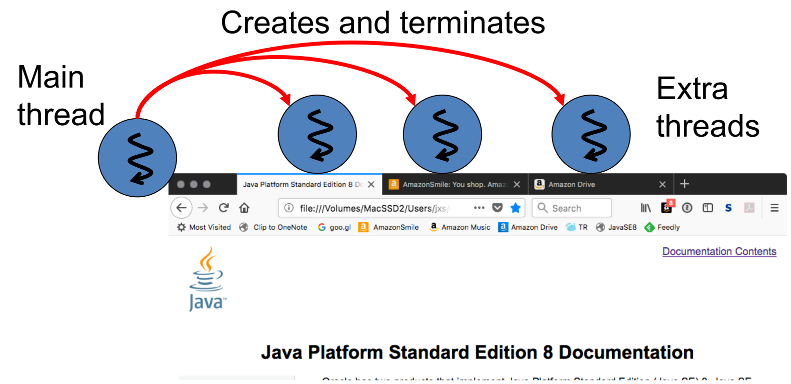
Race Conditions and Thread Synchronization (Locking)

Goals of Concurrency/Multi-threading

- **Responsiveness**



- **Efficiency**
  – c.f. MCTest, multi-threaded prime number generation

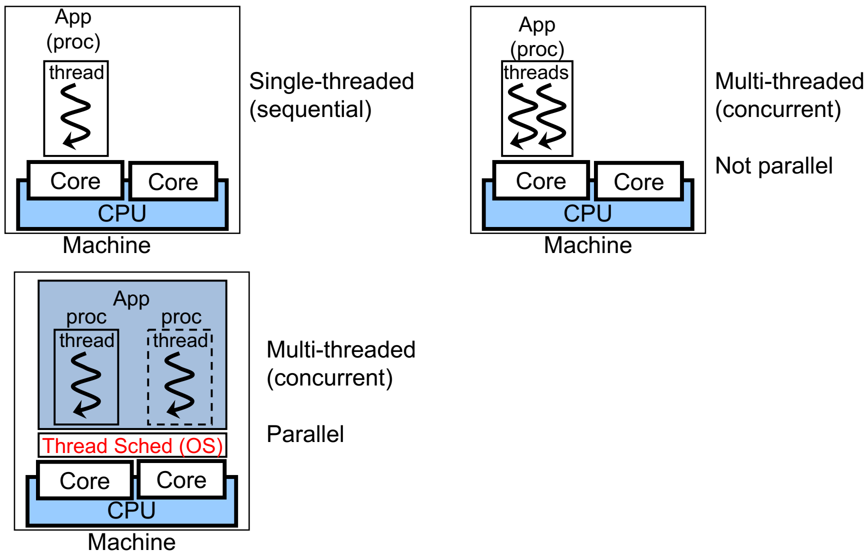
Thread Safety

- Threads are a powerful tool to make your code more responsive and efficient.
- However, multi-threaded code can raise ***"thread safety" issues*** if it is poorly written.
- 2 major thread safety issues
  – Race conditions (data races)
    - Mess up the consistency of data shared among threads
  – Deadlock
    - Make code execution stuck.
- Thread-safe code is free from those 2 issues.

Race Conditions (a.k.a. Data Races)

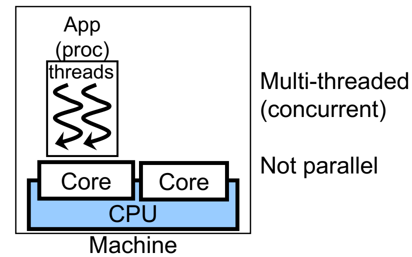
- Threads run *independently*.
  – No coordination among threads by default.
    - c.f. MCTest, PrimeNumberGenerator
    - join() allows threads to coordinate with each other.
- They can share objects/data.
  – Exception: Local variables are NOT shared among threads.
- They can mess up the consistency of the shared objects/data.
  – A thread can write some data to a variable when another thread is reading data from the variable.
  – A thread can write some data to a variable when another thread is writing different data to the variable.

Single- and Multi-threaded Programs



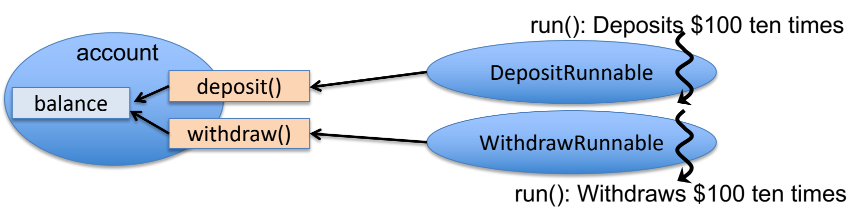
In CS681…

- We always assume a single CPU core that runs multiple threads.
  – The most conservative scenario.
- If your code is thread-safe in the most conservative scenario, it is always thread-safe in less conservative scenarios as well.



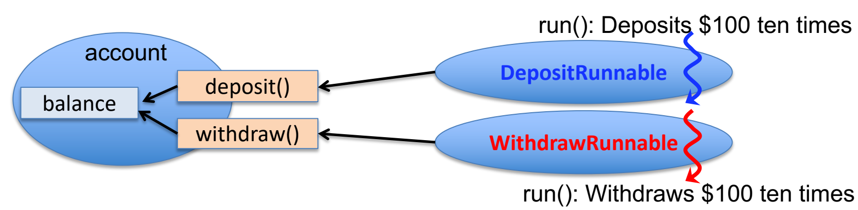
An Example Race Condition:

ThreadUnsafeBankAccount.java



- The variable “balance” is shared by 2 threads.
- They access the variable independently.

```
• public void deposit(double amount){
      System.out.print("Current balance (d): " + balance);
      double newBalance = balance + amount;
      System.out.println(", New balance (d): " + newBalance);
      balance = newBalance;
  }
• public void withdraw(double amount){
      System.out.print("Current balance (w): " + balance);
      double newBalance = balance - amount;
      System.out.println(", New balance (w): " + newBalance);
      balance = newBalance;
  }
```

- Desirable output:
  - `Current balance (w): 0.0, New balance (w): -100.0`
  - `Current balance (d): -100.0, New balance (d): 0.0`
  - `Current balance (w): 0.0, New balance (w): -100.0`
  - `Current balance (d): -100.0, New balance (d): 0.0`
  - `Current balance (d): 0.0, New balance (d): 100.0`
  - `Current balance (w): 100.0, New balance (w): 0.0`
  - `...`
- In reality:
  - `Current balance (w): 0.0Current balance (d): 0.0, New balance (d): 100.0`
  - `, New balance (w): -100.0`

How Can This Happen?

- Current balance (w): 0.0Current balance (d): 0.0, New balance (d): 100.0
- , New balance (w): -100.0

Withdraw thread

print("current balance…) // balance==0
newBalance = balance - 100;

Reaches the end of its time slice (newBalance==-100, balance==0)

Context switch

inactive

Gain a time slice

print (", New balance…");
// newBalance==-100
balance = newBalance
// balance==-100

Deposit thread

inactive

Gain a time slice

print("current balance…);
// balance==0
newBalance=balance+100;
println("new balance…");
// newBalance==100
balance = newBalance
// balance==100

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

Context switch

inactive

- Current balance (w): 0.0Current balance (d): 0.0, New balance (d): 100.0
- , New balance (w): -100.0

Withdraw thread

print("current balance…) // balance==0
newBalance = balance - 100;

Reaches the end of its time slice (newBalance==-100, balance==0)

Gain a time slice

println("new balance…");
// newBalance==-100
balance = newBalance
// balance==-100

Deposit thread

Gain a time slice

print("current balance…);
// balance==0
newBalance=balance+100
println("new balance…");
// newBalance==100
balance = newBalance
// balance==100

"balance" should have been *consistent* between 2 threads.

The Source of the Problem: Visibility

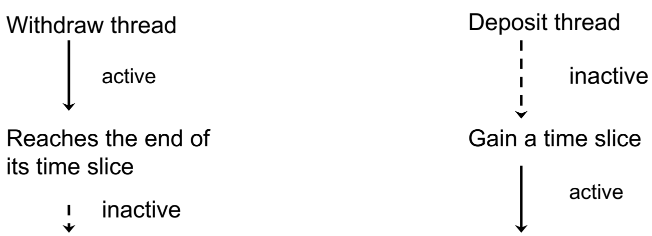
- ThreadUnsafeBankAccount.java is NOT thread safe.
  – Race conditions can occur.
- Race conditions occur due to visibility issues.
  – The current (most up-to-date) value of the shared variable (e.g. "balance") is *not visible* for all threads.

Race Conditions (a.k.a. Data Races)

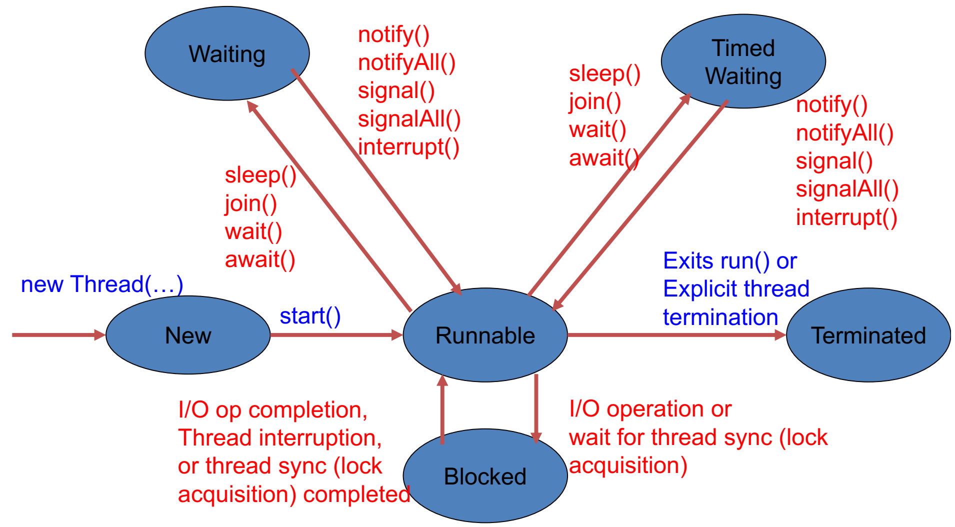
- All threads
  – Run in their *race* to complete their tasks.
  – Manipulate a shared object/data independently.
- The end result depends on which of them happens to win the race.
  – No guarantees on the order of thread execution.
  – No guarantees on how many tasks a thread can perform in a single CPU time slice/quota.
  – No guarantees on the end result on shared data.

Note: Thread States

- Both "active" and "inactive" threads are in the *Runnable* state.
  - The *Runnable* state does NOT distinguish if a thread is "actively running" on a CPU core or it is "inactively waiting" for its next turn.
  - The Waiting state does NOT mean that a thread is runnable but inactive.

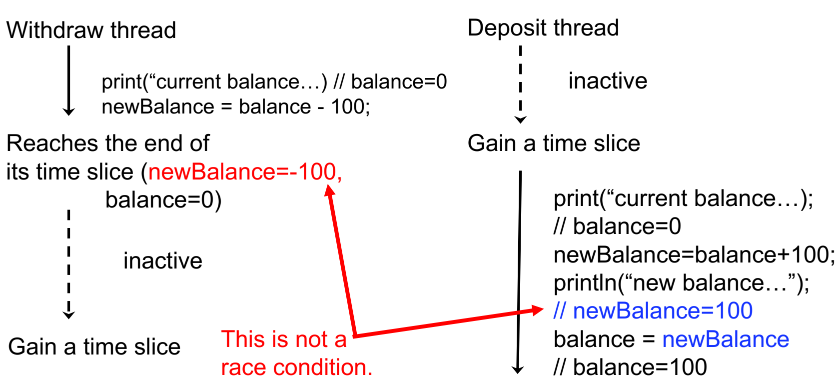


States of a Thread



Note: Local Variables

- Local variables are NOT shared by threads.
  - It is created and maintained in a thread-by-thread manner.
    - The "withdraw" thread has no access to a value of newBalance that the "deposit" thread has created.
    - The "deposit" thread has no access to a value of newBalance that the "withdraw" thread has created.



- Race conditions never occur due to local variables.
- Focus on non-local (i.e. shared) variables in debugging threaded code.

- Two other example local variables

```
– public void deposit(double amount){
        System.out.print("Current balance (d): " + balance);
        double newBalance = balance + amount;
        System.out.println(", New balance (d): " + newBalance);
        balance = newBalance;
  }
– public void withdraw(double amount){
        System.out.print("Current balance (w): " + balance);
        double newBalance = balance - amount;
        System.out.println(", New balance (w): " + newBalance);
        balance = newBalance;
  }
```

Another Example:

ThreadUnsafeBankAccount2

- Local variables (newBalance) are removed from ThreadUnsafeBankAccount

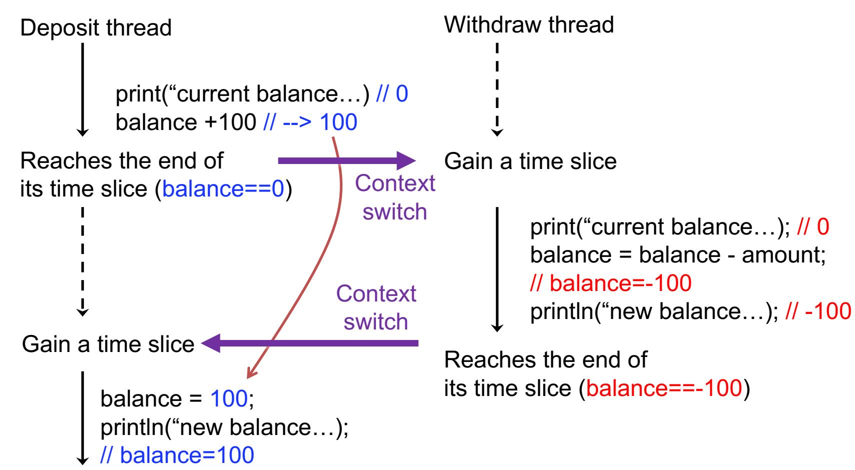
```
– public void deposit(double amount){
       balance = balance + amount;
  }
– public void withdraw(double amount){
       balance = balance - amount;
  }
```

- Output

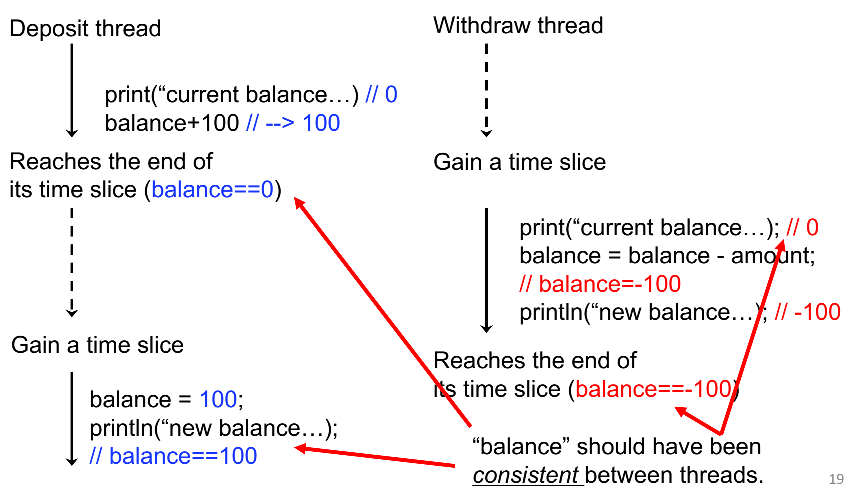
```
– Current balance (d): 0.0, New balance (d): 100.0
– Current balance (w): 100.0, New balance (w): 0.0
– Current balance (d): 0.0, New balance (d): 100.0
– Current balance (w): 100.0, New balance (w): 0.0
– Current balance (d): 0.0Current balance (w): 0.0, New balance (w):
  -100.0
– , New balance (d): 100.0
```


How Can This Happen?

```
• Current balance (d): 0.0Current balance (w): 0.0, New balance (w): -100.0
• , New balance (d): 100.0
```



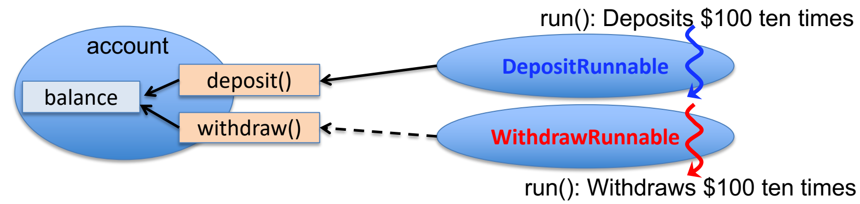

```
• Current balance (d): 0.0Current balance (w): 0.0, New balance (w): -100.0
• , New balance (d): 100.0
```



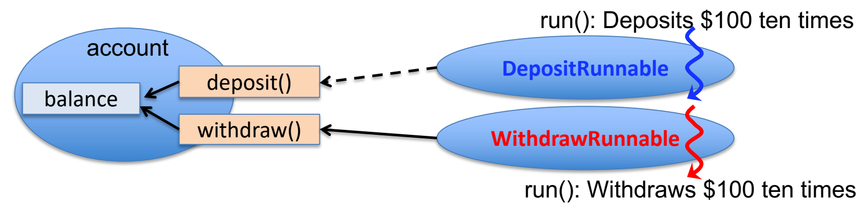
- This is not a solution: `balance -= amount;`
  - Just a syntactic sugar for `balance = balance - amount;`
- All threads
  - Run in their *race* to complete their tasks.
  - Manipulate a shared object/data independently.
- The end result depends on which of them happens to win the race.
  - No guarantees on the order of thread execution.
  - No guarantees on how many tasks a thread can perform in a single CPU time slice.
  - No guarantees on the end result on shared data.

Solution: Thread Synchronization

- Need to *synchronize* threads
  - i.e., Need to *serialize* their concurrent access to a shared variable
- Thread synchronization
  - Enables serialized (or mutually-exclusive) access to a shared variable
  - Allows only one thread to access a shared variable at a time
    - Forces all other threads to wait and take turn to access it.



- Thread synchronization
  - Prevents the "withdraw" thread from withdrawing money from "balance" when the "deposit" thread is depositing money to "balance."
  - Prevents the "deposit" thread from depositing money to "balance" when the "withdraw" thread is withdrawing money from "balance."



Thread Synchronization with Java

- Java implements thread synchronization by
  - Providing locks
  - Allowing you to write *atomic code* (a.k.a critical section) with locks.
    - Atomic code: A piece of code that is executed by multiple threads in a synchronized (or serialized, or mutually-excluded) manner.
      - When a thread is running atomic code, no other threads can run it.
    - No intermediate results/states produced in atomic code can be revealed/exposed to other threads.

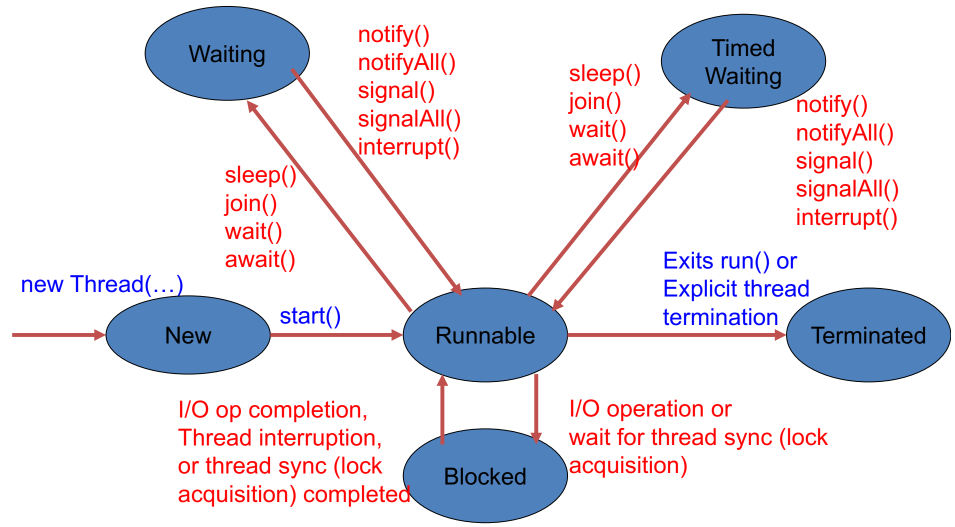
Locks in Java

- Used to synchronize (or serialize, or mutually-exclude) multiple threads that access shared data.
- `java.util.concurrent.locks.Lock` interface
  - `ReentrantLock` class: the most commonly-used class for thread synchronization
    - Defines methods that
      - allow threads to access shared data in a synchronized (or serialized, or mutually-excluded) manner.
      - allow you to write atomic code.
- Atomic code is surrounded by `lock()` and `unlock()` method calls.

```
ReentrantLock aLock = new ReentrantLock();
aLock.lock();
atomic code (access to shared data)
aLock.unlock();
```

- Once a thread calls `lock()`,
  - it acquires and owns a *lock* until it calls `unlock()`.
  - No other threads can acquire the lock until it is released by `unlock()`.
    - No other threads can run atomic code until the lock is released with `unlock()`.
- If a thread calls `lock()` when another thread already owns the lock,
  - it goes to the *blocked* state and *gets blocked* (cannot do anything further) until the lock is released.

States of a Thread



How Can a Blocked Thread Run Again?

- JVM's thread scheduler
  - Periodically reactivates all blocked threads so that they can try to acquire the target lock.
    - If the lock is still unavailable, they get blocked again.
  - Detects a release of the target lock (i.e. completion of atomic code).
    - May notify all blocked threads so that one of them can acquire the target lock.
    - May choose one of the blocked threads to acquire the lock.
- Each blocked thread can eventually acquire the target lock when it is available.

Coding Idiom for Locking

- Call unlock() in a finally clause.
  - ReentrantLock aLock = new ReentrantLock();
    aLock.lock();
    try {
    atomic code (access to a shared variable)
    }
    finally {
    aLock.unlock();
    }
- unlock() is never invoked
  - if run() returns in atomic code
  - if atomic code throws an exception
  - A deadlock occurs.
    - Atomic code is locked forever, and no other threads can acquire the lock to run the atomic code.

- ```
  aLock.lock();
  try{
      atomic code
  }
  finally{
      aLock.unlock();
  }
  ```

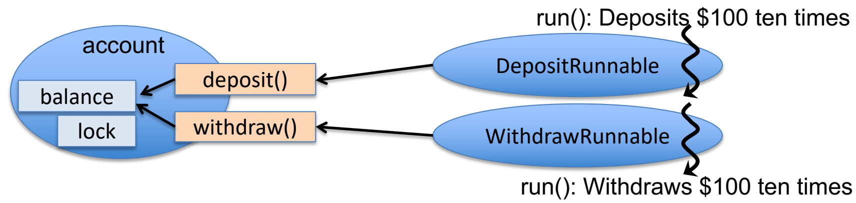
  DO THIS!

- ```
  try{
      aLock.lock();
      atomic code
  }
  finally{
      aLock.unlock();
  }
  ```

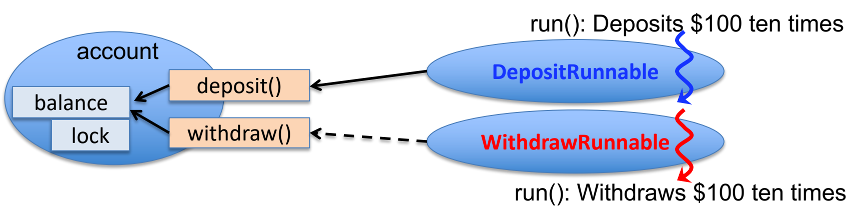
  DON'T DO THIS!

- Make sure to call lock() BEFORE a "try" block.
- If a thread throws an exception in lock(), it will not acquire the lock. However, it will call unlock().
  - lock() can throw an InterruptedExcepetion when another thread call interrupt().

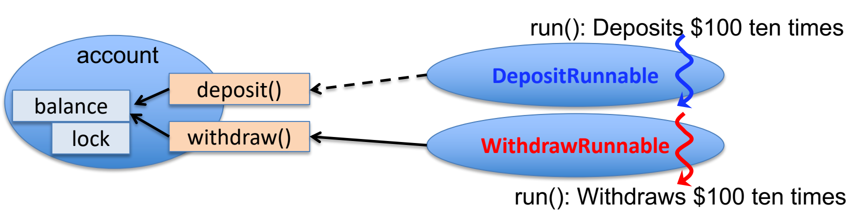
ThreadSafeBankAccount.java




- ```
  private ReentrantLock lock = new ReentrantLock();
  ```
- ```
  public void deposit(double amount){
      lock.lock();
       try{
          balance += amount;  // atomic code
      }finally{
          lock.unlock(); }
  }
  ```
- ```
  public void withdraw(double amount){
      lock.lock();
      try{
          balance -= amount;  // atomic code
      }finally{
          lock.unlock(); }
  }
  ```

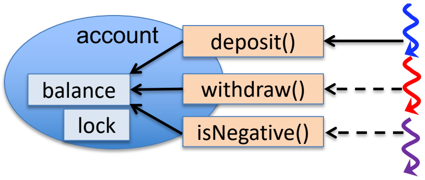



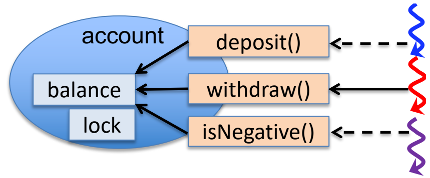
- Thread synchronization
  - Prevents the "withdraw" thread from withdrawing money from "balance" when the "deposit" thread is depositing money to "balance."
  - Prevents the "deposit" thread from depositing money to "balance" when the "withdraw" thread is withdrawing money from "balance."



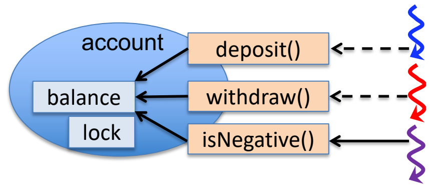
Summary: How to Avoid Race Conditions?

- When multiple threads share and access a variable concurrently,
  - Make sure to guard the shared variable with a lock.
    - Identify ALL read and write logic to be performed on the variable
    - Surround each of them with lock() and unlock().
  - e.g.,
    ```
    public void deposit(double amount){
        lock.lock();
         try{
            balance += amount;  // atomic code (read and write)
        }finally{
            lock.unlock(); }
    }
    ```
  - ```
    public void withdraw(double amount){
        lock.lock();
        try{
            balance -= amount;  // atomic code (read and write)
        }finally{
            lock.unlock(); }
    }
    ```



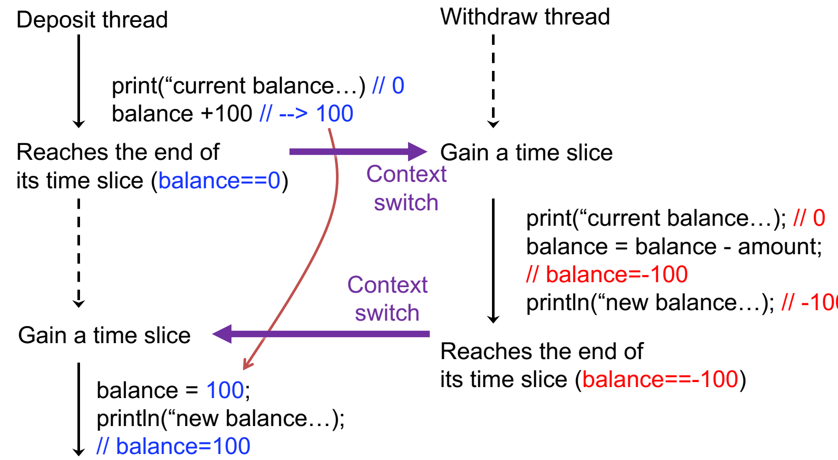


- `private ReentrantLock lock = new ReentrantLock();`
- ```
  public void deposit(double amount){
      lock.lock();
      balance += amount;
      lock.unlock(); }
  ```
- ```
  public void withdraw(double amount){
      lock.lock();
      balance -= amount;
      lock.unlock(); }
  ```
- ```
  Public boolean isNegative(){
      lock.lock();
      if(balance<0){ return true; }
      else if{ return false; }
      lock.unlock(); }
  ```



- Thread synchronization
  - Mutually excludes those 3 threads, so only one of them can run atomic code associated with "lock" at a time.
  - It is important to use the same lock in ALL read and write logic to be performed on "balance." Otherwise, threads are NOT mutually excluded.

When Could a Context Switch Occur?



- A context switch can occur
  - Across atomic operations.
    - e.g., `int i = 1; i = 2;`
  - In a compound operation.
    - e.g., `balance = balance + amount;`

Atomicity of Operations for Primitive Types

- The read and write operations for primitive data types, except double and long (64-bit) types, are atomic.
  - An "atomic" operation is transformed to a single bytecode instruction for a JVM.
  - No context switches occur during the execution of a single byte code instruction.
  - `int x;`
    - Thread A does: `x=1;` Thread B does: `x=2;`
    - An assignment of an int value (write operation) is atomic.
    - x contains 1 or 2 depending on which thread performs assignment earlier.
      - x never contains other values (e.g., 0 and 3) or corrupted data.
      - An example of corrupted data
        - » Some part of x (e.g., the first 16-bit of x) comes from Thread A and the remaining part (e.g., the other 16bit of x) comes from Thread B.
  ```

Compound Operations

- A *compound* of atomic operations is NOT atomic.
  - int i; boolean done;
  - done = true;// 2 steps
  - i = 1;   // 2 steps
  - if(done)   // 2 steps
  - i = j;   // 2 steps
  - j = i +1;   // 5 steps
    - Reading the value of i, reading/loading the value of 1, doing i+1, storing the result of i+1 to a certain memory space, and assigning the result to j.
  - i = i + 1;   // 5 steps
  - i++   // 5 steps
  - A race condition can occur due to a context switch *in between* atomic operations/steps.

An Example Race Condition

- `i = i + 1`
  - A compound of 5 atomic operations.
  - There are 4 places where race conditions can occur.
- Thread synchronization enables serialized (or atomic or exclusive) access to a compound operation.
  - Allows only one thread to perform a compound operation at a time.

```
– ReentrantLock aLock = new ReentrantLock();
  aLock.lock();
  try{
      i = i + 1; // treated as an atomic operation
  }
  finally{
      aLock.unlock();
  }
```

Another Example

```
• public void deposit(double amount){
     balance = balance + amount;
  }
```

  - A compound of 5 atomic operations.
  - There are 4 places where race conditions can occur.
- Thread synchronization enables serialized (or atomic or exclusive) access to a compound operation.
  - Allows only one thread to perform a compound op at a time.

```
– ReentrantLock aLock = new ReentrantLock();
  aLock.lock();
  try{
    balance = balance + amount;
  }
  finally{
      aLock.unlock();
  }
```

What about 64-bit Types?

- The read and write operations for double and long variables are NOT atomic.
  - long x;
    - Thread A does: x = 1L;
    - Thread B does: x = 2L;
    - No guarantee that x contains 1L or 2L.
    - x can contain another value (e.g., 0L or 3L) or corrupted data.
  - aLongVar = 100L; // 2+ bytecode instructions
  - If(aLongVar)   // 2+ bytecode instructions
  - aLongVar ++   // 5+ bytecode instructions

Atomicity of Operations for Reference Types

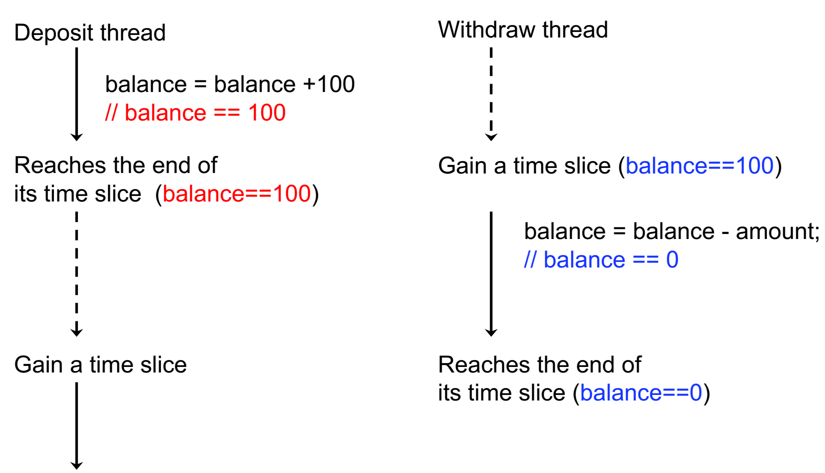
- The read and write operations reference types are atomic.
  - A compound of atomic operations
    - e.g., Foo foo = temp; // 2 byte code instructions
  - A race condition can occur due to a context switch ***in between*** atomic steps.

What's Tricky in Thread Programming

- Your test code may or may not be able to detect race conditions.
  - It may not be able to detect race conditions even if you run it a lot of (e.g. a few hundred) times.

Consider this Lucky Case

```
public void deposit(double amount){
    balance = balance + amount; }
```



Nested Locking

```
class BankAccount {
 private double balance;
 private ReentrantLock lock;

 public void deposit(double amount) {
     lock.lock();
     balance += amount;          // 5 atomic steps
     if(balance < MIN_BALANCE)   // 4 atomic steps
         subractPenaltyFee();
     lock.unlock(); }

 private void subractPenaltyFee() {
     balance -= PENALTY;         // 5 atomic steps
     // NO NEED TO SURROUND THIS LINE BY LOCK() and UNLOCK()
     // because it is called from atomic code.
     }
}
```

Thread Reentrancy

```
class BankAccount {
 private double balance;
 private ReentrantLock lock;

 public void deposit(double amount) {
     lock.lock();
     balance += amount;          // 5 atomic steps
     if(balance < MIN_BALANCE)   // 4 atomic steps
         subractPenaltyFee();
     lock.unlock(); }

 private void subractPenaltyFee() {
     lock.lock();
     balance -= PENALTY;         // 5 atomic steps
     lock.unlock(); } }
```

- This code does not have a deadlock problem.
- A thread can ***re-enter*** the same lock as far as it already owns the lock.


```
class A{
  private B b;
  private ReentrantLock lock;
  public void a1(){
    b = new B();
    lock.lock();
    b.b1(this); //nested locking
    lock.unlock();
  }
  public void a2(){
    lock.lock();
    do something.
    lock.unlock();
  }
}
```

```
Class B{
  public void b1(A a){
    a.a2();
  }
}
```

If a thread performs:

```
A a = new A();
a.a1();
```

it *re-enters (or re-acquires)* the same lock that it already owns.

- This code does not have a deadlock problem.
- A thread can ***re-enter*** the same lock as far as it already owns the lock.