing a time-consuming operation
  - But in OO systems, small synchronized methods often chain to small synchronized methods

Avoiding Synchronization

- Reentrant code doesn't need to be synchronized
  - Code that uses only local variables and arguments (no **`static`** variables, no fields in the class)
- Atomic operations do not need to be synchronized, but beware of reordering
  - Assignment to all non-64-bit things, including **`boolean`**s and references are usually safe, but sequence not preserved
  - Must be declared **`volatile`**, but **`volatile`** might not work
  - Assignment to **`volatile doubles`** and **`floats`** should be atomic (but most VMs don't do it)
  - Code may be reordered, so assignment to several atomic variables must be synchronized
    - Sequence of volatile operations should be preserved,but usually isn't

Avoiding Synchronization

- Synchronize the smallest block possible to minimize the odds of contention
  - Method-level synchronization should be avoided in very-high-performance systems
- Don't synchronize the methods of classes that are called only from one thread
  - Use Collection-style synchronization decorators when you need synchronized behavior

```
Collection c = new ArrayList();
c = Collections.synchronizedCollection(c);00
```

Avoiding Synchronization

- Don't access synchronized methods from synchronized methods
  - Synchronize public methods—Don't synchronize **`private`** ones
  - Don't use **`protected`**
  - Avoid Vector and **`Hashtable`** in favor of **`Collection`** and **`Map`** derivatives
  - Don't use **`BufferedInputStream`**, **`BufferedOutputStream`**, **`BufferedReader`**, or **`BufferedWriter`** unless the stream is shared between multiple threads
    - You can use **`InputStream's read(byte[])`**
    - You can roll your own decorators

Immutable Objects

- **Synchronization not required (all access read-only)**
- **All fields of the object are final (e.g., String)**
  - *Blank* finals are **`final`** fields without initializers
  - Blank finals must be initialized in all constructors

```
class I_am_immutable
{   private final int some_field;
    public I_am_immutable( int initial_value )
    {    some_field = initial_value;
    }
}
```

  - Might not compile with inner classes (there's a long-standing compiler bug)
- Immutable ≠ constant (but it must be constant to be thread safe)
  - A **`final`** reference is constant, <u>but</u> the referenced object can change state
  - Language has no notion of "constant", so you must guarantee it by hand

Critical Sections

- A critical section is a body of code that only one thread can enter at a time
- Do not confuse a critical section with a monitor
  - The monitor is associated with an object
  - A critical section guards code
- The easiest way to create a critical section is by synchronizing on a static field

```
static final Object critical_section = new Object();
synchronized( critical_section )
{   // only one thread at a time
    // can execute this code
}
```

Critical Sections Can Also Synchronize on the Class Object

```
class Flintstone
{ public void fred()
  {  synchronized( Flintstone.class )
     {  // only one thread at a time
         // can execute this code
     }
  }

  public static synchronized void wilma()
  { // synchronizes on the same object
     // as fred().
  }
}
```

Class vs. Instance Variables

- All **`synchronized static`** methods synchronize on the same monitor
- Think class variables vs. instance variables:
  - The class (**`static`**) variables and methods are effectively members of the Class object
  - The class (**`static`**) variables store the state of the class as a whole
  - The class (**`static`**) methods handle messages sent to the class as a whole
  - The instance (**`non-static`**) variables store the state of the individual objects
  - The instance (**`non-static`**) methods handle messages sent to the individual objects

But Remember the Bathroom With Multiple Doors

```
class Foo
{   static long x = 0;
    synchronized static void set_x( long x )
    { this.x = x;
    }
    synchronized /* not static */ double get_x()
    { return x;
    }
}
```

Thread 1:

```
Foo o1 = new Foo();
long x = o1.get_x();
```

Thread 2:

```
Foo.set_x(-1);
```

Results are <u>undefined</u>. (There are two locks here, one on the class object and one on the instance.)

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Lock the Extra Doors

1. Access all **`static`** fields through **`synchronized static`** methods, even if the accessor is a method of the class that contains the field

```
class Okay
{   private static long unsafe;
    private static synchronized get()
    {return unsafe;}
    private static synchronized set(long x)
    {unsafe = x;}

    public /*not static*/ void foo(long x)
    {   //...
        set(x);
    }
}
```

Lock the Extra Doors

2. Synchronize explicitly on the class object when accessing a static field from an instance method

```
class Okay
{   private static long unsafe;
    public void foo(long x)
    {   //...
        synchronized( Okay.class )
        {   unsafe = x;
        }
    }
}
```

Lock the Extra Doors

3. Encapsulate all static fields in an inner class and provide exclusive access through synchronized methods of the inner class

```
class Okay
{   private class Class_Variables
    {   private long unsafe;
        public synchronized void do_something(long x)
        {   unsafe = x;   //. . .
        }
    }
    static Class_Variables statics =
                                  new Class_Variables();
    public foo(long x)
    {   statics.do_something( x );
    }
}
```

Singletons (One-of-a-kind Objects)

- Singletons often use critical sections for initialization

```
public final class Singleton
{   static{new JDK_11_unloading_bug_fix(Std.class);}

    private static Singleton instance;
    private Singleton(){} // prevent creation by new

    public synchronized static Singleton instance()
    {   if( instance == null )
            instance = new Singleton();
        return instance;
    }
}
Singleton s = Singleton.instance()
```

Avoiding Sychronization in a Singleton by Using Static

- A degraded case, avoids synchronization

```
public final class Singleton
{   static{ new JDK_11_unloading_bug_fix(Std.class); }
    private Singleton(){}

    private static final Singleton instance
                                         = new Singleton();

    public
    /*unsynchronized*/ static Singleton instance()
    {   return instance;
    }
}
```

Or Alternatively…

- Thread safe because VM loads only one class at a time and method can't be called until class is fully loaded and initialized
- No way to control constructor arguments at run time

```
public final class Singleton
{   private static Singleton instance;
    private Singleton(){}

    static{ instance = new Singleton(); }

    public static Singleton instance()
    {       return instance;
    }
}
```

While We're on the Subject…

```
public class JDK_11_unloading_bug_fix
{ public JDK_11_unloading_bug_fix(final Class keep)
  { if (System.getProperty("java.version")
                                .startsWith("1.1") )
    { Thread t =  new Thread()
      {  public void run()
         {  Class singleton_class = keep;
            synchronized(this)
            {  try{ wait();}
               catch(InterruptedException e){}
            }
         }
      };
      t.setDaemon(true);
      t.start();
    }
  }
}
```

In the JDK™ 1.1 release, all objects not accessible via a local-variable or argument were subject to garbage collection

Condition Variables

- All objects have a “condition variable” in addition to a mutex
  - A thread blocks on a condition variable until the condition becomes true
  - In the Java™ environment, conditions are “pulsed”—condition reverts to false immediately after waiting threads are released
- **`wait()`** and **`notify()`** use this condition variable

`wait` and `notify` Have Problems

- Implicit condition variables don't stay set!
  - A thread that comes along after the **`notify()`** has been issued blocks until the next **`notify()`**
- **`wait()`** does not tell you if it returned because of a timeout or because the wait was satisfied (hard to solve)
- There's no way to test state before waiting
- **`wait()`** releases only one monitor, not all monitors that were acquired along the way (nested monitor lockout)

wait(), notify(), and L

```
class Notifying_queue
{   private static final queue_size = 10;
    private Object[]      queue = new Object[queue_size];
    private int           head  = 0;
    private int           tail  = 0;
    public void synchronized enqueue( Object item )
    {   queue[++head %= queue_size] = item;
        this.notify();
    }
    public Object synchronized dequeue( )
    {   try
        {   while( head == tail) //<-- MUST BE A WHILE
                this.wait();      //     (NOT AN IF)
        }
        catch( InterruptedException e )
        {   return null; // wait abandoned
        }
        return queue[++tail %= queue_size ];
    }
}
```

Condition Variables—Wait Is Not Atomic (1)

T1

```
synchronized enqueue(. . .)  ....this.mutex.acquire();
{
    this.notify(); .............................. this.condition.set_true();
} .................................................. this.mutex.release();

synchronized dequeue(. . .) .... this.mutex.acquire();
{
    while( head == tail ) ................ while( head==tail )
        this.wait(); .............................. this.mutex.release();
                                                    this.condition.wait_for_true();
                                                    this.mutex.acquire();
} .................................................. this.mutex.release()
```

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Condition Variables— Wait Is Not Atomic (2)

```
                                                                    T1
                                                              T2
synchronized enqueue(. . .)  ____this.mutex.acquire();
{
    this.notify();  ..........................  this.condition.set_true();
}........................................... this.mutex.release();

synchronized dequeue(. . .) .... this.mutex.acquire();
{
    while( head == tail )  ..............  while( head==tail )
        this.wait();  ..........................  this.mutex.release();
                                               this.condition.wait_for_true();
                                               this.mutex.acquire();
}............................................ this.mutex.release()
```

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Condition Variables—Wait Is Not Atomic (3)

T1

T2

```
synchronized enqueue(. . .)  ----  this.mutex.acquire();
{
    this.notify(); --------------  this.condition.set_true();
} -------------------------------  this.mutex.release();

synchronized dequeue(. . .)  ----  this.mutex.acquire();
{
    while( head == tail ) -------  while( head==tail )
        this.wait(); ------------    this.mutex.release();
                                     this.condition.wait_for_true();
                                     this.mutex.acquire();
} -------------------------------  this.mutex.release()
```

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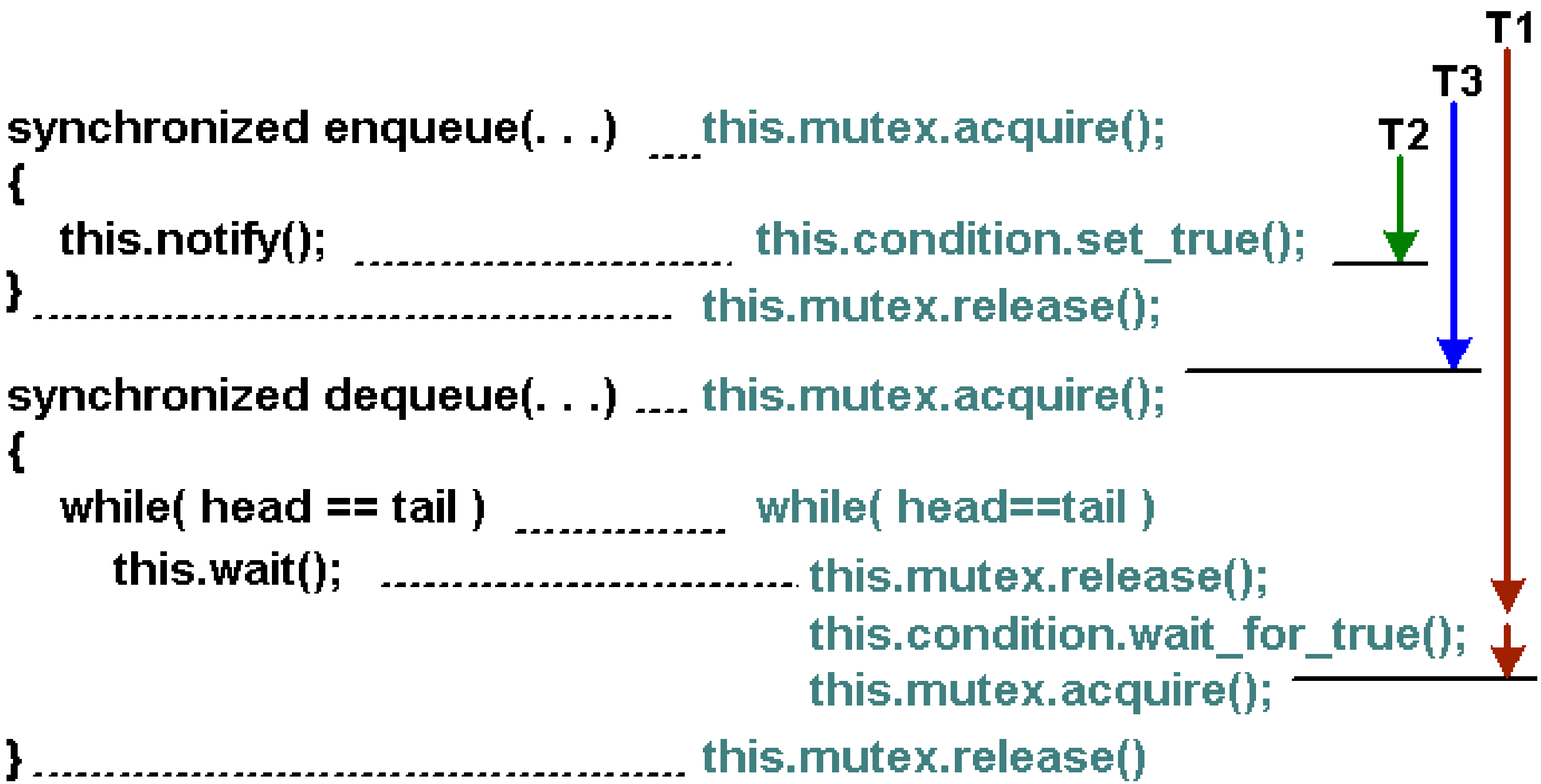
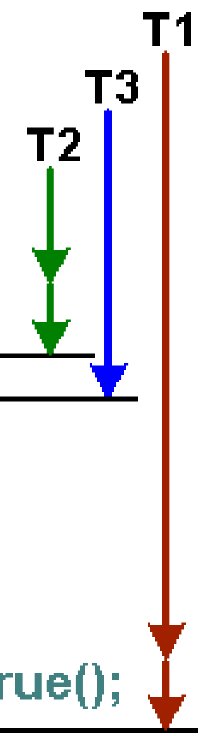
Condition Variables— Wait Is Not Atomic (4)



Condition Variables— Wait Is Not Atomic (5)

`synchronized enqueue(. . .)`	`this.mutex.acquire();`
`{`	
`    this.notify();`	`this.condition.set_true();`
`}`	`this.mutex.release();`
`synchronized dequeue(. . .)`	`this.mutex.acquire();`
`{`	
`    while( head == tail )`	`while( head==tail )`
`        this.wait();`	`this.mutex.release();`
	`this.condition.wait_for_true();`
	`this.mutex.acquire();`
`}`	`this.mutex.release()`



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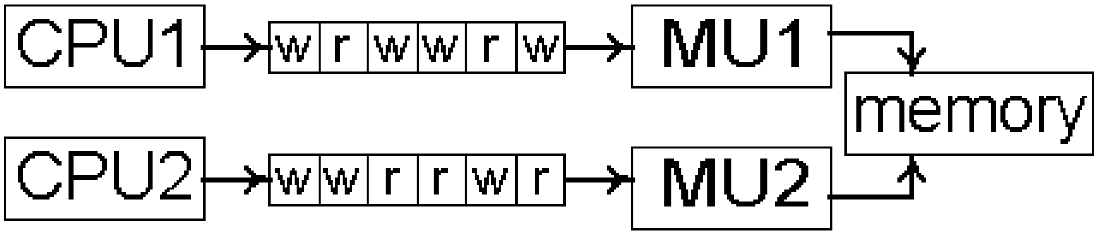
Summarizing `wait()` Behavior

- **`wait()`** doesn't return until the notifying thread gives up the lock
- A condition tested before entering a **`wait()`** may not be true after the **`wait`** is satisfied
- There is no way to distinguish a timeout from a **`notify()`**

Beware of Symmetric Multi-Processing (SMP) Environments

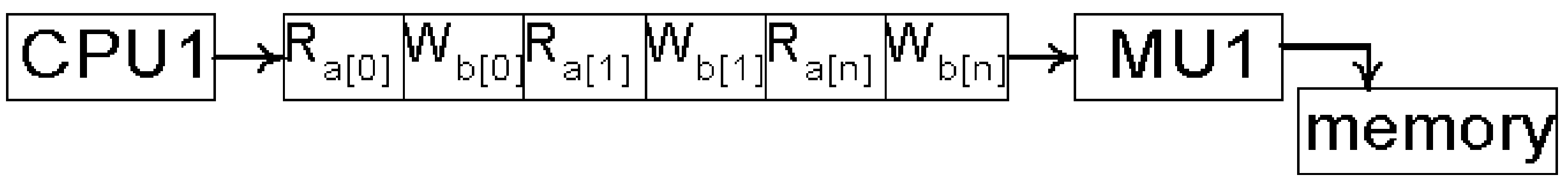
- The CPU does not access memory directly
- CPU read/write requests are given to a “memory unit,” which actually controls the movement (at the hardware level) of data between the CPU and main memory store



Some Common Memory Operations Are Inefficient

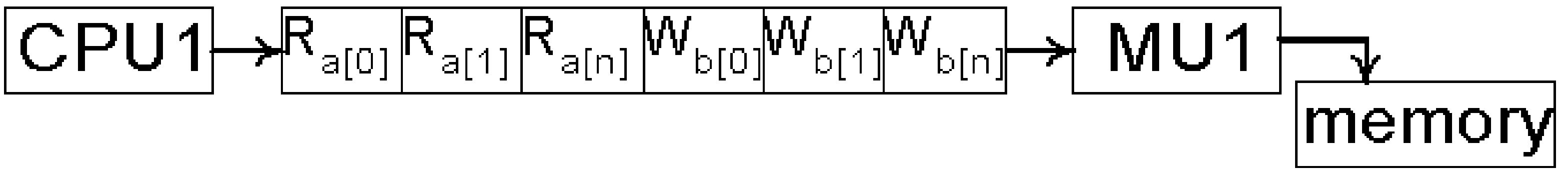
- Processors supporting a “relaxed memory model” can transfer blocks of memory between cache and the main memory store in undefined order!
- Consider:

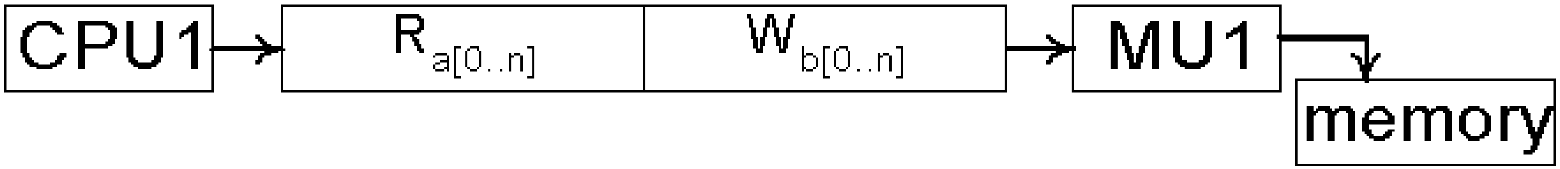
```
int a[] = new int[10];
int b[] = new int[10];
for( int i = 0; I < a.length; ++i )
   b[i] = a[i];
```



Presto Chango!

- The memory unit notices the inefficiency and rearranges the requests!



- To produce:
- 

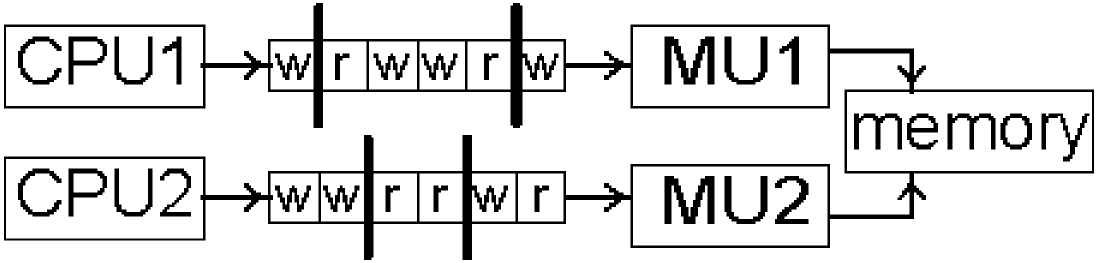
- This change is good—it speeds memory access

BUT...

- The order in which changes are made in the source code may not be preserved at run time!

Don’t Panic

- Reordering doesn’t matter in single-threaded systems
- Reordering not permitted across “memory barriers” (effectively inserted around synchronized access)



Memory Barriers Are Created Indirectly by Synchronization

- **`synchronized`** is implemented using a memory barrier
  - So modifications made within a **`synchronized`** block will not move outside that block
- **`volatile`** should force memory synchronization, but don't count on it
  - But might add access inefficiencies
  - JVM implementation of volatile is spotty—some don't implement it at all

Avoiding Synchronization (Revisited)

- You **cannot** use `volatile` fields (e.g., boolean) to guard other code

```
class I_wont_work
{   private volatile boolean okay      = false;
    private long                field     = -1;
    //. . .
    public /*not synchronized*/ void wont_work()
    {    if( okay )
         { do something( field );
         }
    }
    public /*not synchronized*/ void enable()
    {   field = 0;
        okay = true;
    }
}
```

Might be –1.

Even Worse

- Memory modifications made in the constructor may not be visible, even though the object is accessible!

```
class Surprise
{   public long field;
    //. . .
    public Surprise()
    { field = -1;
    }
}
```

Modification of `s` might become visible before modification of `field` if memory unit rearranges operations

Thread 1:

```
    Surprise s = new Surprise();
```

Thread 2:

```
    System.out.println(s.field);
```

Synchronization Can Fix Things

- This works

```
Object lock = new Object();
```

Thread 1:

```
    synchronized( lock )
    {   Surprised s = new Surprised();
    }
```

Thread 2:

```
    synchronized( lock )
    {   System.out.println(s.get_field());
    }
```

But Then Again, Maybe Not

- This might not work

```
class Might_work
{   public long field;
    //. . .
    public Might_work()
    {   synchronized(this)
        {   field = -1;
        }
    }
    public synchronized get_field()
    {   return field;
    }
}
```

Implicit assignment of zero to `field` is not inside the synchronized block. Modification of 0 to –1 may not be visible in `get_field()`.

Thread 1:

```
    Might_work m = new Might_work();
```

Thread 2:

```
    System.out.println(m.get_field());
```

Double-checked Locking Doesn't Work!

- Is **unreliable** even in single-CPU machine

```
public final class Singleton
{   static{ new JDK_11_unloading_bug_fix(Std.class); }

    private static Singleton instance;
    private Singleton(){}     // prevent creation by new

    public static Singleton instance()
    {   if( instance == null )
        {   synchronized( Singleton.class )
            {   if( instance == null )
                    instance = new Singleton();
            }
        }
        return instance;
    }
}
```

"Rules to Live By" in an SMP Environment (Gotchas)

- To assure that shared memory is visible to two threads: the writing thread must give up a lock that is subsequently acquired by the reading thread
- Modifications made while sleeping may not be visible after sleep() returns
- Operations are not necessarily executed in source-code order (not relevant if code is synchronized)
- Modifications to memory made after a thread is created, but before it is started, may not be visible to the new thread

"Rules to Live By" in an SMP Environment (Things That Work)

- Modifications made by a thread before it issues a **`notify()`** **will** be visible to the thread that's released from the associated **`wait()`**
- Modifications made by a thread that terminates **are** visible to a thread that joins the terminated thread [must call **`join()`**]
- Memory initialized in a **`static`** initializer **is** safely accessible by all threads, including the one that caused the class-file load

A Few Articles on SMP Problems

- Paul Jakubik (ObjectSpace)
  - www.primenet.com/~jakubik/mpsafe/MultiprocessorSafe.pdf
- Bill Pugh (Univ. of Maryland) mailing list
  - www.cs.umd.edu/~pugh/java/memoryModel/
- Allen Holub
  - www.javaworld.com/javaworld/jw-02-2001/jw-0209-toolbox.html
- Brian Goetz
  - www.javaworld.com/javaworld/jw-02-2001/jw-0209-double.html

Memory-Model JSR

- JSR-000113: Memory Model and Thread Specification Revision
  - http://www.javasoft.com/aboutJava/communityprocess/jsr/jsr_133.html
- But it’ll take time to implement, and may not be implemented correctly

Deadlock: The Simplest Scenario (1)

- Two or more threads, all waiting for each other
- Threads trying to acquire multiple locks, but in different order

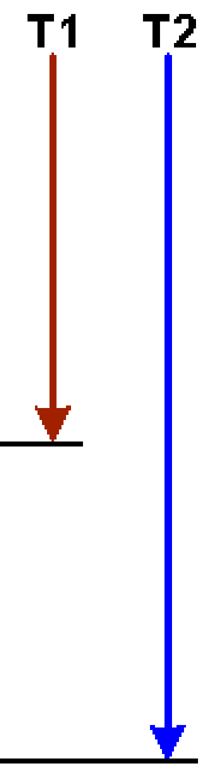
Deadlock: The Simplest Scenario (2)

```
double field1; Object lock1 = new Object();
double field2; Object lock2 = new Object();
public void pebbles()
{     synchronized(lock1){ field1 = 0; }
}
public void bambam()
{     synchronized(lock2){ field2 = 0; }
}
public void fred()
{     synchronized(lock2)
      {     synchronized(lock1)
            {     field2 += field1;
            }
      }
}
public void wilma()
{     synchronized(lock1)
      {     synchronized(lock2)
            {     field2 -= field1;
            }
      }
}
```

T1

Deadlock: The Simplest Scenario (3)

```
double field1; Object lock1 = new Object();
double field2; Object lock2 = new Object();
public void pebbles()
{     synchronized(lock1){ field1 = 0; }
}
public void bambam()
{     synchronized(lock2){ field2 = 0; }
}
public void fred()
{     synchronized(lock2)
      {     synchronized(lock1)
            {     field2 += field1;
            }
      }
}
public void wilma()
{     synchronized(lock1)
      {     synchronized(lock2)
            {     field2 -= field1;
            }
      }
}
```



Deadlock: A More-Realistic Scenario

```
class Boss
{   private Sidekick robin;
    synchronized
    void set_side_kick(Sidekick kid)
    {   robin = kid;   };
    synchronized void to_the_bat_cave()
    {   robin.lets_go();   }
    synchronized void report(String s)
    {/*...*/}
}
class Sidekick
{   private Boss batman;
    Sidekick(Boss boss)
    {   batman = boss; }
    synchronized void lets_go()
    {   batman.report( "yeah boss" );}
    synchronized void sock_bam()
    {   batman.report("Ouch!");   }
}

Boss      batman = new Boss();
Sidekick robin  = new Sidekick(batman);
batman.set_side_kick( robin );
```

1. Thread 1 (Alfred) calls batman.to_the_bat_cave(); Alfred now has the lock on batman
2. Thread 1 is preempted just before calling lets_go()
3. Thread 2 (Joker) calls robin.sock_bam()—Joker now has the lock on robin
4. Robin tries to report() to batman (on thread 2), but can't because Alfred has the lock. Joker is blocked
5. Thread 1 wakes up, tries to call lets_go(), but can't because Joker has the lock

Nested-monitor Lockout

- Can happen any time you call a method that can block from any synchronized method
- Consider the following (I've removed exception handling):

```
class Black_hole
{ private InputStream input =
                 new Socket("www.holub.com",80)
                                .getInputStream();
  public synchronized int read()
  { return input.read();
  }
  public synchronized void close()
  { input.close();
  }
}
```

How do you close the socket?

Nested-monitor Lockout: Another Example

- The notifying queue blocks if you try to dequeue from an empty queue

```
class Black_hole2
{   Notifying_queue queue =
                  new Notifying_queue();

    public synchronized void put(Object thing)
    { queue.enqueue(thing);
    }

    public synchronized Object get( )
    { return queue.dequeue();
    }
}
```

Why Was `stop()` Deprecated?

- NT leaves DLLs (including some system DLLs) in an unstable state when threads are stopped externally
- **`stop()`** causes all monitors held by that thread to be released
  - But thread may be stopped half way through modifying an object, and
  - Other threads can access the partially modified (now unlocked) object

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Why Was `stop()` Deprecated (2)?

- The only way to safely terminate a thread is for **`run()`** to return normally
- Code written to depend on an external **`stop()`** will have to be rewritten to use **`interrupted()`** or **`isInterrupted()`**

interrupt(), don't stop()

```
class Wrong
{ private Thread t =
    new Thread()
    { public void run()
      { while( true )
        { //...
          blocking_call();
        }
      }
    };
  public stop()
  { t.stop();
  }
}
```

```
class Right
{ private Thread t =
  new Thread()
  { public void run()
    { try
      { while( !isInterrupted() )
        {  //...
           blocking_call();
        }
      }catch(InterruptedException e)
      {/*ignore, stop request*/}
    }
  };
  public stop()
  {t.interrupt();}
}
```

- But there's no safe way to stop a thread that doesn't check the "interrupted" flag

`interrupt()` gotchas

- **`interrupt()`** works only with the methods of the **`Thread`** and **`Object`** classes (e.g., **`wait()`**, **`sleep()`**, **`join()`**, etc.)
- It is not possible to interrupt out of a blocking I/O operation like **`read()`**
  - You can break out of a socket read by closing the socket, but that’s hideous

Why Were `suspend()` and `resume()` Deprecated?

- The suspend() method does not release the lock

```
class Wrong
{ public synchronized
  void take_a_nap()
  {    suspend();
  }
  public synchronized
  void wake_up()
  {    resume();
  }
}
```

Once a thread has entered **`take_a_nap`**(), all other threads will block on a call to **`wake_up`**(). (Someone has gone into the bathroom, locked the door, and fallen into a drug-induced coma)

```
class Right
{    public synchronized
    void take_a_nap()
    {  try
        {     wait();
        }
        catch(InterruptedException e)
        {/*do something reasonable*/}
    }
    public synchronized
    void wake_up()
    {    notify();
    }
}
```

The lock is released by **`wait()`** before the thread is suspended.

The Big-picture Coding Issues

- Design-to-coding ratio is 10:1 in threaded systems
- Formal code inspection or pair programming is essential
- Debugging multithreaded code takes longer
  - Bugs are usually timing related
- It’s not possible to fully debug multithreaded code in a visual debugger
  - Instrumented VMs cannot find all the problems because they change timing
  - Classic Heisenberg uncertainty: observing the process impacts the process
- Complexity can be reduced with architectural solutions (e.g., Active Objects)

Given That the Best Solution Isn't Finding a New Profession…

- Low-level solutions (roll-your-own semaphores)
  - I'll look at a few of the simpler classes covered in depth in *Taming Java Threads*
  - My intent is to give you a feel for multithreaded programming, not to provide an exhaustive toolkit
- Architectural solutions (active objects, etc.)

Roll Your Own (A Catalog)

- **Exclusion Semaphore** (mutex)
  - Only one thread can own at one time
  - Roll-your-own version can contain a timeout
- **Condition Variable**
  - Wait while condition false
  - Roll-your-own version can have state
- **Counting Semaphore**
  - Control pool of resources
  - Blocks if resource is unavailable

Roll Your Own (Cont.)

- **Message Queues** (interthread communication)
  - Thread blocks until a message is enqueued
  - Typically, only thread per queue
- **Thread Pools**
  - A group of dormant threads wait for something to do
  - A thread activates to perform an arbitrary task
- **Timers**
  - Allow operation to be performed at regular intervals
    - Block until a predetermined time interval has elapsed
    - Block until a predetermined time arrives

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Roll Your Own (Cont.)

- **Reader/Writer Locks**
  - Allow thread-safe access to global resources such as files:
    - Must acquire the lock to access a resource
    - Writing threads are blocked while a read or write operation is in progress
    - Reading threads are blocked only while a write operation is in progress. Simultaneous reads are okay

Threads From an OO Perspective

- Think messages, not functions
- Synchronous messages—handler doesn't return until it's done doing whatever sender requests
- Asynchronous messages—handler returns immediately—Meanwhile request is processed in the background

```
Toolkit.getDefaultToolkit.getImage(some_URL);
```

The Java™ Programming Language Threading Model Is Not OO

- No language-level support for asynchronous messaging
- Threading system is based entirely on procedural notions of control flow
- Deriving from **`Thread`** is misleading
- Novice programmers think that all methods of a class that extends **`Thread`** run on that thread, when in reality, the only methods that run on a thread are methods that are called either directly or indirectly by **`run()`**

Implementing Asynchronous Methods—One-Thread-Per-Method

```
class Receiver
{   //. . .
    public asynch_method()
    { new Thread()
      {public void run()
           {   synchronized( Receiver.this )
               {   // Make local copies of
                   // outer-class fields here.
               }
               // Code here doesn't access outer
               // class (or uses only constants).
           }
      }.start();
    }
}
```


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A More Realistic One-Thread-Per-Method Example

```
// This class demonstrates an asynchronous flush of a
// buffer to an arbitrary output stream

class Flush_example
{   public interface Error_handler
    {    void error( IOException e );
    }
    private final OutputStream out;
    private Reader_writer      lock =
                                      new Reader_writer();
    private byte[]                buffer;
    private int                   length;

    public Flush_example( OutputStream out )
    { this.out = out;
    }
```

A More Realistic One-Thread-Per-Method Example

```
synchronized void flush( final Error_handler handler )
{   new Thread()                    // Outer object is locked
    {   byte[] copy;                // while initializer runs.
        { copy = new byte[Flush_example.this.length];
          System.arraycopy(Flush_example.this.buffer,
                      0, copy, 0, Flush_example.this.length]);
          Flush_example.this.length = 0;
        }
        public void run()                 // Lock is released
        {   try                           // when run executes
            {   lock.request_write();
                out.write( copy, 0, copy.length );
            }
            catch( IOException e ){ handler.error(e); }
            finally{ lock.write_accomplished(); }
        }
    }.start();
}
}
```


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A More Realistic One-Thread-Per-Method Strategy

- It is a worse-case synchronization scenario
  - Many threads all access the same outer-class object simultaneously
  - Since synchronization is required, all but one of the threads are typically blocked, waiting to access the object
- Thread-creation overhead can be stiff:

Create String	**=**	**.0040 ms.**
Create Thread	**=**	**.0491 ms.**
Create & start Thread	**=**	**.8021 ms. (NT 4.0, 600MHz)**

Use Thread Pools

- The real version:
  - Grows from the initial size to a specified maximum if necessary
  - Shrinks back down to original size when extra threads aren't needed
  - Supports a "lazy" close

```
public final class Simplified_Thread_pool
{   private final Blocking_queue pool
                                    = new Blocking_queue();
```

Implementing a Simple Thread Pool

```
private final class Pooled_thread extends Thread
{
    public void run()
    {   synchronized( Simplified_thread_pool.this )
        {   try
            {   while( !isInterrupted() )
                 {    ((Runnable)(
                               pool.dequeue() )).run();
                 }
            }
        }
        catch(InterruptedException  e){/* ignore */}
        catch(Blocking_queue.Closed e){/* ignore */}
    }
}
```

Implementing a Simple Thread Pool

```
    public Simplified_Thread_pool(int pool_size )
    {   synchronized( this )
        {   while( --pool_size >= 0 )
                new Pooled_thread().start();
        }
    }

    public synchronized void execute(Runnable action) {
    pool.enqueue( action );
    }

    public synchronized void close()
    {   pool.close();
    }
}
```

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The *Active Object* Design Pattern

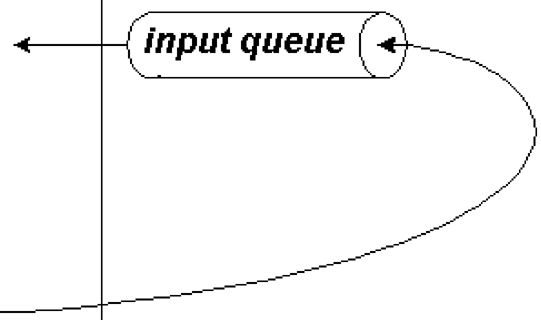
- An architectural solution to threading synchronization
- Asynchronous requests are executed serially on a thread created for that purpose
- Think *Tasks*
  - An I/O task, for example, accepts asynchronous read requests to a single file and executes them serially
  - Message-oriented Middleware (MQS, Tibco …)
  - Ada and Intel RMX (circa 1979)

A Generalized Active Object

- The solution can be generalized in the Java programming language like this:

```
run()
{
   while(true)
   {
      Runnable obj =
              queue.dequeue();
      obj.run();
   }
}


void message()
{    queue.enqueue
     (   new Runnable()
         {   public void run()
             {  // do work here
             }
         }
     );
}
```



The `javax.swing.*` Thread Is an Active Object

- The Java™ Foundation Classes API (JFC/Swing)/AWT uses it's own thread to handle the incoming OS-level messages and to dispatch appropriate notifications to listeners
- JFC/Swing is not thread safe
- The JFC/Swing subsystem is effectively a "UI task" to which you enqueue requests:

```
SwingUtilities.invokeLater // enqueue a request
(   new Runnable()
    {   public void run()
        {   some_window.setSize(200,100); }
    }
);
```

Implementing Active Object

```
public class Active_object extends Thread
{   private Msg_queue requests = new Msg_queue();
    public Active_object(){ setDaemon( true ); }
    public void run()
    {   try
        {   Runnable request;
            while((request=(Runnable)(
                        requests.dequeue()))!= null)
            {   request.run();
                request = null;  yield();
            }
        }catch( InterruptedException e ){}
    }
    public final void dispatch(Runnable operation )
    {   requests.enqueue( operation );
    }
}
```

Using an Active Object (Detangling UNIX® Console Output)

```
class Console
{   private static Active_object dispatcher
                        = new Active_object();
  static{ dispatcher.start(); }
  private Console(){}

  public static void println(final String s)
  {  dispatcher.dispatch
      (   new Runnable()
          {   public void run()
              {   System.out.println(s);
              }
          }
      );
  }
}
```

Summing Up

- Java™ programming language threads ("Java threads") are not platform independent—they can't be
- You have to worry about threads, like it or not
  - GUI code is multithreaded
  - No telling where your code will be used in the future
- Programming threads is neither easy nor intuitive
- Synchronized is your friend—Grit your teeth and use it
- Supplement language-level primitives to do real work
- The threading system isn't object oriented
- Use good architecture, not semaphores

In-depth Coverage and Code

- For in-depth coverage, see Taming Java™ Threads

  www.apress.com

- For source code, etc., go to my web page

  www.holub.com

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