Deadlock

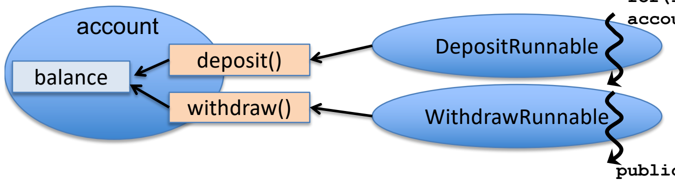
Thread Safety Issues

- Race conditions
- Deadlocks

- Thread-safe code is free from race conditions and deadlocks.

DeadlockedBankAccount.java

```
public void run(){
 for(int i = 0; i < 10; i++){
 account.deposit(100); }
```



```
public void run(){
 for(int i = 0; i < 10; i++){
 account.withdraw(100); }
```

DeadlockedBankAccount.java

```
public void run(){
 for(int i = 0; i < 10; i++){
 account.deposit(100); }
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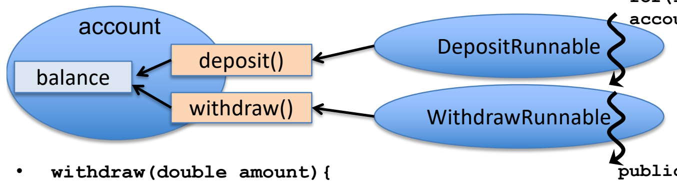


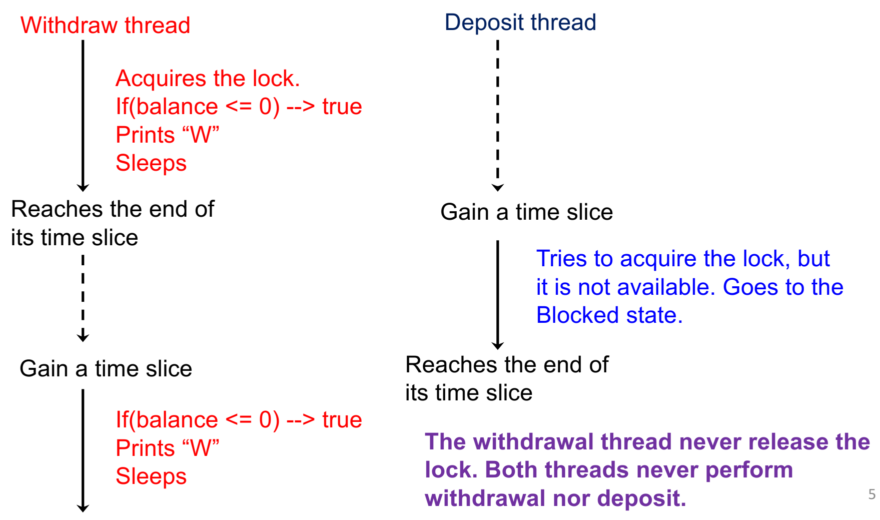
```
public void run(){
 for(int i = 0; i < 10; i++){
 account.withdraw(100); }
```

-
  ```
  withdraw(double amount){
   lock.lock();
   while(balance <= 0){
       System.out.print("W");
       // waiting for the balance to exceed 0
       Thread.sleep(1000);
   }
   balance -= amount;
   lock.unlock(); }
  ```

-
  ```
  deposit(double amount){
   lock.lock();
   while(balance >= 300){
       System.out.print("W");
       // waiting for the balance to go below 300
       Thread.sleep(1000)
   }
   balance += amount;
   lock.unlock(); }
  ```

How Can a Deadlock Occur?

- Suppose the withdrawal thread goes ahead.


Withdraw thread
Acquires the lock.
If(balance <= 0) --> true
Prints “W”
Sleeps
Reaches the end of its time slice
Gain a time slice
If(balance <= 0) --> true
Prints “W”
Sleeps
Deposit thread
Gain a time slice
Tries to acquire the lock, but it is not available. Goes to the Blocked state.
Reaches the end of its time slice

The withdrawal thread never release the lock. Both threads never perform withdrawal nor deposit.

Note

- A JVM can perform context switches even when a thread runs atomic code.
  - A lock guarantees that only one thread exclusively runs atomic code at a time.
  - Some resources explicitly/implicitly say that context switches never occur when a thread runs atomic code.
    - It is WRONG!

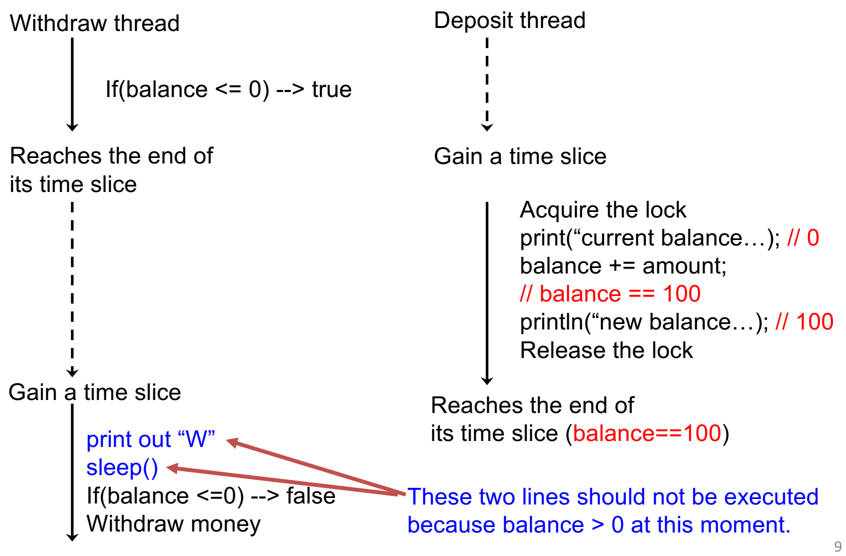
DeadlockedBankAccount2.java

- Previous version
  - withdraw(double amount){
```
  lock.lock();
  while( balance <= 0 ){
      System.out.print("W");
      // waiting for the
      // balance to exceed 0
      Thread.sleep(1000);
  }
  balance -= amount;
  lock.unlock();
}
```
  - deposit(double amount){
```
  lock.lock();
  while( balance >= 300 ){
      System.out.print("W");
      // waiting for the balance
      // to go below 300
      Thread.sleep(1000)
  }
   balance += amount;
  lock.unlock(); }
```

- New version
  - withdraw(double amount){
```
  while( balance <= 0 ){
      System.out.print("W");
      Thread.sleep(1000);
  }
  lock.lock();
  balance -= amount;
  lock.unlock();
}
```
  - deposit(double amount){
```
  while( balance >= 300 ){
      System.out.print("W");
      Thread.sleep(1000);
  }
  lock.lock();
  balance += amount;
  lock.unlock();
}
```

- Has no deadlock problems.
- Can generate race conditions.

A Potential Race Condition in DeadlockedBankAccount2



Withdraw thread

If(balance <= 0) --> true

Reaches the end of its time slice

Gain a time slice

print out "W"

sleep()

If(balance <=0) --> false

Withdraw money

Deposit thread

Gain a time slice

Acquire the lock
print("current balance…); // 0
balance += amount;
// balance == 100
println("new balance…); // 100
Release the lock

Reaches the end of its time slice (balance==100)

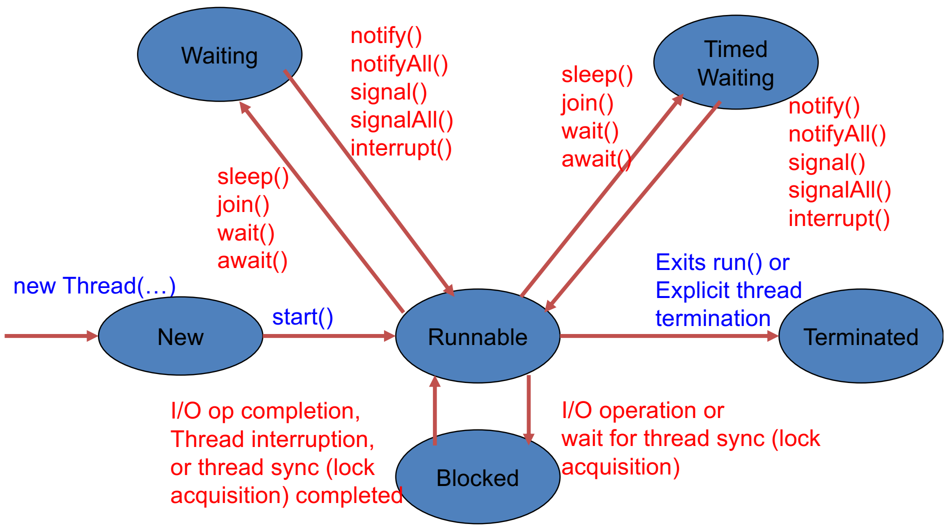
These two lines should not be executed because balance > 0 at this moment.

Avoiding Deadlocks and Race Conditions

- Use a `Condition` object(s).
  - Allows a thread to
    - Temporarily release a lock so that another thread can acquire it and proceed.
    - Re-acquire the lock later.
- `java.util.concurrent.locks.Condition`
  - Obtain its instance from a lock object

    -
      ```
      ReentrantLock lock = new ReentrantLock();
      Condition condition = lock.newCondition(); // Factory method
      condition.await();   // Temporarily releases the lock
                           // Goes to the Waiting state until getting
                           // signaled.
      ```

States of a Thread



ThreadSafeBankAccount2.java

-
  ```
  Condition sufficientFundsCondition = lock.newCondition();
  Condition belowUpperLimitFundsCondition = lock.newCondition();
  ```

-
  ```
  withdraw(double amount){
   lock.lock();
   while(balance <= 0){
        // Wait for the balance to exceed 0
       sufficientFundsCondition.await(); }
   balance -= amount;
   belowUpperLimitFundsCondition.signalAll();
   lock.unlock(); }
  ```

-
  ```
  deposit(double amount){
   lock.lock();
   while(balance >= 300){
       // Wait for the balance to go below 300.
       belowUpperLimitFundsCondition.await(); }
   balance += amount;
   sufficientFundsCondition.signalAll();
   lock.unlock(); }
  ```

ThreadSafeBankAccount2.java

```
• Condition sufficientFundsCondition = lock.newCondition();
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• withdraw(double amount){
   lock.lock();
   while(balance <= 0){
        // Wait for the balance to exceed 0
       sufficientFundsCondition.await(); }
   balance -= amount;
   belowUpperLimitFundsCondition.signalAll();
   lock.unlock(); }

• deposit(double amount){
   lock.lock();
   while(balance >= 300){
       // Wait for the balance to go below 300.
       belowUpperLimitFundsCondition.await(); }
   balance += amount;
   sufficientFundsCondition.signalAll();
   lock.unlock(); }
```

A “deposit” thread calls signalAll() to wake up a thread(s) that is/are waiting until balance > 0.

ThreadSafeBankAccount2.java

```
• Condition sufficientFundsCondition = lock.newCondition();
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        // Wait for the balance to exceed 0
       sufficientFundsCondition.await(); }
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   lock.unlock(); }

• deposit(double amount){
   lock.lock();
   while(balance >= 300){
       // Wait for the balance to go below 300.
       belowUpperLimitFundsCondition.await(); }
   balance += amount;
   sufficientFundsCondition.signalAll();
   lock.unlock(); }
```

A “withdraw” thread calls signalAll() to wake up a thread(s) that is/are waiting until balance < 300.

ThreadSafeBankAccount2.java

```
• Condition sufficientFundsCondition = lock.newCondition();
  Condition belowUpperLimitFundsCondition = lock.newCondition();

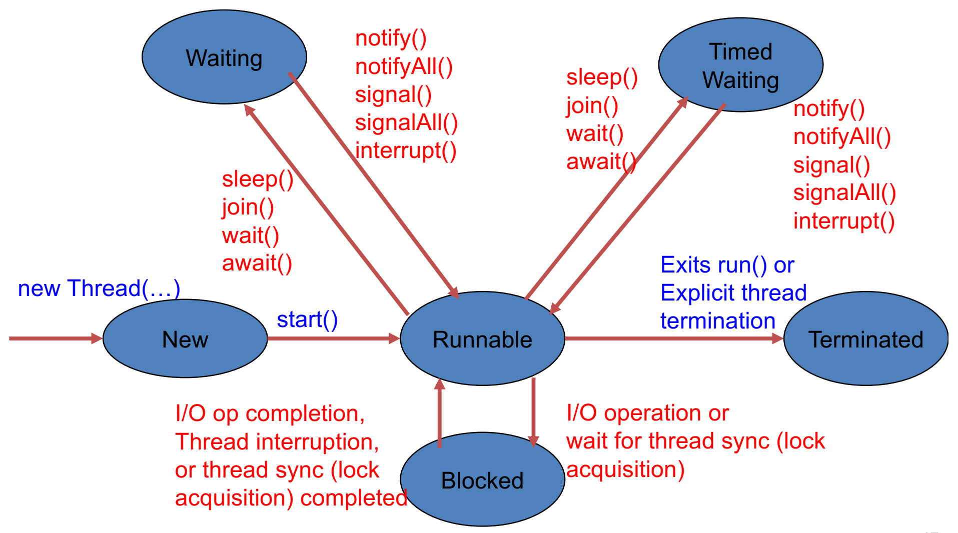
• withdraw(double amount){
   lock.lock();
   while(balance <= 0){
        // Wait for the balance to exceed 0
       sufficientFundsCondition.await(); }
   balance -= amount;
   belowUpperLimitFundsCondition.signalAll();
   lock.unlock(); }

• deposit(double amount){
   lock.lock();
   while(balance >= 300){
       // Wait for the balance to go below 300.
       belowUpperLimitFundsCondition.await(); }
   balance += amount;
   sufficientFundsCondition.signalAll();
   lock.unlock(); }
```

Condition

- `await()`
  - Will wait until it is signaled or interrupted
  - Will wait until it is signaled or interrupted, or until a specified waiting time (relative time) elapsed.
  - Will wait until it is signaled or interrupted, or until a specified deadline (absolute time).
  - If signaled, goes to the Runnable state and re-acquires a lock.
    - Will be “blocked” if the thread re-acquisition fails.
  - Throws an `InterruptedException` if interrupted.
    - c.f. A previous lecture note on thread interruption
- `signalAll()`
  - Wakes up all waiting threads on a condition object.
    - All of them go to the “runnable” state.
    - One of them will re-acquire a lock.

States of a Thread

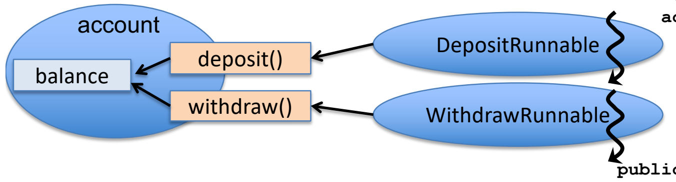


Waiting
Timed Waiting
New
Runnable
Terminated
Blocked
new Thread(…)
start()
sleep() join() wait() await()
notify() notifyAll() signal() signalAll() interrupt()
sleep() join() wait() await()
notify() notifyAll() signal() signalAll() interrupt()
Exits run() or Explicit thread termination
I/O op completion, Thread interruption, or thread sync (lock acquisition) completed
I/O operation or wait for thread sync (lock acquisition)

17

- When a thread calls await(), signal() or signalAll() on a Condition object,
  - the thread is assumed to hold a lock associated with the Condition object.
  - If the thread does not, an `IllegalMonitorStateException` is thrown.

2-Step Thread Termination



```
public void run(){
 while(done){
    account.deposit(100);} }
```

```
public void run(){
 while(done){
    account.withdraw(100);} }
```

```
withdraw(double amount){
    lock.lock();
    while(balance =< 0){
        try{
            // waiting for the balance to exceed 0
            sufficientFundsCondition.await();
        }catch(InterruptedException e){
            break; // Balking
        }
    }
    ...}
```

HW 16

- Implement 2-step termination for “deposit” and “withdraw” threads.
  - Implement a flag-based termination scheme in DepositRunnable and WithdrawRunnable
    - To let “deposit” and “withdraw” threads to return run().
  - Have the main thread call interrupt() on “deposit” and “withdraw” threads
    - To let those threads to wake up in case they are in the Waiting state due to await() or sleep().
- Due: Nov 29 (Thu) midnight

`signalAll()` *Before* or *After* a State Change?

-
  ```
  withdraw(double amount){
   lock.lock();
   while(balance =< 0){
       // waiting for the balance to exceed 0
      sufficientFundsCondition.await(); }
   balance -= amount;
   belowUpperLimitFundsCondition.signalAll();
   lock.unlock(); }
  ```

-
  ```
  deposit(double amount){
   lock.lock();
   while(balance >= 300){
      // waiting for the balance to go below 300.
      belowUpperLimitFundsCondition.await(); }
   balance += amount;
   sufficientFundsCondition.signalAll();
   lock.unlock(); }
  ```
- What if you call signalAll() first and then update the balance? Will any thread safety issues come out?

-
  ```
  withdraw(double amount){
   lock.lock();
   while(balance =< 0){
       // waiting for the balance to exceed 0
      sufficientFundsCondition.await(); }
   belowUpperLimitFundsCondition.signalAll();
   balance -= amount;
   lock.unlock(); }
  ```

-
  ```
  deposit(double amount){
   lock.lock();
   while(balance >= 300){
      // waiting for the balance to go below 300.
      belowUpperLimitFundsCondition.await(); }
   sufficientFundsCondition.signalAll();
   balance += amount;
   lock.unlock(); }
  ```
- For example, do you need to worry about race conditions in this case?

(1) W thread: "waiting" temporarily releases the lock

```
withdraw(double amount){
 lock.lock();
 while(balance <= 0){
     // waiting for the balance to exceed 0
    sufficientFundsCondition.await(); }
 belowUpperLimitFundsCondition.signalAll();
 balance -= amount;
 lock.unlock(); }
```

D thread: wakes up W thread, which is waiting until balance > 0.

```
deposit(double amount){
 lock.lock();
 while(balance >= 300){
     // waiting for the balance to go below 300.
    belowUpperLimitFundsCondition.await(); }
 sufficientFundsCondition.signalAll();
 balance += amount;
 lock.unlock(); }
```

(2) D thread: signalAll(). Ctx switch

- Can the "W" thread withdraw money before the "D" thread deposits money?
  - Can the balance have a negative value?
    - The answer is NO.

(1) W thread: "waiting" temporarily releases the lock

```
withdraw(double amount){
 lock.lock();
 while(balance <= 0){
     // waiting for the balance to exceed 0
    sufficientFundsCondition.await(); }
 belowUpperLimitFundsCondition.signalAll();
 balance -= amount;
 lock.unlock(); }
```

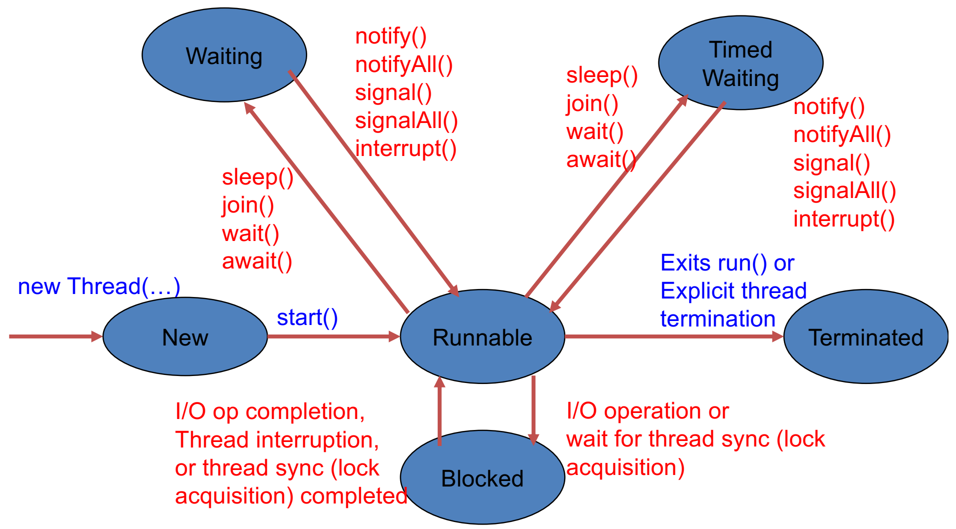
(3) W thread: "runnable" Tries to acquire the lock again and fails. Goes to "blocked."

```
deposit(double amount){
 lock.lock();
 while(balance >= 300){
     // waiting for the balance to go below 300.
    belowUpperLimitFundsCondition.await(); }
 sufficientFundsCondition.signalAll();
 balance += amount;
 lock.unlock(); }
```

(2) D thread: signalAll(). Ctx switch

- "W" thread CANNOT withdraw money before "D" thread deposits money.
- "D" thread CANNOT deposit money before "W" thread withdraws money.

States of a Thread



Two Important Things (1)

- You can safely change the state/value of a shared variable after calling signalAll().
  - AS FAR AS the state changes in atomic code
- Common programming convention/practice:
  - A state change first, followed by signalAll().

Two Important Things (2)

- A JVM can perform context switches even when a thread runs atomic code.
  - A lock guarantees that only one thread exclusively runs atomic code at a time.
  - Some resources (books, online materials, etc.) explicitly/implicitly say that context switches never occur when a thread runs atomic code.
    - It is WRONG!

signal() and signalAll()

- signalAll()
  - Wakes up all waiting threads on a condition object.
    - All of them go to the "runnable" state.
    - One of them will re-acquire a lock. The others will go to the "blocked" state.
- signal()
  - Wakes up one of waiting threads on a condition object.
    - The selected thread goes to the "runnable" state. The others stay at the "waiting" state.
    - JVM's thread scheduler selects one of them. Assume random selection.
      - Not predictable which waiting thread to be selected.

signal() and signalAll()?

- Either one works well.
- signalAll() is favored in many cases/projects.
  - I prefer signalAll() in my personal taste.

ThreadSafeBankAccount2.java

-
  ```
  Condition sufficientFundsCondition = lock.newCondition();
  Condition belowUpperLimitFundsCondition = lock.newCondition();
  ```

-
  ```
  withdraw(double amount){
   lock.lock();
   while(balance <= 0){
       // waiting for the balance to exceed 0
      sufficientFundsCondition.await(); }
   balance -= amount;
   belowUpperLimitFundsCondition.signalAll();
   lock.unlock(); }
  ```

-
  ```
  deposit(double amount){
   lock.lock();
   while(balance >= 300){
      // waiting for the balance to go below 300.
      belowUpperLimitFundsCondition.await(); }
   balance += amount;
   sufficientFundsCondition.signalAll();
   lock.unlock(); }
  ```

“while” or “if” to Surround await()?

-
  ```
  withdraw(double amount){
   lock.lock();
   while(balance <= 0){
       // waiting for the balance to exceed 0
      sufficientFundsCondition.await(); }
   balance -= amount;
   belowUpperLimitFundsCondition.signalAll();
   lock.unlock(); }
  ```

-
  ```
  deposit(double amount){
   lock.lock();
   while(balance >= 300){
      // waiting for the balance to go below 300.
      belowUpperLimitFundsCondition.await(); }
   balance += amount;
   sufficientFundsCondition.signalAll();
   lock.unlock(); }
  ```
- “while” should be used rather than “if” when multiple threads call withdraw() concurrently. Why?

A Potential Problem

(1) b==0. Two W threads: “waiting”

-
  ```
  withdraw(double amount){
   lock.lock();
   if(balance =< 0){
       // waiting for the balance to excee
      sufficientFundsCondition.await(); }
   balance -= amount;
   belowUpperLimitFundsCondition.signalAl
   lock.unlock(); }
  ```

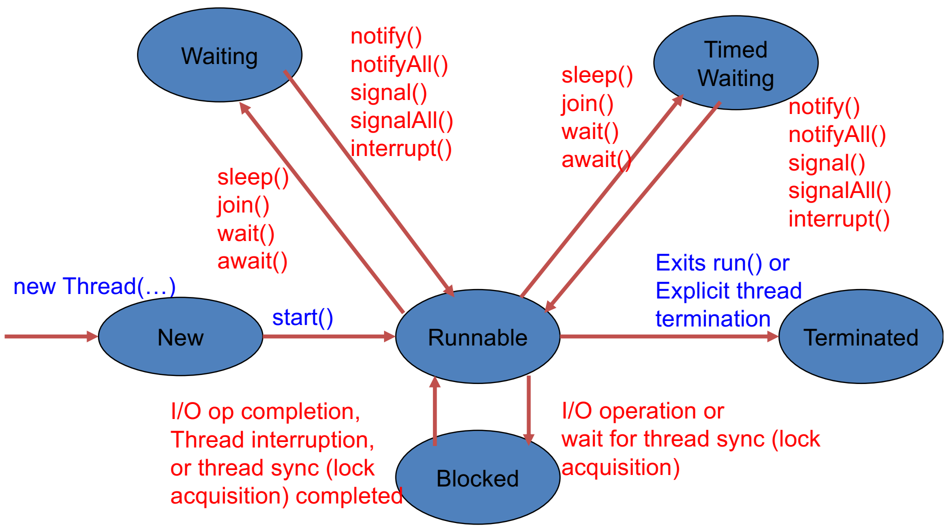
(3) Two W threads: Go to “runnable” One of them acquires the lock again.

The other W thread: Go to “blocked” on acquiring the lock.

```
deposit(double amount){
 lock.lock();
 if(balance >= 300){
    // waiting for the balance to go below 300.
    belowUpperLimitFundsCondition.await(); }
 balance += amount;
 sufficientFundsCondition.signalAll();
 lock.unlock(); }
```

(2) D thread: signalAll() followed by unlock() b==100

States of a Thread



(1) b==0. Two W threads: “waiting”

```
withdraw(double amount){
 lock.lock();
 if(balance =< 0){
     // waiting for the balance to exceed 0
    sufficientFundsCondition.await(); }
 balance -= amount;
 belowUpperLimitFundsCondition.signalAll();
 lock.unlock(); }
```

(3) Two W threads: Go to “runnable” One of them acquires the lock again, withdraws money and releases the lock. b==0.

(4) The 2nd W thread acquires the lock and withdraws money. b==-100.

```
deposit(double amount){
 lock.lock();
 if(balance >= 300){
    // waiting for the balance to go below 300.
    belowUpperLimitFundsCondition.await(); }
 balance += amount;
 sufficientFundsCondition.signalAll();
 lock.unlock(); }
```

(2) D thread: signalAll() followed by unlock() b==100

(1) b=0. Two W threads: “waiting”

```
withdraw(double amount){
 lock.lock();
 if(balance =< 0){
     // waiting for the balance to excee
    sufficientFundsCondition.await(); }
 balance -= amount;
 belowUpperLimitFundsCondition.signalAll
 lock.unlock(); }
```

(3) Two W threads: “runnable” One of them acquires the lock again and releases it. balance==0. The other W thread: “blocked” on acquiring the lock.

```
deposit(double amount){
 lock.lock();
 if(balance >= 300){
    // waiting for the balance to go below 300.
    belowUpperLimitFundsCondition.await(); }
 balance += amount;
 sufficientFundsCondition.signalAll();
 lock.unlock(); }
```

(4) The 2nd W thread acquires the lock and releases it. b==-100.

(2) D thread: signalAll() followed by unlock() balance==100

- The 2nd “W” thread should have made sure if balance>0.
- If only one “W” thread runs, this problem does not occur.
- Just always use a while loop regardless of the number of threads you use.

“if” or “while” in Atomic Code?

- You can use “if”, rather than “while,” for a conditional check
  – if you use signal(), not signalAll().
- However, in practice, the **while-signalAll** pair is more common than the **if-signal** pair.