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();
  }
}
```

Data Race Example

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

Shared state cnt = 0

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

Data Race Example

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

y = 0

Shared state cnt = 0

T1 executes, grabbing the global counter value into y.

Data Race Example

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

Shared state cnt = 0

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

Data Race Example

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

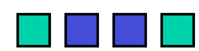
Shared state **cnt = 1**

T2 executes, storing the incremented cnt value.

Data Race Example

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

Shared state **cnt = 1**



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

But When I Run it Again?

Data Race Example

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

Shared state cnt = 0

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

Data Race Example

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

y = 0

Shared state cnt = 0

T1 executes, grabbing the global counter value into y.

Data Race Example

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

y = 0

Shared state **cnt = 1**

T1 executes again, storing the counter value

Data Race Example

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

Shared state cnt = 1

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

Data Race Example

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

y = 0

y = 1

Shared state **cnt = 2**

T2 executes, storing the incremented cnt value.

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.

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

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

What can this example generate?

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

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*

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

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;
  }
}
```

y = 0

Shared state cnt = 0

T1 reads cnt into y

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;
  }
}
```

y = 0

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

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;
  }
}
```

$y = 0$

Shared state **cnt = 1**

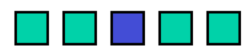
T1 runs, assigning to cnt

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;
  }
}
```

y = 0

Shared state cnt = 1



T1 releases the lock and terminates

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;
  }
}
```

$y = 0$

Shared state cnt = 1

T2 now can acquire the lock.

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
  }
}
```

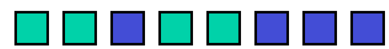
Shared state cnt = 1

T2 reads cnt into y.

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

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 attempt to acquire a lock in Java 1.4
  - Either succeeds, or blocks the thread

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

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** (there is no this)

Synchronization Example

```
public class State {
  private int cnt = 0;
  public synchronized void incCnt(int x) {
    cnt += x;
  }
  public synchronized int 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.

Locking

- The object locked, and the fields protected by the lock, may be different
- It is common to protect fields by holding a lock on the object they are fields of
  - but this is not required
- For example, fields of all the nodes of a tree might be protected by a lock on the tree

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, …

Need for Synchronization

- Need to use synchronization to ensure that two threads cannot access a shared memory location at the same time
  - Unless both are reading the memory
  - **volatile** is a special case we'll come to later

What can go wrong?

- Deadlock
- Insufficient atomicity
- Non-determinism
- Just plain wrong

Synchronization not a Panacea

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

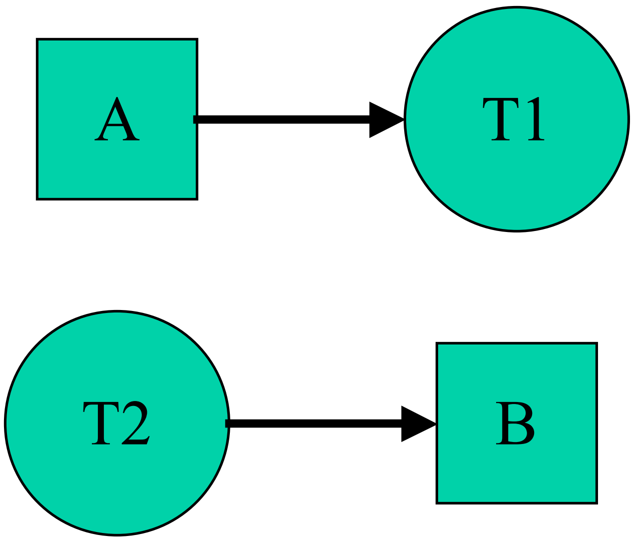
```
Object A = new Object();
Object B = new Object();
T1.run() {
  synchronized (A) {
    synchronized (B) {
      …
    }
  }
}
```

```
T2.run() {
  synchronized (B) {
    synchronized (A) {
      …
    }
  }
}
```

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

Deadlock: Wait graphs

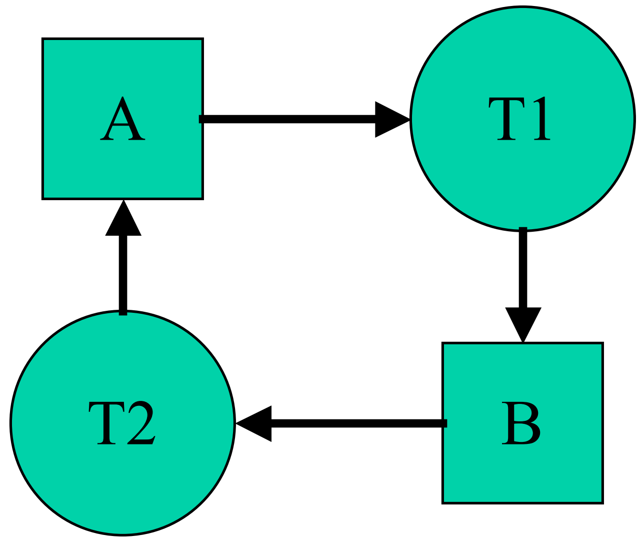


Thread T1 holds lock A

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**

Deadlock happens

- Consider:
  - each bank account is protected by a distinct lock
  - Operations on an account acquire the lock on that account
  - You want to move money from one account to the other
    - You need to hold both locks

Avoiding deadlock

- Can try to never hold a lock on more than one object at a time
  - Be careful what you call while holding a lock
- Can impose a lock ordering
  - A total order such that if X < Y and I hold a lock on both X and Y, I grab the lock on X before the lock on Y

Insufficient Atomicity

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

Insufficient Atomicity

- In a number of situations, you will want to
  - Examine the current state of the system
  - Update the system based on that examination
- You write this assuming that this will be done as an atomic action
  - But if the operations to examine the system and update the system are separate synchronized methods, doesn't work

Synchronized Maps

```
public class WordCounter extends Thread {

  static Map<String, Integer> wordCount
    = Collections.synchronizedMap(
       new HashMap<String, Integer>());

  public void run() {
    while (…) {
       String word = …;
       Integer v = wordCount.get(word);
       if (v == null) wordCount.put(word, 1);
       else wordCount.put(word, v+1);
   }
  }

}
```

Nondeterminism

- Even if your program is entirely “correct”, it may be non-deterministic
  - Not consistently producing the same result

- Makes testing your code difficult
- Makes finding bugs difficult
- Generally, no fix for nondeterminism in multithreaded code

Just plain wrong

- Multithreaded code can be subtle, and testing is difficult
- Easy to make mistakes when writing multithreaded code
- Use building blocks built by experts if possible
  - java.util.concurrent