CMSC 433 – Programming Language Technologies and Paradigms

Synchronization

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

What Will This Program Print?

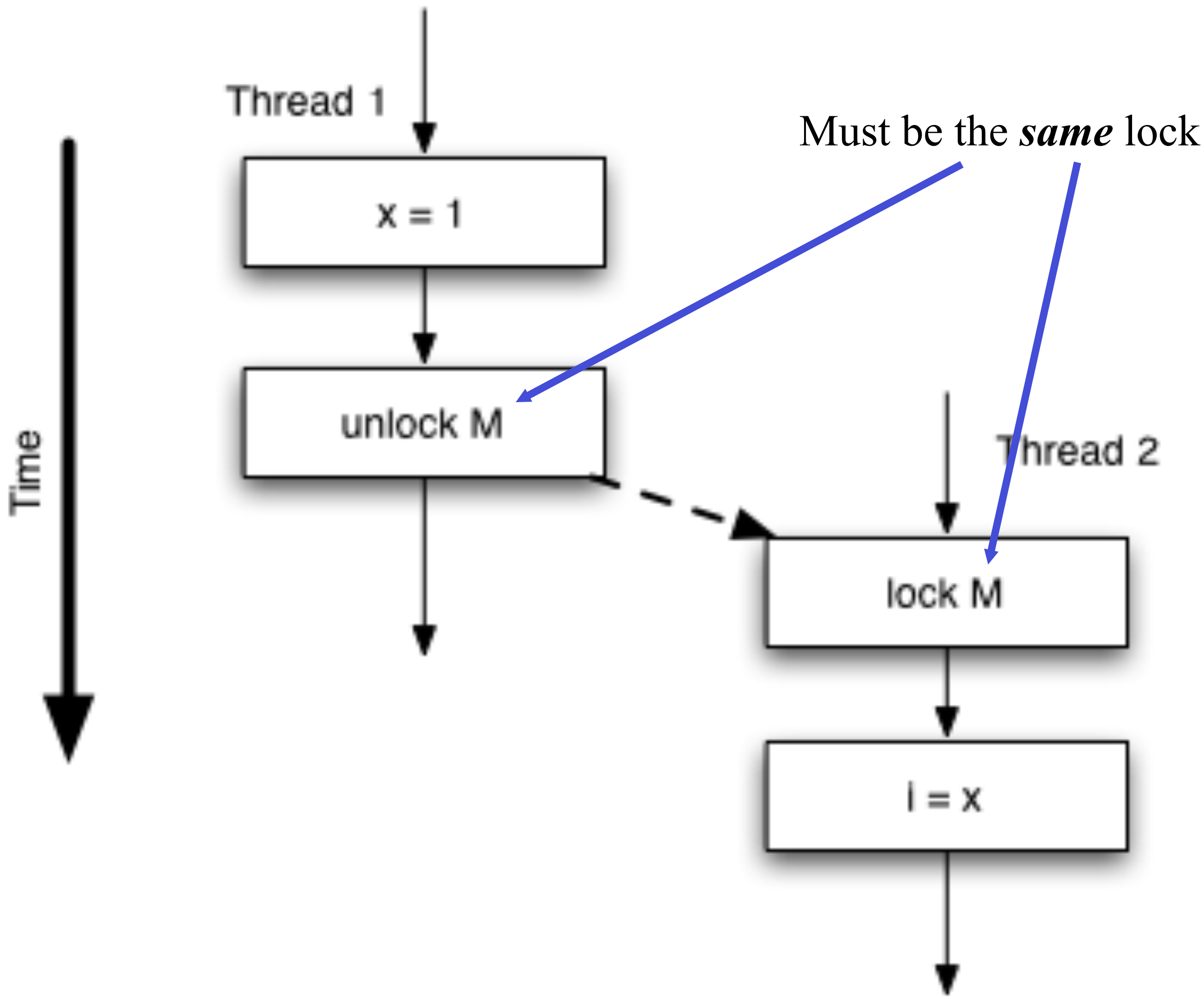
```
public class NoVisibility {
    private static boolean ready;
    private static int number;

    private static class ReaderThread extends Thread {
        public void run() {
            while (!ready)   Thread.yield();
            System.out.println(number);
        }
    }

    public static void main(String[] args) {
        new ReaderThread().start();
        number = 42;
        ready = true;
    }
}
```

- Some possible answers
  a) 42
  b) 0
  c) Nothing

When Are Actions Visible?



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
- When accesses are unsynchronized you get no guarantees
- One effect of synchronization is to enforce **visibility**

Happens-Before

- "Happens before" is a partial order describing program events, invented by Leslie Lamport.

Event Traces

- Consider multithreaded executions as traces R of events E

```
Events E ::= start(T) //i.e., T.start()
        | end(T)
        | read(T,x,v)
        | write(T,x,v)
        | spawn(T1,T2) // i.e., in T1: T2 = new Thread();
        | join(T1,T2) // i.e., in T1: T2.join();
        | lock(T,x)
        | unlock(T,x)
```

- Where T is a thread identifier, x is a variable, and v is a value.
- Event read(T,x,v) indicates that thread T read value v from variable x.
- Assume traces R are well-formed

Happens-Before

- Let E1 < E2 be the ordering of events as they appear in the trace
- Define happens-before ordering <: in a trace R as follows:

E1 <: E2 iff E1 < E2 and one of the following holds:

a) thread(E1) = thread(E2)
b) E1 is spawn(T1,T2), and E2 is start(T2)
c) E2 is join(T1,T2), and E1 is end(T2)
d) E1 is unlock(T1,x) and E2 lock(T2,x)
e) there exists E3 with E1 <: E3 and E3 <: E2 (i.e., the happens-before ordering is transitive)

Visibility

- For a trace R containing
  - WE== write(T1,x,v1) and RE == read(T2,x,v2)
- WE "is not visible" to RE if
  - RE <: WE
  - There exists some event WE2== write(T,x,v3) such that WE<: WE2<: RE (i.e., the first write is overwritten by the second)
- Otherwise WE is visible at ER

Trace R1

Initially x == 0

Thread 1:

x = 1

y = 2;

Thread 2:

y = x;

- R1 == write(T1,x,1); <u>read(T2,x,0);</u> write(T2,y,0); write(T1,y,2)
- read(T2,x,0) does not happen-before write(T1,x,1)
- So other behaviors are possible
  - For example, both x==1 and x==0 are visible

Trace R2

Initially x == 0

Thread 1:	Thread 2:
x = 1	y = x;
y = 2;	

- R2 == write(T1,x,1); read(T2,x,1); write(T2,y,1); write(T1,y,2)
- read(T2,x,1) does not happen-before write(T1,x,1)
- Both x==1 and x==0 are visible

Trace R3

Initially x == 0

Thread 1:

x = 1

y = 2;

Thread 2:

y = x;

- R3 == read(T2,x,0); write(T1,x,1); write(T2,y,0); write(T1,y,2)
- read(T2,x,0) goes first, so only x==0 is visible

Trace R4

Initially x == 0

Thread 1:

x = 1

y = 2;

Thread 2:

y = x;

- R4 == write(T1,x,1); read(T2,x,1); write(T1,y,2); write(T2,y,1)
- write(T2,y,1) goes last

Trace R5

Initially x == 0

Thread 1:

x = 1

y = 2;

Thread 2:

y = x;

- R5 == read(T2,x,0); write(T1,x,1); write(T1,y,2); write(T2,y,0)
- write(T2,y,0) goes last

Example

- So y can end up being {0,1,2}

R1 == write(T1,x,1); read(T2,x,0); write(T2,y,0); write(T1,y,2)

R2 == write(T1,x,1); read(T2,x,1); write(T2,y,1); write(T1,y,2)

R3 == read(T2,x,0); write(T1,x,1); write(T2,y,0); write(T1,y,2)

R4 == write(T1,x,1); read(T2,x,1); write(T1,y,2); write(T2,y,1)

R5 == read(T2,x,0); write(T1,x,1); write(T1,y,2); write(T2,y,0)

Another Example

(starting with x == 0)

Thread 1:

```
lock(y);
x = 1;
unlock(y);
```

Thread 2:

```
lock(y);
x = x + 1;
unlock(y);
```

Another Example

(starting with x = 0)

Thread 1:	Thread 2:
lock(y);	lock(y);
x = 1;	x = x + 1;
unlock(y);	unlock(y);

R1: lock(T1,y); write(T1,x,1); unlock(T1,y); lock(T2,y); read(T2,x,1); write(T2,x,2); unlock(T2,y)

Another Example

(starting with x = 0)

Thread 1:

```
lock(y);
x = 1;
unlock(y);
```

Thread 2:

```
lock(y);
x = x + 1;
unlock(y);
```

R2: lock(T2,y); read(T2,x,0); write(T2,x,1); unlock(T2,y); lock(T1,y); write(T1,x,1); unlock(T1,y);

Data Races

- The happens-before relation allows us to formally define data races
- A data race takes place when there are two events in trace R that
  - access the same memory location
  - at least one is a write
  - they are unordered according to happens-before

Data Race

Initially x == 0

Thread 1:	Thread 2:
x = 1	y = x;
y = 2;	

- R1 == write(T1,x,1); read(T2,x,0); write(T2,y,0); write(T1,y,2)
- Happens-before
  - write(T1,x,1) <: write(T1,y,2) and read(T2,x,0) <: write(T2,y,0)
- Data races between
  - write(T1,x,1) and read(T2,x,0)
  - write(T1,y,1) and write(T2,y,0)

Volatile Fields

- When a field is declared volatile, the JVM ensures that all threads see the latest value for the variable
- This allows you to access a shared field without using synchronization

Using Volatile

- A one-writer/many-reader value
  - Simple control flags:
    - volatile boolean done = false;

- Keeping track of a “recent value” of something

Limitations

- Incrementing a volatile field is not atomic
  – 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

Example

```
class Test {
    static int i = 0, j = 0;
    static void one() { i++; j++; }
    static void two() {System.out.println("i=" + i + " j=" + j);}
}
```

- Thread A calls Test.one() repeatedly
- Thread B calls Test.two() repeatedly
- Can the printed value of j ever be greater than that of i?
  - Yes. This is completely unsynchronized.

Example

```
class Test {
    static int i = 0, j = 0;
    static synchronized void one() { i++; j++; }
    static synchronized void two() {
        System.out.println("i=" + i + " j=" + j);
    }
}
```

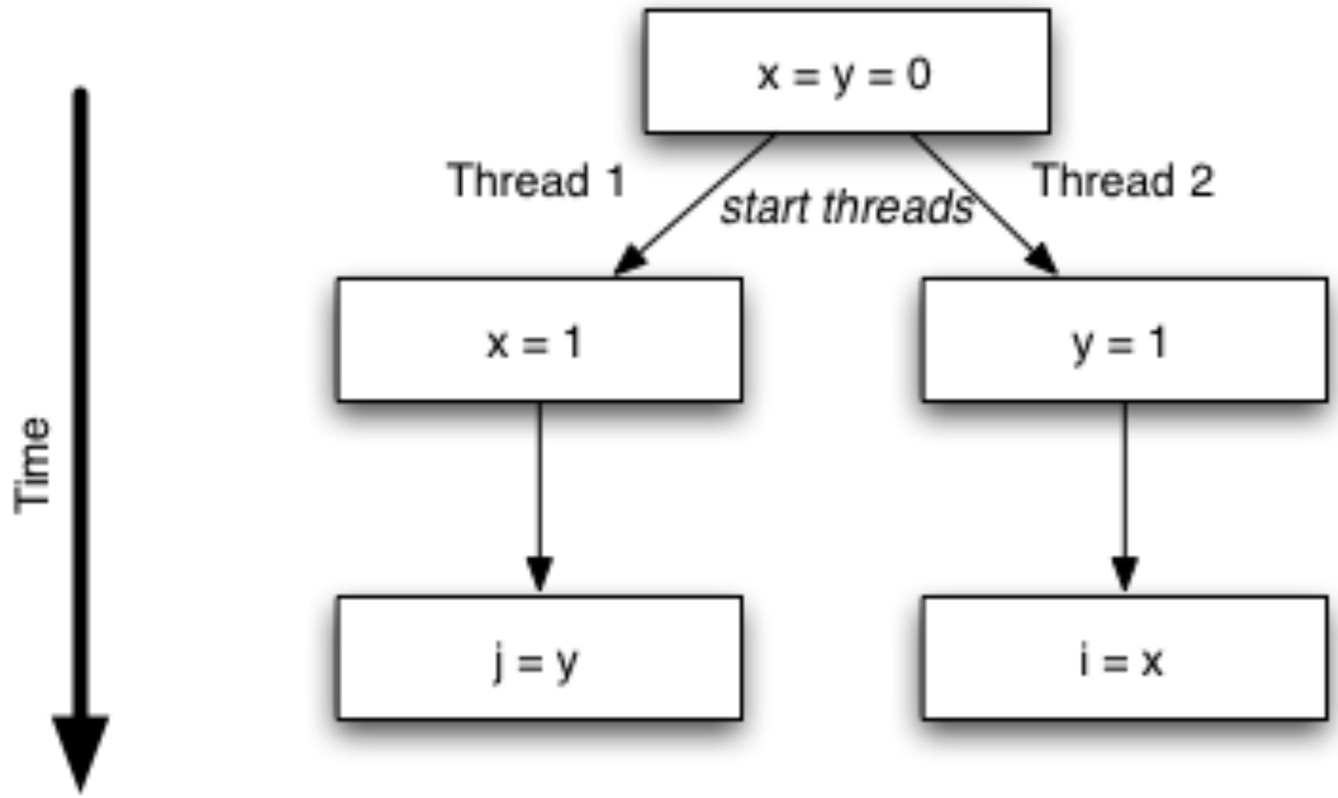
- How about now?
  - No. i and j are updated and read in apparent textual order

Example

```
class Test {
    static volatile int i = 0, j = 0;
    static void one() { i++; j++; }
    static void two() {System.out.println("i=" + i + " j=" + j);}
}
```

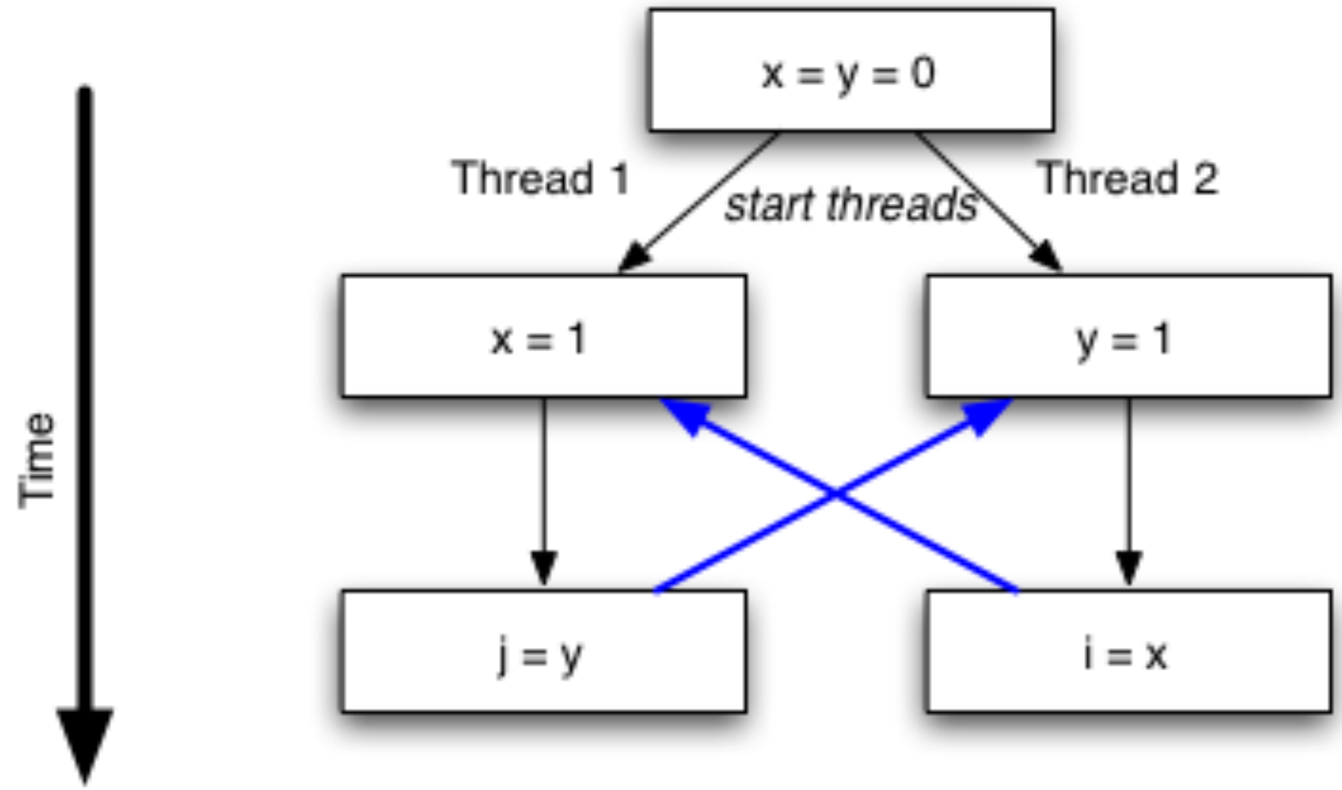
- How about now?
  - j could be < i, or it could be a lot bigger
  - I is incremented in one(). Both i and j are printed in two() before j is incremented in one()
  - e.g., one() could be called many times between the time two() accesses the value of i and then accesses the value of j.

Quiz Time



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

Doesn’t Seem Possible...



- But this can happen!

How Can This Happen?

- Compiler can reorder statements
  - Or keep values in registers
- Processor can reorder them
- On multi-processor systems, values not synchronized in global memory

Data Race

Initially x == 0

Thread 1:	Thread 2:
x = 1	y = x;
y = 2;	

- R1 == write(T1,x,1); read(T2,x,0); write(T2,y,0); write(T1,y,2)
- Happens-before
  - write(T1,x,1) <: write(T1,y,2)
  - read(T2,x,0) <: write(T2,y,0)
- Compiler might reorder the writes to x and y because they are independent and not ordered with accesses outside T1

Ordering

- Synchronization also influences the ordering of statements

Synchronization not a Panacea

- Two threads can block on locks held by the other; this is called *deadlock*
  - A set of threads is *deadlocked* if each thread is waiting for an event that only another thread in the set (including itself) can cause.

Deadlock

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

Deadlock Example

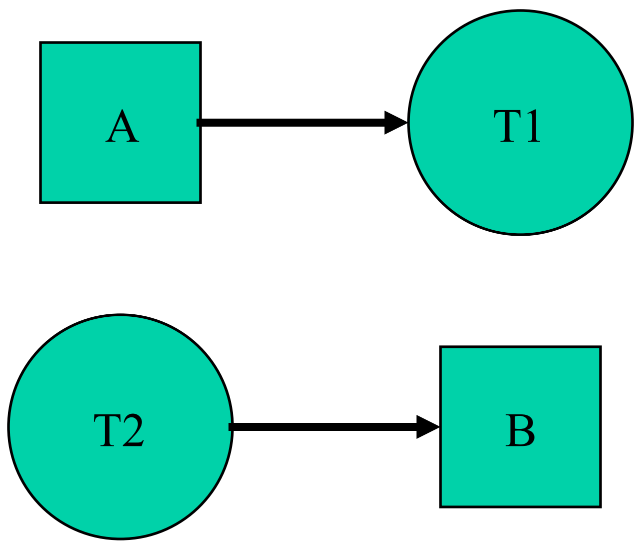
```
Object A = new Object();
Object B = new Object();
T1.run() {
  synchronized (A) {
    synchronized (B) {
      …
    }}}
T2.run() {
  synchronized (B) {
    synchronized (A) {
      …
    }}}
```

Deadlock Conditions

- For deadlock to occur the following conditions must hold simultaneously

1. Mutual exclusion: a non-sharable resource exists
2. Hold and wait: processes already holding resources may request new resources held by other processes
3. No preemption: No resource can be forcibly removed from a process that holds it
4. Circular wait: two or more processes form a circular chain where each process waits for a resource that the next process in the chain holds

Deadlock: Wait graphs

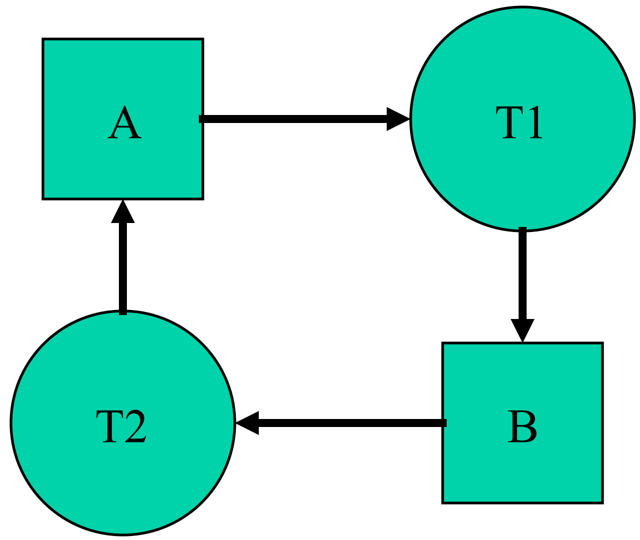


Thread T1 holds lock A

Thread T2 attempting to acquire lock B

Deadlock occurs when there is a cycle in the graph

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**

Key Ideas

- Multiple threads can run simultaneously
  - Either truly in parallel on a multiprocessor
  - Or effectively in parallel on a single processor
    - Assuming a running thread can be preempted at any time
- Threads can share data
  - Need to prevent interference
    - Synchronization, immutability, and other methods
  - Overuse use of synchronization can create deadlock
    - Violation of liveness

Ungraded Assignment

- Project
  - DeadLockExample
- This code can deadlock. See if you can figure out why.

In-Class Assignment

Initally $x=y=0$

$x=1$	$y=1$
$y=x$	$j=y$

- Write out 4 traces that could occur given this program
- Work out the happens-before relations for this code
- Use the happens-before relation to prove the existence of one or more data races