

CMSC 433 – Programming Language
Technologies and Paradigms
Spring 2005

Threads and Synchronization
March 29, 2005

(thanks to Doug Lea for some slides)

Project 4

- Project 4 has been posted
- Please start this project early
 - It is harder than it appears

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Tools Available for Project 4

- FindBugs
 - Finds some common wait/notify problems
 - Not guaranteed to be correct
- Dynamic lock checking tool checkSync
 - Every shared object must be guarded by a lock
 - Again, not guaranteed to be correct

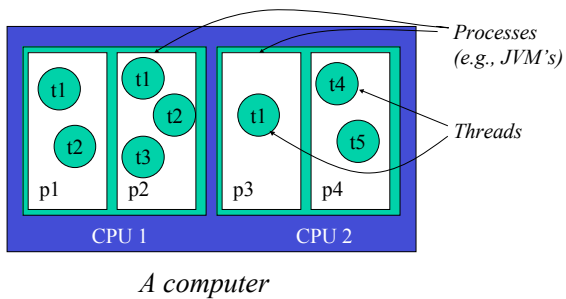
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Overview

- What are threads?
 - Concept
 - Basic Java mechanisms
- Thread concerns
 - Safety and Liveness
 - Use of synchronization and signalling
- Threading design patterns

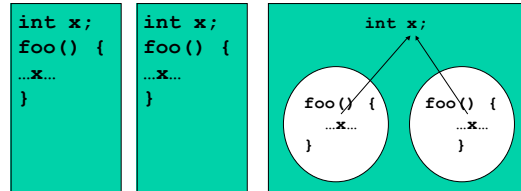
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Computation Abstractions



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Processes vs. Threads



Processes do not share data

Threads share data within a process

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So, What Is a Thread?

- **Conceptually:** it is a parallel computation occurring within a process
- **Implementation view:** it's a program counter and a stack. The heap and static area are shared among all threads
- All programs have at least one thread (main)

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Why Multiple Threads?

- Performance:
 - Parallelism on multiprocessors
 - Concurrency of computation and I/O
- Can easily express some programming paradigms
 - Event processing
 - Simulations
- Keep computations separate, as in an OS
 - Java OS

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Why Not Multiple Threads?

- Complexity:
 - Dealing with safety, liveness, composition
- Overhead
 - Higher resource usage
- We'll compare threads to their alternatives a bit later ...

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Programming Threads

- Threads are available in many languages
 - C, C++, Objective Caml, Java, SmallTalk ...
- In many languages (e.g., C and C++), threads are a platform specific add-on
 - Not part of the language specification
- Part of the Java language specification

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Java Threads

- Every application has at least one thread
 - The “main” thread, started by the JVM to run the application's **main()** method
- The code executed by **main()** can create other threads
 - Explicitly, using the **Thread** class
 - Implicitly, by calling libraries that create threads as a consequence
 - RMI, AWT/Swing, Applets, etc.

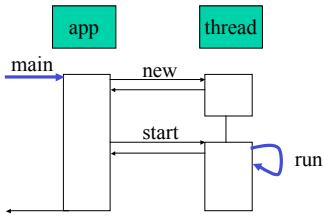
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Java Threads: Creation

- To explicitly create a thread
 - Instantiate a **Thread** object
 - An object of class **Thread** or a subclass of **Thread**
 - Invoke the object's **start()** method
 - This will start executing the **Thread**'s **run()** method concurrently with the current thread
 - Thread terminates when its **run()** method returns

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Java Threads: Creation



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Running Example: Alarms

- Goal: let us set alarms that will be triggered in the future
 - Input: Time t (seconds) and message m
 - Result: We'll see m printed after t seconds

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Example: Synchronous alarms

```
while (true) {
    System.out.print("Alarm> ");

    // read user input
    String line = b.readLine();
    parseInput(line); // sets timeout

    // wait (in secs)
    try {
        Thread.sleep(timeout * 1000);
    } catch (InterruptedException e) { }
    System.out.println("(" + timeout + ") " + msg);
}
```

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Making It Threaded (1)

```
public class AlarmThread extends Thread {
    private String msg = null;
    private int timeout = 0;

    public AlarmThread(String msg, int time) {
        this.msg = msg;
        this.timeout = time;
    }

    public void run() {
        try {
            Thread.sleep(timeout * 1000);
        } catch (InterruptedException e) { }
        System.out.println("(" + timeout + ") " + msg);
    }
}
```

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Making It Threaded (2)

```
while (true) {
    System.out.print("Alarm> ");

    // read user input
    String line = b.readLine();
    parseInput(line);
    if (m != null) {
        // start alarm thread
        Thread t = new AlarmThread(m, tm);
        t.start();
    }
}
```

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Alternative: The Runnable Interface

- Extending **Thread** prohibits a different parent
- Instead implement **Runnable**
 - Declares that the class has a **void run()** method
- Construct a **Thread** from the **Runnable**
 - Constructor **Thread(Runnable target)**
 - Constructor **Thread(Runnable target, String name)**

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Thread Example Revisited

```
public class AlarmRunnable implements Runnable {
    private String msg = null;
    private int timeout = 0;

    public AlarmRunnable(String msg, int time) {
        this.msg = msg;
        this.timeout = time;
    }

    public void run() {
        try {
            Thread.sleep(timeout * 1000);
        } catch (InterruptedException e) {}
        System.out.println(("+"+timeout+"") +msg);
    }
}
```

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Thread Example Revisited (2)

```
while (true) {
    System.out.print("Alarm> ");

    // read user input
    String line = b.readLine();
    parseInput(line);
    if (m != null) {
        // start alarm thread
        Thread t = new Thread(
            new AlarmRunnable(m, tm));
        t.start();
    }
}
```

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Notes: Passing Parameters

- **run()** doesn't take parameters
- We "pass parameters" to the new thread by storing them as private fields
 - In the extended class
 - Or the **Runnable** object
 - Example: the time to wait and the message to print in the AlarmThread class

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Thread Scheduling

- Once a new thread is created, how does it interact with existing threads?
- This is a question of scheduling:
 - Given N processors and M threads, which thread(s) should be run at any given time?

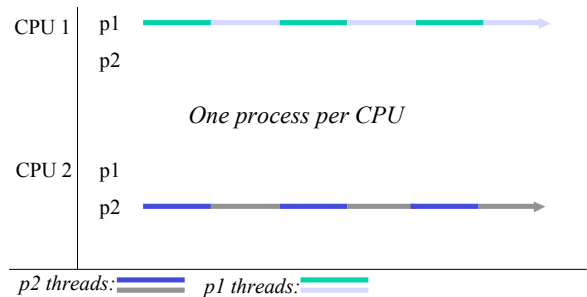
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Thread Scheduling

- OS schedules a single-threaded process on a single processor
- Multithreaded process scheduling:
 - One thread per processor
 - Effectively splits a process across CPU's
 - Exploits hardware-level concurrency
 - Many threads per processor
 - Need to share CPU in slices of time

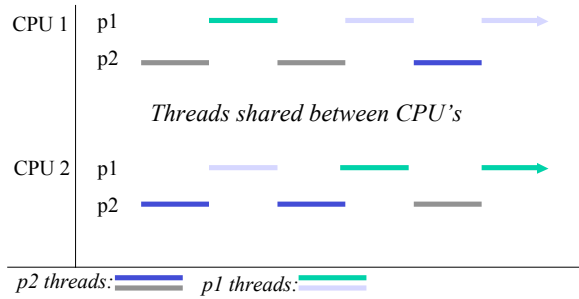
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Scheduling Example (1)



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Scheduling Example (2)



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Scheduling Consequences

- **Concurrency**
 - Different threads from the same application can be running *at the same time* on different processors
- **Interleaving**
 - Threads can be **pre-empted** *at any time* in order to schedule other threads

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Thread Scheduling

- When multiple threads share a CPU, must decide:
 - When the current thread should stop running
 - What thread to run next
- A thread can voluntarily **yield()** the CPU
 - Call to yield may be ignored; don't depend on it
- *Preemptive schedulers* can de-schedule the current thread at any time
 - Not all JVMs use preemptive scheduling, so a thread stuck in a loop may *never* yield by itself. Therefore, put **yield()** into loops
- Threads are de-scheduled whenever they block (e.g., on a lock or on I/O) or go to sleep

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Thread Lifecycle

- While a thread executes, it goes through a number of different phases
 - **New**: created but not yet started
 - **Runnable**: is running, or can run on a free CPU
 - **Blocked**: waiting for I/O or on a lock
 - **Sleeping**: paused for a user-specified interval
 - **Terminated**: completed

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Which Thread to Run Next?

- The scheduler looks at all of the runnable threads, including threads that were unblocked because
 - A lock was released
 - I/O became available
 - They finished sleeping, etc.
- Of these threads, it considers the thread's priority. This can be set with **setPriority()**. Higher priority threads get preference.
 - Oftentimes, threads waiting for I/O are also preferred

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Simple Thread Methods

- void start()
- boolean isAlive()
- void setPriority(int newPriority)
 - Thread scheduler might respect priority
- void join() throws InterruptedException
 - Waits for a thread to die/finish

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Example: Threaded, Sync Alarm

```
while (true) {
    System.out.print("Alarm> ");

    // read user input
    String line = b.readLine();
    parseInput(line);

    // wait (in secs) asynchronously
    if (m != null) {
        // start alarm thread
        Thread t = new AlarmThread(m,tm);
        t.start();
        // wait for the thread to complete
        t.join();
    }
}
```

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(thanks to Doug Lea for some slides)

Administrivia

- Please pick up your midterm from me
- Final exam date set
- Triple dispatch example posted
- Ship/bridge question from last class answered on newsgroup

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Simple Static Thread Methods

- void yield()
 - Give up the CPU
- void sleep(long milliseconds)
 - throws InterruptedException
 - Sleep for the given period
- Thread.currentThread()
 - Thread object for currently executing thread
- All apply to thread invoking the method

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Daemon Threads

- void setDaemon(boolean on)
 - Marks thread as a daemon thread
 - Must be set before thread started
- By default, thread acquires status of thread that spawned it
- Program execution terminates when no threads running except daemons

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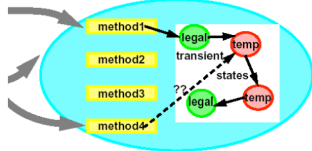
Concurrency Issues

- Threads allow concurrent activities, which can be both good and bad!
- Two opposing design forces
 - **Safety**: “Nothing bad ever happens”
 - **Liveness**: “Something (useful) eventually happens”
- A safe system may not be live and a live system may not be safe. Balance is key.

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Safe Objects

- Perform actions only when in consistent states
 - Don't want one thread to access an object while another thread is modifying its internal state.



- This boils down to ensuring *object invariants* in the face of concurrent access

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Violating Safety

- Data can be shared by threads
 - Scheduler can interleave or overlap threads arbitrarily
 - Can lead to *interference*
 - Storage corruption (e.g., a *data race/race condition*)
 - Violation of representation invariant
 - Violation of a protocol (e.g., *A* occurs before *B*)

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Data Race Example

```
public class Example extends Thread {
    private static int cnt = 0; // shared state
    public void run() {
        int y = cnt;
        cnt = y + 1;
    }
    public static void main(String args[]) {
        Thread t1 = new Example();
        Thread t2 = new Example();
        t1.start();
        t2.start();
    }
}
```

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Data Race Example

```
static int cnt = 0;    Shared state  cnt = 0
t1.run() {
    int y = cnt;
    cnt = y + 1;
}
t2.run() {
    int y = cnt;
    cnt = y + 1;
}
```

Start: both threads ready to run. Each will increment the global count.

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Data Race Example

```
static int cnt = 0;    Shared state cnt=0
t1.run() {
  int y = cnt; y=0
  cnt = y + 1;
}
t2.run() {
  int y = cnt;
  cnt = y + 1;
}
```

T1 executes, grabbing the global counter value into y.

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Data Race Example

```
static int cnt = 0;    Shared state cnt=0
t1.run() {
  int y = cnt; y=0
  cnt = y + 1;
}
t2.run() {
  int y = cnt; y=0
  cnt = y + 1;
}
```

T1 is pre-empted. T2 executes, grabbing the global counter value into y.

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Data Race Example

```
static int cnt = 0;    Shared state cnt=1
t1.run() {
  int y = cnt; y=0
  cnt = y + 1;
}
t2.run() {
  int y = cnt; y=0
  cnt = y + 1;
}
```

T2 executes, storing the incremented cnt value.

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Data Race Example

```
static int cnt = 0;    Shared state cnt=1
t1.run() {
  int y = cnt; y=0
  cnt = y + 1;
}
t2.run() {
  int y = cnt; y=0
  cnt = y + 1;
}
```

T2 completes. T1 executes again, storing the old counter value (1) rather than the new one (2)!

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But When I Run it Again?

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Data Race Example

```
static int cnt = 0;    Shared state  cnt = 0
t1.run() {
  int y = cnt;
  cnt = y + 1;
}
t2.run() {
  int y = cnt;
  cnt = y + 1;
}
```

Start: both threads ready to run. Each will increment the global count.

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Data Race Example

```
static int cnt = 0;    Shared state  cnt = 0
t1.run() {
  int y = cnt;  y=0
  cnt = y + 1;
}
t2.run() {
  int y = cnt;
  cnt = y + 1;
}
```

■

T1 executes, grabbing the global counter value into y.

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Data Race Example

```
static int cnt = 0;    Shared state  cnt = 1
t1.run() {
  int y = cnt;  y=0
  cnt = y + 1;
}
t2.run() {
  int y = cnt;
  cnt = y + 1;
}
```

■■■

T1 executes again, storing the counter value

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Data Race Example

```
static int cnt = 0;    Shared state  cnt = 1
t1.run() {
  int y = cnt;  y=0
  cnt = y + 1;
}
t2.run() {
  int y = cnt;  y=1
  cnt = y + 1;
}
```

■ ■ ■ ■

T1 finishes. T2 executes, grabbing the global counter value into y.

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Data Race Example

```
static int cnt = 0;    Shared state  cnt = 2
t1.run() {
  int y = cnt;  y=0
  cnt = y + 1;
}
t2.run() {
  int y = cnt;  y=1
  cnt = y + 1;
}
```

■ ■ ■ ■

T2 executes, storing the incremented cnt value.

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What Happened?

- In the first example, **t1** was preempted after it read the counter but before it stored the new value.
 - Depends on the idea of an *atomic action*
 - Violated an object invariant
- A particular way in which the execution of two threads is interleaved is called a *schedule*. We want to prevent this undesirable schedule.
- Undesirable schedules can be hard to reproduce, and so hard to debug.

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Question

- If instead of

```
int y = cnt;
cnt = y+1;
```
- We had written

```
– cnt++;
```
- Would the result be any different?
- Answer: NO!
 - Don't depend on your intuition about atomicity

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Question

- If you run a program with a race condition, will you always get an unexpected result?
 - No! It depends on the scheduler
 - ...i.e., which JVM you're running
 - ...and on the other threads/processes/etc that are running on the same CPU
- Race conditions are hard to find

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Avoiding Interference: Synchronization

```
public class Example extends Thread {
    private static int cnt = 0;
    static Object lock = new Object();
    public void run() {
        synchronized (lock) {
            int y = cnt;
            cnt = y + 1;
        }
        ...
    }
}
```

Lock, for protecting the shared state

Acquires the lock; Only succeeds if not held by another thread

Releases the lock

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Applying Synchronization

```
int cnt = 0;
t1.run() {
    synchronized(lock) {
        int y = cnt;
        cnt = y + 1;
    }
}
t2.run() {
    synchronized(lock) {
        int y = cnt;
        cnt = y + 1;
    }
}
```

Shared state cnt = 0

■

T1 acquires the lock

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Applying Synchronization

```
int cnt = 0;
t1.run() {
    synchronized(lock) {
        int y = cnt;
        cnt = y + 1; y=0
    }
}
t2.run() {
    synchronized(lock) {
        int y = cnt;
        cnt = y + 1;
    }
}
```

Shared state cnt = 0

■ ■

T1 reads cnt into y

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Applying Synchronization

```
int cnt = 0;
t1.run() {
  synchronized(lock) {
    int y = cnt;
    cnt = y + 1; y=0
  }
}
t2.run() {
  synchronized(lock) {
    int y = cnt;
    cnt = y + 1;
  }
}
```

Shared state cnt = 0



*T1 is pre-empted.
T2 attempts to
acquire the lock but fails
because it's held by
T1, so it blocks*

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Applying Synchronization

```
int cnt = 0;
t1.run() {
  synchronized(lock) {
    int y = cnt;
    cnt = y + 1; y=0
  }
}
t2.run() {
  synchronized(lock) {
    int y = cnt;
    cnt = y + 1;
  }
}
```

Shared state cnt = 1



*T1 runs, assigning
to cnt*

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Applying Synchronization

```
int cnt = 0;
t1.run() {
  synchronized(lock) {
    int y = cnt;
    cnt = y + 1; y=0
  }
}
t2.run() {
  synchronized(lock) {
    int y = cnt;
    cnt = y + 1;
  }
}
```

Shared state cnt = 1



*T1 releases the lock
and terminates*

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Applying Synchronization

```
int cnt = 0;
t1.run() {
  synchronized(lock) {
    int y = cnt;
    cnt = y + 1; y=0
  }
}
t2.run() {
  synchronized(lock) {
    int y = cnt;
    cnt = y + 1;
  }
}
```

Shared state cnt = 1



*T2 now can acquire
the lock.*

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Applying Synchronization

```
int cnt = 0;
t1.run() {
  synchronized(lock) {
    int y = cnt;
    cnt = y + 1; y=0
  }
}
t2.run() {
  synchronized(lock) {
    int y = cnt;
    cnt = y + 1; y=1
  }
}
```

Shared state cnt = 1



T2 reads cnt into y.

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Applying Synchronization

```
int cnt = 0;
t1.run() {
  synchronized(lock) {
    int y = cnt;
    cnt = y + 1; y=0
  }
}
t2.run() {
  synchronized(lock) {
    int y = cnt;
    cnt = y + 1; y=1
  }
}
```

Shared state cnt = 2



T2 assigns cnt,
then releases the lock

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Locks

- Any Object subclass has (can act as) a lock
- Only one thread can hold the lock on an object
 - Other threads block until they can acquire it
- If a thread already holds the lock on an object
 - The thread can reacquire the same lock many times
 - ...Locks are *reentrant*
 - Lock is released when object unlocked the corresponding number of times
- No way to only attempt to acquire a lock
 - ...in Java 1.4
 - Either succeeds, or blocks the thread

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Synchronized Statement

- **synchronized (obj) { statements }**
- Obtains the lock on **obj** before executing statements in block
- Releases the lock when the statement block completes
 - Either normally, or due to a return, break, or exception being thrown in the block

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Synchronized Methods

- A method can be synchronized
 - Add **synchronized** modifier before return type
- Obtains the lock on object referenced by **this** before executing method
 - Releases lock when method completes
- For a **static synchronized** method
 - Locks the **Class** object for the class
 - Accessible directly, e.g. **Foo.class**
 - Not the same as **this**!

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Synchronization Example

```
public class State {
    private int cnt = 0;
    public int synchronized incCnt(int x) {
        cnt += x;
    }
    public int synchronized getCnt() { return cnt; }
}
public class MyThread extends Thread {
    State s;
    public MyThread(State s) { this.s = s; }
    public void run() {
        s.incCnt(1)
    }
}
public void main(String args[]) {
    State s = new State();
    MyThread thread1 = new MyThread(s);
    MyThread thread2 = new MyThread(s);
    thread1.start(); thread2.start();
}
}
```

Synchronization occurs in State object itself, rather than in its caller.

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Synchronization Style

- Design decision
 - Internal synchronization (class is thread-safe)
 - Have a stateful object synchronize itself (e.g., with synchronized methods)
 - External synchronization (class is thread-compatible)
 - Have callers perform synchronization before calling the object
- Can go both ways:
 - Thread-safe: Random
 - Thread-compatible: ArrayList, HashMap, ...

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Synchronization not a Panacea

- Two threads can block on locks held by the other; this is called *deadlock*

```
Object A = new Object();
Object B = new Object();
T1.run() {
    synchronized (A) {
        synchronized (B) {
            ...
        }
    }
}
T2.run() {
    synchronized (B) {
        synchronized (A) {
            ...
        }
    }
}
```

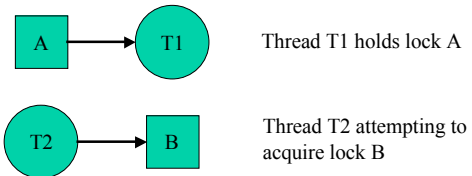
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Deadlock

- Quite possible to create code that deadlocks
 - Thread 1 holds lock on **A**
 - Thread 2 holds lock on **B**
 - Thread 1 is trying to acquire a lock on **B**
 - Thread 2 is trying to acquire a lock on **A**
 - Deadlock!
- Not easy to detect when deadlock has occurred
 - Other than by the fact that nothing is happening

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Deadlock: Wait graphs



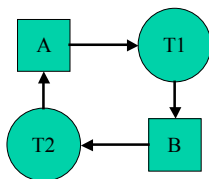
Thread T1 holds lock A

Thread T2 attempting to acquire lock B

Deadlock occurs when there is a cycle in the graph

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Wait graph example



T1 holds lock on **A**
T2 holds lock on **B**
T1 is trying to acquire a lock on **B**
T2 is trying to acquire a lock on **A**

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Key Ideas

- Multiple threads can run simultaneously
 - Either truly in parallel on a multiprocessor
 - Or can be scheduled on a single processor
 - A running thread can be pre-empted at any time
- Threads can share data
 - In Java, only fields can be shared
 - Need to prevent interference
 - Synchronization is one way, but not the only way
 - Overuse use of synchronization can create deadlock
 - Violation of liveness

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Guaranteeing Safety

- Ensure objects are accessible only when in a **consistent** and appropriate state
 - All invariants are maintained
 - Presents subclass obligations
- Use locks to enforce this
 - Rule of thumb 1: You must hold a lock when accessing shared data
 - Rule of thumb 2: You must not release a lock until shared data is in a valid state

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Guaranteeing Liveness

- Ensuring availability of services
 - Called methods eventually execute
- Ensuring progress of activities
 - Managing resource contention
 - Freedom from deadlock
 - Fairness
 - Fault tolerance

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Producer/Consumer Design

- Suppose we are communicating with a shared variable
 - E.g., some kind of a buffer holding messages
- One thread *produces* input to the buffer
- One thread *consumes* data from the buffer
- How do we implement this?
 - Use wait and notify

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Producer/Consumer Example

```
public class ProducerConsumer {
    private boolean valueReady = false;
    private Object value;

    synchronized void produce(Object o)
        throws InterruptedException {
        while (valueReady) wait();
        value = o; valueReady = true;
        notifyAll();
    }

    synchronized Object consume()
        throws InterruptedException {
        while (!valueReady) wait();
        valueReady = false;
        Object o = value;
        value = null; // why do we do this?
        notifyAll();
        return o;
    }
}
```

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Wait and Notify

- Both must be called while lock is held on **a**
- **a.wait()**
 - Releases the lock on **a**
 - But not any other locks acquired by this thread
 - Adds the thread to the wait set for **a**
 - Blocks the thread
- **a.wait(int m)**
 - Limits wait time to **m** milliseconds

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Wait and Notify (cont.)

- **a.notify()** resumes *one* thread from **a**'s wait set
 - No control over which thread
- **a.notifyAll()** resumes *all* threads on **a**'s wait set
- Resumed thread(s) must reacquire lock before continuing
 - Java performs the reacquire automatically

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April 5, 2005

(thanks to Doug Lea for some slides)

Condition Variables

- Want access to shared data, but only when some condition holds
 - Implies that threads play different *roles* in accessing shared data
- Examples
 - Want to read shared variable **v**, but only when it is non-null
 - Want to insert myself in a data structure, but only if it is not full

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CVs: Use Wait and Notify

To wait for a condition to become true:

```
synchronized (obj) {  
    while (condition does not hold)  
        obj.wait();  
    ... perform appropriate actions  
}
```

To notify waiters that a condition has changed:

```
synchronized (obj) {  
    ... perform actions that change condition  
    obj.notifyAll();  
}
```

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Use This Design

- This is the right solution to the problem
 - Tempting to try to just use locks directly
 - Very hard to get right
 - Problems with other approaches often very subtle
 - E.g., double-checked locking is broken

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Broken Producer/Consumer Example

```
public class ProducerConsumer {  
    private boolean valueReady = false;  
    private Object value;  
  
    synchronized void produce(Object o) {  
        while (valueReady) {};  
        value = o; valueReady = true;  
    }  
  
    synchronized Object consume() {  
        while (!valueReady) {};  
        valueReady = false;  
        Object o = value;  
        value = null;  
        return o;  
    }  
}
```

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Broken Producer/Consumer Example

```
public class ProducerConsumer {  
    private boolean valueReady = false;  
    private Object value;  
  
    void produce(Object o) {  
        while (valueReady) {};  
        synchronized (this) {  
            value = o; valueReady = true;  
        }  
    }  
  
    Object consume() {  
        while (!valueReady) {};  
        synchronized (this) {  
            valueReady = false;  
            Object o = value;  
            value = null;  
            return o;  
        }  
    }  
}
```

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Broken Producer/Consumer Example

```
public class ProducerConsumer {
    private boolean valueReady = false;
    private Object value;

    synchronized void produce(Object o)
        throws InterruptedException {
        if (valueReady) wait();
        value = o; valueReady = true;
        notifyAll();
    }

    synchronized Object consume()
        throws InterruptedException {
        if (!valueReady) wait();
        valueReady = false;
        Object o = value;
        value = null;
        notifyAll();
        return o;
    }
}
```

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notify() vs. notifyAll()

- Very tricky to use notify() correctly
 - notifyAll() generally much safer
- To use notify() correctly, should:
 - Have all waiters be equal
 - Each notify only needs to wake up one thread
 - Doesn't matter which thread it is
 - Handle exceptions correctly
 - Including InterruptedException
- For this course, just use notifyAll()

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Wait and Notify Gotcha's

- wait *must* be in a loop
 - Don't assume that when wait returns conditions are met
- Avoid holding other locks when waiting
 - Wait only gives up locks on the object you wait on

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Preventing Data Races

- One programming technique to prevent races:
 - Ensure that for every shared field x, there is some lock l such that no thread accesses x without holding lock l
- Note: This is not the *only* way to avoid races
 - There are fancier, more complicated techniques
 - But this is what you should do for your project

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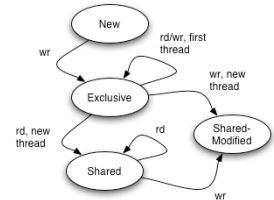
Detecting Races with checkSync

- Algorithm
 - Locks_held(t) = set of locks held by thread t
 - For each shared field x, $C(x) := \{ \text{all locks} \}$
 - On each access to x by thread t,
 - $C(x) := C(x) \cap \text{locks_held}(t)$
 - If $C(x) = \emptyset$ then issue a warning
 - From Savage et al, “Eraser: A Dynamic Race Detector for Multithreaded Programs,” TOCS 1997

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An Improvement

- Unsynchronized reads of a shared location are OK
 - As long as no one writes to the field after it becomes shared
- Track state of each field
 - Only enforce locking protocol when it becomes shared and written



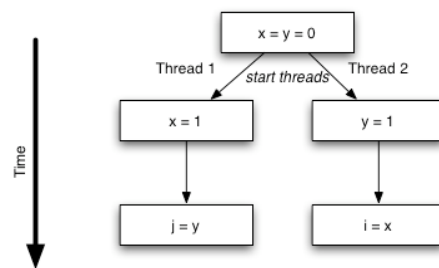
90

Aspects of Synchronization

- Atomicity
 - Locking to obtain mutual exclusion
 - What we most often think about
- Visibility
 - Ensuring that changes to object fields made in one thread are seen in other threads
- Ordering
 - Ensuring that you aren't surprised by the order in which statements are executed

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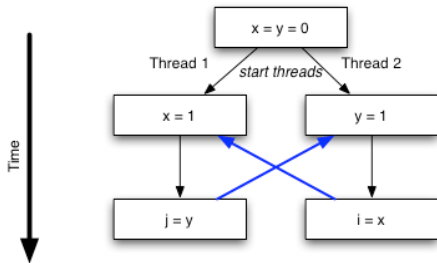
Quiz Time



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

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Doesn't Seem Possible...



- But this can happen!

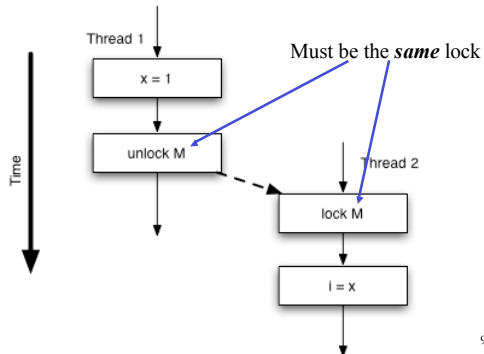
93

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

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When Are Actions Visible?



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Forcing Visibility of Actions

- All writes from thread that holds lock M are visible to next thread that acquires lock M
 - Must be the same lock
- Use synchronization to enforce **visibility** and **ordering**
 - As well as mutual exclusion

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Volatile Fields

- If you are going to access a shared field without using synchronization
 - It needs to be **volatile**
- Semantics for **volatile** have been strengthened in JSR-133
 - Many VM's already compliant
- If you don't try to be too clever
 - Declaring it **volatile** just works

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Using Volatile

- A one-writer/many-reader value
 - Simple control flags:
 - `volatile boolean done = false;`
- Keeping track of a “recent value” of something

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Misusing Volatile

- Incrementing a volatile field doesn't work
 - In general, writes to a volatile field that depend on the previous value of that field don't work
- A volatile reference to an object isn't the same as having the fields of that object be volatile
 - No way to make elements of an array volatile
- Can't keep two volatile fields in sync

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Thread Cancellation

- Example scenarios: want to cancel thread
 - Whose processing the user no longer needs (i.e., she has hit the “cancel” button)
 - That computes a partial result and other threads have encountered errors, ... etc.
- Java used to have `Thread.kill()`
 - But it and `Thread.stop()` are deprecated
 - Use `Thread.interrupt()` instead

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Thread.interrupt()

- Tries to wake up a thread
 - Sets the thread's interrupted flag
 - Flag can be tested by calling
 - **interrupted()** method
 - Clears the interrupt flag
 - **isInterrupted()** method
 - Does not clear the interrupt flag
- Won't disturb the thread if it is working
 - Not asynchronous!

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Cancellation Example

```
public class CancellableReader extends Thread {
    private FileInputStream dataFile;
    public void run() {
        try {
            while (!Thread.interrupted()) {
                try {
                    int c = dataFile.read();
                    if (c == -1) break;
                    else process(c);
                } catch (IOException ex) { break; }
            }
        } finally { // cleanup here }
    }
}
```

This could acquire locks, be on a wait set, etc.

What if the thread is blocked on a lock or wait set, or sleeping when interrupted?

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InterruptedException

- Thrown if interrupted while doing a **wait**, **sleep**, or **join**
 - Also thrown when *interrupt* flag is set and attempt to do a **wait**, **sleep**, or **join**
 - Not thrown when blocked (or blocking on) on a lock or I/O

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Responses to Interruption

- Early Return
 - Clean up and exit without producing errors
 - May require rollback or recovery
 - Callers can poll cancellation status to find out why an action was not carried out
- Continuation (i.e., ignore interruption)
 - When it is too dangerous to stop
 - When partial actions cannot be backed out
 - When it doesn't matter

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Responses to Interruption (cont'd)

- Re-throw **InterruptedException**
 - When callers must be alerted on method return
- Throw a general failure exception
 - When interruption is a reason method may fail
- In general
 - Must reset invariants before cancelling
 - E.g., close file descriptors, notify other waiters, etc.

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Handling InterruptedException

```
synchronized (this) {  
    while (!ready) {  
        try { wait(); }  
        catch (InterruptedException e) {  
            // make shared state acceptable  
            notifyAll();  
            // cancel processing  
            return;  
        }  
        // do whatever  
    }  
}
```

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Why No Thread.kill()?

- What if the thread is holding a lock when it is killed? The system could
 - Free the lock, but the data structure it is protecting might be now inconsistent
 - Keep the lock, but this could lead to deadlock
- A thread needs to perform its own cleanup
 - Use `InterruptedException` and `isInterrupted()` to discover when it should cancel

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Guidelines for Programming with Threads

- Synchronize access to shared data
- Don't hold multiple locks at a time
 - Could cause deadlock
- Hold a lock for as little time as possible
 - Reduces blocking waiting for locks
- While holding a lock, don't call a method you don't understand
 - E.g., a method provided by someone else, especially if you can't be sure what it locks
 - Corollary: document which locks a method acquires

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