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Multi-Threaded Concurrency in Java

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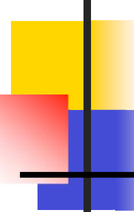

Overview of This Session

- What is a Thread?
- Thread States
- Thread Priorities
- Semaphore/signaling Concepts
- Creating Threads
- Daemon Threads
- Thread Groups
- Thread Methods

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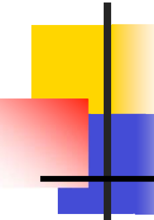

Overview *(Continued)*

- Synchronization
- Avoiding Deadlocks, and miscellaneous tips
- Demos and Discussion

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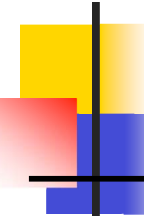

Multi-Threading Examples

- Multiple file I/O / Database access
- Access to the network
- Communication programs
- Long computations
- Animation – screen updates
- Preliminary data entry validation
- Logically parallel tasks
- Anything the user or program doesn't HAVE to wait for

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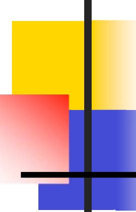

Semaphore Concepts

- Critical Sections
- Mutual Exclusion
- Event Signaling
- Multiple Events

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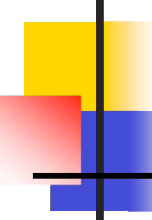

Critical Sections

- The concept that one thread must own the processor for the duration of some section of code, to the exclusion of all other threads
- Deadlock possible or even likely if critical section waits for a resource
- A method of synchronization or signaling should be used for safety

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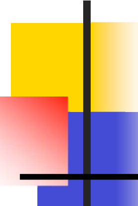

Mutual Exclusion Semaphores

- One thread has control of/access to a resource (can run) or another does, but not both.
- For serializing access to some resource
  - file
  - memory
  - *etc*.
- Order can't matter, only that they don't run over each other

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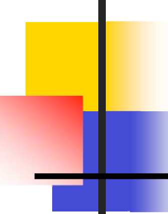

Mutual Exclusion Semaphores

Thread A	Thread B	Thread C

```
// do something

// request the
// semaphore
.
.  // use resource
.
// release the
// semaphore

// do something
```

running/runnable

```
// do something

// request the
// semaphore
.
.  // use resource
.
// release the
// semaphore

// do something
```

running/runnable

```
// do something

// request the
// semaphore
.
.  // use resource
.
// release the
// semaphore

// do something
```

running/runnable

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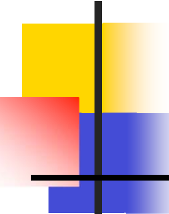

Mutual Exclusion Semaphores

Thread A

```
// do something

// request the
// semaphore
.
. // use resource
.
// release the
// semaphore

// do something
```

running/runnable

Thread B

```
// do something

// request the
// semaphore
.
. // use resource
.
// release the
// semaphore

// do something
```

running/runnable

Thread C

```
// do something

// request the
// semaphore
.
. // use resource
.
// release the
// semaphore

// do something
```

running/runnable

Who gets the semaphore???

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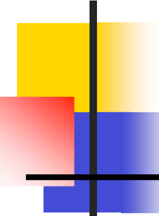

Mutual Exclusion Semaphores

Thread A	Thread B	Thread C

// do something
 	
→ // request the
// semaphore
.
. // use resource
.
// release the
// semaphore
 	
// do something
	// do something
	
	// request the
	// semaphore
	.
	→ . // use resource
	.
	// release the
	// semaphore
	
	// do something
		// do something
		
		→ // request the
		// semaphore
		.
		. // use resource
		.
		// release the
		// semaphore
		
		// do something

Not runnable	running/runnable	Not runnable

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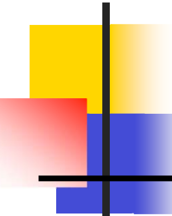

Mutual Exclusion Semaphores

Thread A	Thread B	Thread C

// do something
 	
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// semaphore
.
. // use resource
.
// release the
// semaphore
 	
// do something
	// do something
	
	// request the
	// semaphore
	.
	. // use resource
	.
	// release the
	// semaphore
	
	// do something
		// do something
		
		// request the
		// semaphore
		.
		. // use resource
		.
		// release the
		// semaphore
		
		// do something

Not runnable	running/runnable	Not runnable

Who gets the semaphore???

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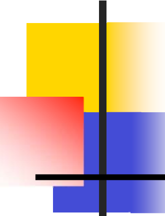

Mutual Exclusion Semaphores

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// release the
// semaphore
 	
// do something
	// do something
	
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	// semaphore
	.
	. // use resource
	.
	// release the
	// semaphore
	
	// do something
		// do something
		
		// request the
		// semaphore
		.
		. // use resource
		.
		// release the
		// semaphore
		
		// do something

running/runnable	running/runnable	Not runnable

And so on…

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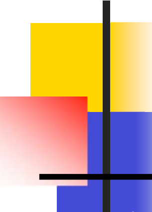

Event Semaphores

- Used to signal one or more threads of an event
- Two analogies:
  - Horse race starting gate
  - Traffic light
- There is no "owner" of the semaphore.
- Any thread with a 'handle' may green light (post) or red light (reset) the semaphore at any time

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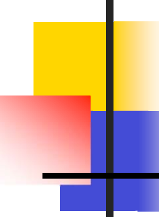

Event Semaphores

- Horse race
  - All horses wait at the gate (set state) until the starting gun (event) goes off (posted), then they ALL go
- Traffic light
  - Turn the light green (post)
  - Turn the light red (set)
  - Wait – see if the light is green or red, proceed accordingly

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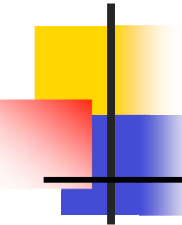


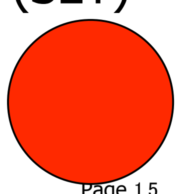
Event Semaphores

Thread A	Thread B	Thread C

// create it
// ‘red’ (set)
 	
// wait for the
// semaphore
 	
// event must
// have happened
 	
// keep going
	// do something
	
	// wait for the
	// semaphore
	
	// event must
	// have happened
	
	// keep going
		// doing
		// something
		
		// event everyone
		// is waiting on
		
		// ‘green light’
		// the semaphore
		
		// keep going

running/runnable	running/runnable	Not started yet

RED LIGHT (SET)



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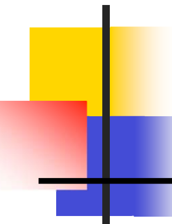

Event Semaphores

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	// keep going
		// doing
		// something
		
		// event everyone
		// is waiting on
		
		// 'green light'
		// the semaphore
		
		// keep going

Not runnable	Not runnable	running

Thread A and B are waiting for the light to turn green (posted)

RED LIGHT (SET)

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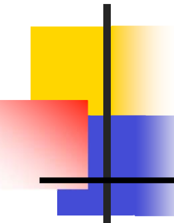

Event Semaphores

Thread A	Thread B	Thread C

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// keep going
	// do something
	
	// wait for the
	// semaphore
	
	// event must
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		// something
		
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		// is waiting on
		
		// 'green light'
		// the semaphore
		
		// keep going

Not runnable	Not runnable	running

RED LIGHT (SET)

Thread A and B are waiting for the light to turn green (posted)

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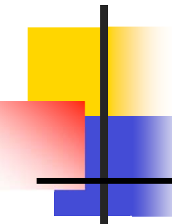


Event Semaphores

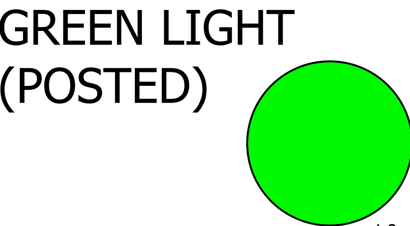
Thread A	Thread B	Thread C

// create it
// 'red' (set)
 	
// wait for the
// semaphore
 	
// event must
// have happened
 	
// keep going
	// do something
	
	// wait for the
	// semaphore
	
	// event must
	// have happened
	
	// keep going
		// doing
		// something
		
		// event everyone
		// is waiting on
		
		// 'green light'
		// the semaphore
		
		// keep going

Ready/running	Ready/running	Ready/running

Thread A and B are unblocked and ready to go!

GREEN LIGHT
(POSTED)



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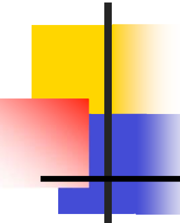

Event Semaphores

Thread A	Thread B	Thread C

// create it
// 'red' (set)
 	
// wait for the
// semaphore
 	
// event must
// have happened
 	
// keep going
	// do something
	
	// wait for the
	// semaphore
	
	// event must
	// have happened
	
	// keep going
		// doing
		// something
		
		// event everyone
		// is waiting on
		
		// 'green light'
		// the semaphore
		
		// keep going

Ready/running	Ready/running	Ready/running

And so on…

GREEN LIGHT
(POSTED)

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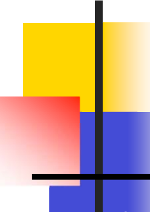

Multiple Events

- The semaphore concept of waiting for a set of events, or resources
- Can wait on:
  - ANY of them or
  - ALL of them
  - Four combinations:
    - exclusive access to ALL resources in a collection
    - exclusive access to ANY resource in a collection
    - waiting for ALL events in a collection
    - waiting for ANY event in a collection

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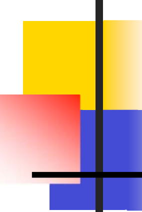

Other Semaphore Concepts

- Counting “mutex”
  - Java 5.0 Semaphore class
- Reentrant mutex
  - Java 5.0 ReentrantLock class
- Read/Write “mutex”
  - Java 5.0 ReentrantReadWriteLock class

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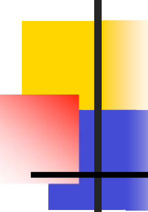

Semaphore Wrap Up

- These concepts exist in any multi-threaded/multi-tasking environment
- Java 1.0-1.4 doesn't have a built in mechanism to specifically support each of these types of semaphores
- Java 5.0 has many new multi-threading features based originally on Doug Lea's concurrent classes
  - See Aidon Jennery's advanced talk on concurrency for details
- Classes *similar* (but not the same) to the java.util.concurrent library can be used in earlier versions of Java instead of "rolling your own." They can be found at:

  http://gee.cs.oswego.edu/dl/concurrency-interest/index.html

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Threads

- Are functions which run asynchronously (in the case of a multi-processor system) or "apparently asynchronously"
- Start at well-known pre-defined locations (main() or run())
- Are executed by the JVM thread scheduler based on a variety of rules and available resources
- Are methods in separate threads, and thus have their own local variables
- Share static data between all threads in a Java program

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Threads

- When the JVM starts up there is usually a single non-daemon thread which typically calls the `main` method of some designated class
- The JVM continues to execute threads until either of the following occurs:
  - The `exit` method of class `Runtime` has been called and the security manager has permitted the exit operation to take place.
  - All threads that are not daemon threads have died, either by returning from the call to the `run` method or by throwing an exception that propagates beyond the `run` method.

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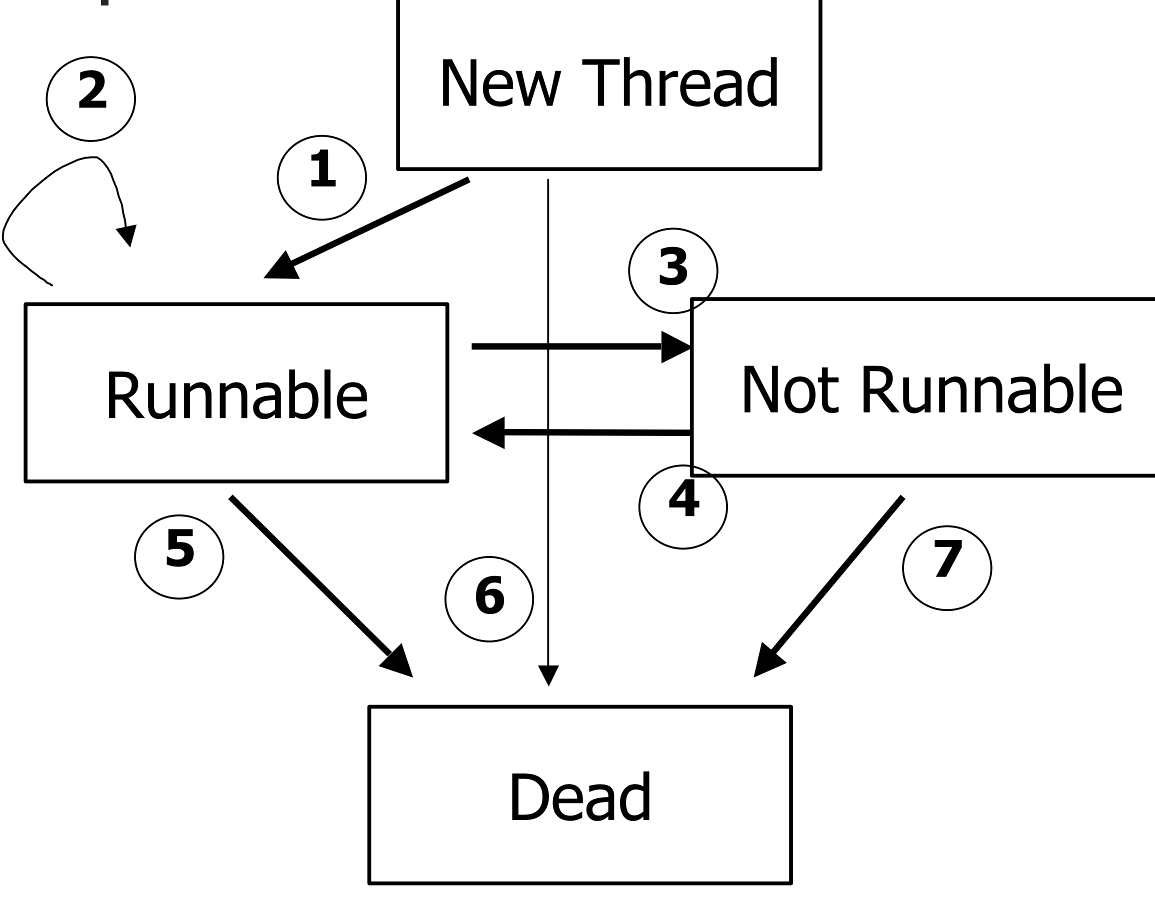
Thread States



1) method invoked
   start
2)method invoked
   yield
3) Wait condition
   blocked i/o
   wait
   sleep, suspend, *etc.*
4) Wait condition satisfied
   notify, *etc.*
5) stop, or run exits
6) method invoked
   stop
7) method invoked
   stop

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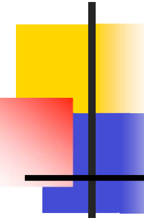

Thread Priorities

- Thread scheduler decides which non-blocked thread to dispatch based on priority
- Pre-emptive scheduling
- Timeslicing within equal priorities is currently system dependent
- Don't write code which depends on time-sharing/slicing – use yield() in tight loops

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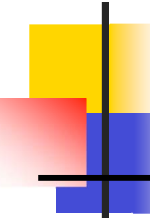

Thread Priorities

- Integer between:
  - Thread.MIN_PRIORITY (= 1)
  - Thread.MAX_PRIORITY (= 10)
- Default:
  - Thread.NORM_PRIORITY (= 5)
- Methods
  - void setPriority(int p)
  - int getPriority()

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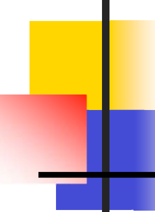

Creating Threads

- Extend Thread class
  - Override run() method
  - Use if you simply want to run something asynchronously, but don't have a class with existing behavior you want to use
- Extend other class using Runnable interface
  - Override run() method
  - Create new Thread object, and pass Runnable object during Thread instantiation
  - Use if you have an existing class with methods you want to run asynchronously

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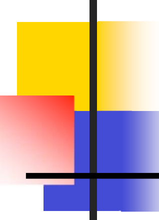

Extend Thread Class

```
class ThreadSample {
        public static void main(String[ ] args) {
         DummyThread d = new DummyThread();
         d.start();
         // do something main()-like here
        }
}

class DummyThread extends Thread {
        public void run() {
         // do something asynch here
        }
}
```

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Using Runnable Interface

```
class ThreadSample {
    public static void main(String[] args)
     {
     Thread d = new Thread(new DummyThread());
     d.start();
     // do something main()-like here
     }
}

class DummyThread extends DummyOther implements Runnable
{
    public void run()
     {
     // do something asynch here
     }
}
```

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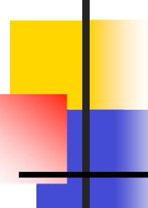

Using Runnable Interface

```
class ThreadSample {
public static void main(String[] args)
    {
    Thread d = new Thread(new ThreadedCustomer());
    d.start();
    // do something main()-like here
    }
}

class ThreadedCustomer extends Customer implements Runnable {
public void run()
    {
    // do something asynch here
    }
}
```

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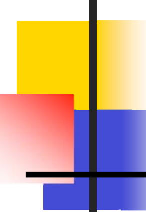

Important Considerations

- Never, EVER make assumptions about the order in which threads will execute
- If the order of processing is important between threads, use some mechanism of inter-thread communication to control it
- Debugging can be tricky – the debugger will almost certainly change the timing of threads

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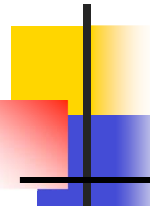

Let's look at Some Sample Code

ThreadTest1

ThreadTest2

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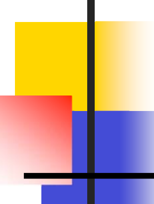

Interrupting a Thread

- If you need to stop a thread which may be waiting for long periods you can interrupt it with `Thread.interrupt()`
- Any thread which catches an interrupt exception must do one of the following:
  - Deal with the situation immediately
  - Reassert the exception with:
    - `Thread.currentThread().interrupt();`
  - Rethrow the Exception, if allowed
- Note: Threads do not always respond to interruptions
- Check the interrupt state with:
  - `public static boolean interrupted()` – returns true/false results of current thread's interrupt state and resets the state
  - `public boolean isInterrupted()` – returns true/false results of current thread's interrupt state and leaves the status as is

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How to Kill a Thread or: Cooperative Suicide

- Developers are not given a reliable, programmatic mechanism for killing a thread from the outside.
- stop() suspend() and resume() have all been deprecated since 1.2, for good reason.
  - stop() is inherently unsafe because you have no way to know what state objects running in the thread are in, if you stop it from the outside.
  - suspend() is likewise unsafe, with the added danger of the thread not releasing any locks it holds while suspended. Deadlocks are likely.
- If a thread is going to need to potentially be stopped from the outside, this needs to be prearranged and programmed for with a simple "suicide pact".

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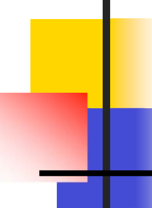

Stopping a Thread – Method 1

- Follow these simple steps to allow your thread to be stopped from the outside:
  - create a volatile boolean flag variable for your Thread class (default false).
  - create a method which sets the flag to true when called (clobber() or whatever).
  - periodically, within your code, check the value of the flag and if it's true, immediately (and gracefully) get out.

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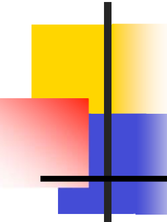

Stopping a Thread

It has always been recommended that you terminate threads through thread cooperation – stop()/suspend() deprecation helps enforce this idea.

```
class test extends Thread {
    private volatile boolean stop;

    public void stopThread() {
        stop = true;
    }

    public void run() {
        stop = false;
        while (!stop) {
            // do work
        }
        // do cleanup
    }
}
```

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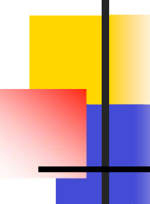

Stopping a Thread – Method 2

- Follow these simple steps to allow your thread to be stopped from the outside:
  - Use the interrupt status as your flag
  - Create a method which interrupts the thread when called (clobber() or whatever).
  - Periodically, within your code, check the interrupted state and if it's true, immediately (and gracefully) get out.
  - This is additionally useful if you need to kill a thread which spends time in wait() or sleep() – you will need to handle InterruptedException accordingly

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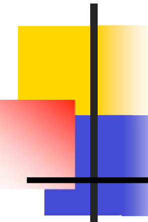

Daemon Threads

- Service provider threads
- Use `setDaemon(true)` to specify
- Use `isDaemon()` to determine if a thread is a Daemon thread
- When only daemon threads remain in a process, interpreter exits
- Often used for resource pools – when there are no more clients, the resource pool is no longer necessary

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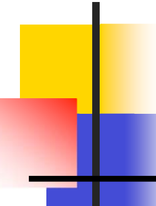

Let's Look at Some Sample Code

- DaemonThreadTest

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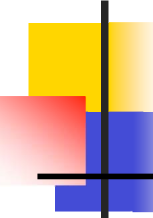

Thread Groups

- For managing multiple threads as a group
- ThreadGroup class has methods for:
  - Collection Management
  - Operating on a Group
  - Operating on all Threads within a Group
  - Access Restriction to threads
- Possibly most useful for the typical developer is the ability for a ThreadGroup to catch all exceptions thrown by its Threads by overriding uncaughtException(Thread, Throwable)
  - Java 5.0 allows this functionality at the Thread level

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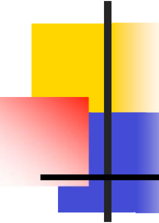

Thread Groups

- All threads belong to a ThreadGroup
  - If not specified, new threads are put in the default ThreadGroup
  - main ThreadGroup created at application start up
  - Threads are put in same group as thread that created it
- Threads cannot be moved to a new group after creation

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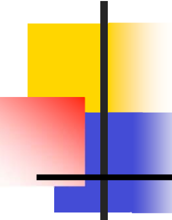

Creating a Thread in a Group

Thread Constructors

```
public Thread(ThreadGroup group, Runnable target)
public Thread(ThreadGroup group, String name)
public Thread(ThreadGroup group, Runnable target,
String name)
```

Creating a thread as a member of a specified group

```
ThreadGroup dummyThreadGroup = new ThreadGroup("Some
Fine Group");
Thread myThread = new Thread(dummyThreadGroup, "Some
silly thread");
```

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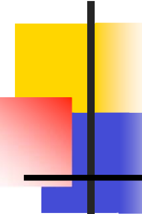

Let's Look at Some Sample Code

- ThreadGroupTest1
- ThreadGroupTest2

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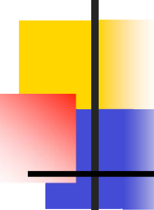

Synchronization

- Care needs to be taken to have not more than one thread access the same data at the same time
- Java offers implicit monitors (mutexes) as exclusive locks on objects by use of the keyword synchronized
- A method, or a block of code, may be protected by synchronization
- Synchronization is accomplished by using the keyword ‘synchronized’
- Only one synchronized method may run on any *object* at any one time

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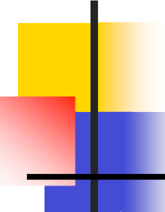

synchronized keyword

```
class threadSample
{
  public synchronized void someMethod() {
   // code here is protected
  }

  public void someOtherMethod() {
   // an example of a synchronized block instead of method
        // some code here
        synchronized (someObj)
        {
        // some code for which it was important that someObj
        // was locked
    }
  }
}
```

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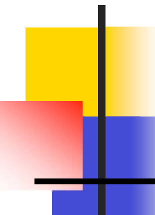

`synchronized` keyword

- Think of the word 'synchronized' to mean "request a specific lock" and that anyone requesting the same exact lock will be forced to wait until they obtain it before executing the code

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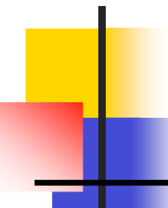

Every Object Has a Lock

Class:
Employee
Objects:
Bob
Sue
Elmer

Employee: Bob Jones

Employee: Sue Smith

Employee: Elmer Fudd

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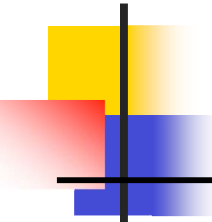
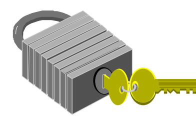
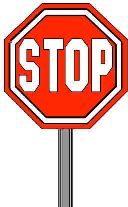


Employee: Bob Jones






```
synchronized float getSalary ()
{
// the salary can't be
// changed or set by other
// thread while we
// are in here - we must
// have the lock
}
```

```
synchronized setSalary (float a)
{
// the salary can't be
// read (or set) by any other
// thread while we
// are in here - we must
// have the lock
}
```

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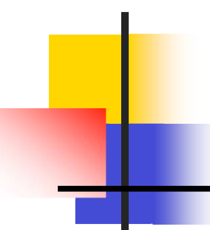

Thread 1
`bob.setSalary();`

Bob's lock

Thread2
`elmer.setSalary();`

Elmer's lock

Thread 3
`bob.setSalary();`

Waiting for Bob's lock

```
synchronized float getSalary ()
{
// the salary can't be
// changed or set by other
// thread while we
// are in here - we must
// have the lock
}
```

```
synchronized setSalary (float a)
{
// the salary can't be
// read (or set)by any other
// thread while we
// are in here - we must
// have the lock
}
```

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Java's Guarantees for *synchronized* Blocks

- One, and only one, thread can own a specific monitor/lock at any one time
- If a block of code, protected by the keyword 'synchronized' is executing, it MUST therefore own the associated lock

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Further *synchronized* Discussion

- The idea of synchronization in Java is both one of the most important, and one of the most misunderstood in its implementation
- Common misconceptions include:
  - a synchronized chunk of code is 'locked' and can never be running at the same time as another synchronized block.
  - the granularity of the requested lock is often not well understood.
  - not realizing that synchronization is on a per OBJECT basis.
- PLEASE ask questions – there is time allowed for it right now.

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Communication/ Synchronization

- Inter-thread communication is sometimes necessary in multi-threaded programs
- In order to avoid polling/looping practices, Java offers event waiting and notification using:
  - wait() – waits for a condition to be satisfied
  - notify() – notifies one waiting thread that an event has occurred
  - notifyAll() – notifies all waiting threads that an event has occurred
- Can only be called from synchronized methods or blocks – *i.e.* the lock must be obtained before making any of these calls

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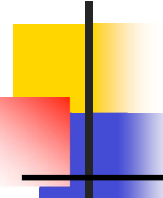

Event Notification

Thread 1	Thread 2	Thread 3
`synchronized (x) { // some before stuff x.wait(); // some after stuff }`	`synchronized (x) { // some before stuff x.wait(); // some after stuff }`	`synchronized (x) { // some before stuff x.notify(); // some after stuff }`

- Java requires wait() and notify() to be called only from within synchronized blocks. *i.e.* you must own the monitor before waiting for the event.
- Does this make an impossible dead-lock situation? How can notify() in Thread 3 take place if the monitor is already owned by Thread 1 or 2?

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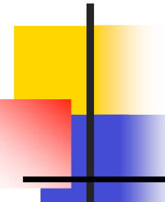

Event Notification

Thread 1	Thread 2	Thread 3

`synchronized (x)`
`{ // lock obtained`
`  // some before stuff`
`  x.wait();`
`  // some after stuff`
`} // lock released`
	`synchronized (x)`
	`{ // lock obtained`
	`  // some before stuff`
	`  x.wait();`
	`  // some after stuff`
	`} // lock released`
		`synchronized (x)`
		`{ // lock obtained`
		`  // some before stuff`
		`  x.notify();`
		`  // some after stuff`
		`} // lock released`

- wait() releases the lock until a notify() condition is recognized
- The thread won't be able to continue until it has re-obtained the lock (it must first be released by the current owner)

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wait() – Temporarily Releases a Lock within a synch. Block

```
public void someMethod() {
synchronized (someObj) {
    // we have the lock if  we're here
    someObj.wait();  // this releases the lock,
                     // and blocks until notify()/notifyAll()
    someCode();      // the lock has been reacquired
                     // before this line will execute
    }
}
```

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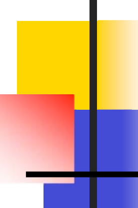

Let's Look at Some Sample Code

- ThreadWaitTest1
- ThreadWaitTest2

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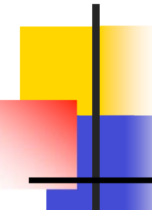

Thread Methods of Interest

- currentThread()
  - Returns a reference to the currently executing thread object.
- dumpStack()
  - Prints a stack trace of the current thread. Can be useful for debugging.
- getName()
  - Returns this thread's name.
- getPriority()
  - Returns this thread's priority.
- getState() (5.0 only)
  - Returns the state of this thread.
- getUncaughtExceptionHandler() (5.0 only)
  - Returns the handler invoked when this thread abruptly terminates due to an uncaught exception.

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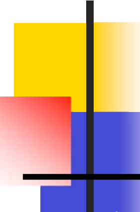

Thread Methods of Interest

- holdsLock(Object obj) (since 1.4)
  - Returns true if and only if the current thread holds the monitor lock on the specified object.
- interrupt()
  - Interrupts this thread.
- interrupted()
  - Tests if the current thread has been interrupted. Clears the interrupt status.
- isInterrupted()
  - Tests if the current thread has been interrupted. Interrupt status unaffected.

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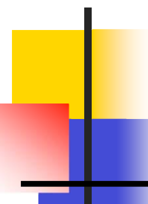

Thread Methods of Interest

- join()
  - Waits for this thread to die.
- join(long millis)
  - Waits at most *millis* milliseconds for this thread to die.
- join(long millis, int nanos)
  - Waits at most *millis* milliseconds plus *nanos* nanoseconds for this thread to die.
- run()
  - If this thread was constructed using a separate Runnable run object, then that Runnable object's run method is called; otherwise, this method does nothing and returns.
- setUncaughtExceptionHandler(Thread.UncaughtExceptionHandler eh) (5.0 only)
  - Set the handler invoked when this thread abruptly terminates due to an uncaught exception.

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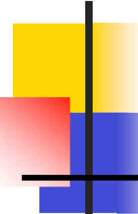

Thread Methods of Interest

- sleep(long millis)
  - Causes the currently executing thread to sleep (temporarily cease execution) for the specified number of milliseconds.
- sleep(long millis, int nanos)
  - Causes the currently executing thread to sleep (cease execution) for the specified number of milliseconds plus the specified number of nanoseconds.
- start()
  - Causes this thread to begin execution; the Java Virtual Machine calls the run method of this thread.
- toString()
  - Returns a string representation of this thread, including the thread's name, priority, and thread group.
- yield()
  - Causes the currently executing thread object to temporarily pause and allow other threads to execute.

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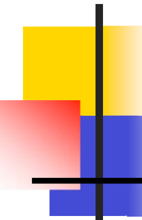

Avoiding Deadlocks

- Difficult to detect – good offense is the best defense
- Acquire multiple locks in the same order
- Know your code well

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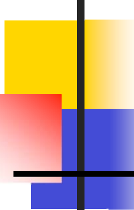

Performance Issues and Tips

- Thread where applicable, but don't start dozens of threads if not needed – use thread pools for intensely multithreaded programs if possible.
- For operations involving multiple objects with state that must be synchronized for all of them, lock all objects
- Never depend on thread prioritization for exclusive access to an object
- Never depend solely on thread pre-emption or prioritization for performance

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Performance Issues and Tips

- If you are creating an object solely for the purpose of using it as a lock to synchronize on, the cheapest object is a zero element byte array
  - byte[] lock = new byte[0]; // much cheaper than
  - Object lock = new Object(); // this
- Vector and Hashtable are both fully synchronized – don't use them for a single-threaded program – you'll pay the performance penalty for no purpose.

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Performance Issues and Tips

- In general your data members should be private anyway, but especially if more than one thread can be accessing an object:
  - Make data members private
  - Use synchronized accessors
- In summary – any data that is protected somewhere in your code in a synchronized method should also be private to the class to be fully protected

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- Local copies of variables in threads
  - The JVM may make local copies of global variables in each thread. Values are not guaranteed to be written to main memory unless the variable is either: a) updated within a synchronized block; or b) declared volatile
- Never reassign the object reference of a locked object!

```
synchronized (obj) {
      // DON'T do this:
      obj = new Object();
      // I don't have the
      // lock on obj
}
```

```
synchronized (obj) {
      // I may not be
      // using obj safely
}
```

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Miscellaneous Tidbits and Gotchas

- A thread may acquire the same lock multiple times, and will not release it until the count has gone back down to 0
- Thread.sleep(5000) is supposed to sleep for 5 seconds. However, if somebody changes the system time, you may sleep for a very long time or no time at all. The OS records the wake up time in absolute form, not relative.
- Thread scheduling is not guaranteed to be round-robin. A task may totally hog the CPU at the expense of threads of the same priority. You can use Thread.yield() to have a conscience. “Fairness” is a new concept for 5.0.

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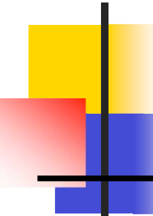

Threads – What Cost?

- Small CPU overhead at initialization
- Complicates design
- Requires parallel thinking
- Debugging can be very tricky
  - Running in a debugger can alter timing, making bugs harder to trace
  - Breakpoints in a thread does alter timing
- Adding threads to a project, if it wasn't designed with threads in mind can be particularly problematic

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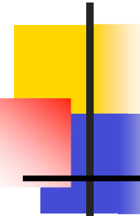

Other Sessions to See

- Aidon Jennery's talk "Stop. Go. No, Stop! How many ways are there to block a thread in Java?"

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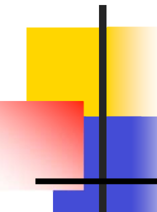

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Demos, Discussion, Questions?

- (and if there's time – a relevant story with a moral)

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