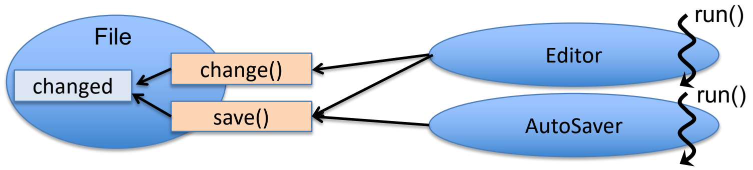
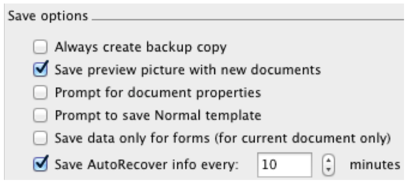
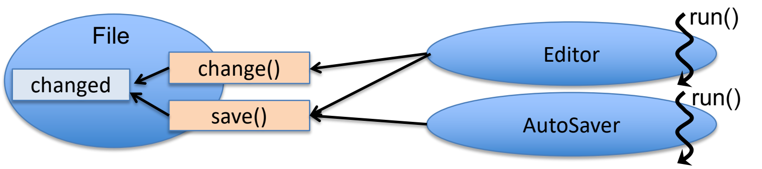
# Exercise: Concurrent Access to a File


File
changed
change()
save()
Editor
AutoSaver
run()
run()

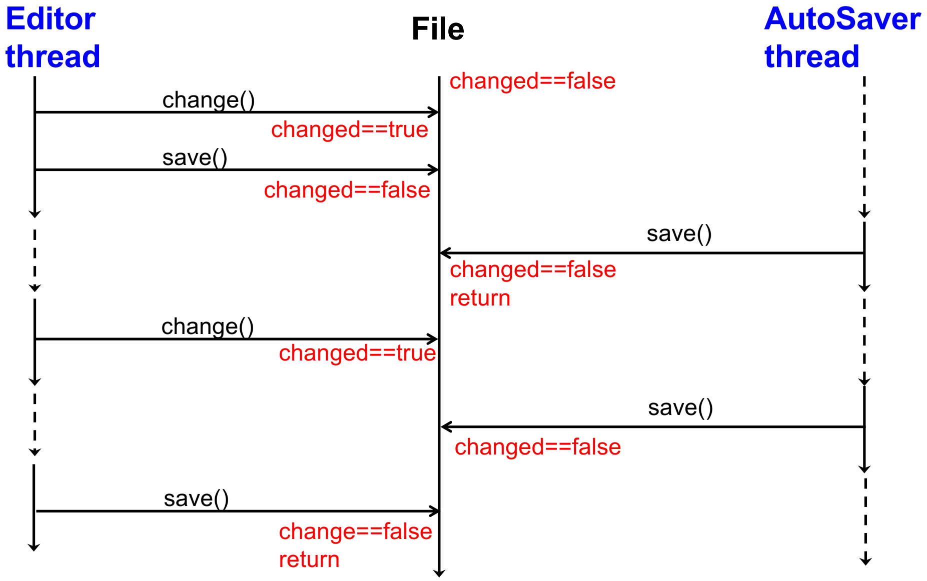

Save options
☐ Always create backup copy
☑ Save preview picture with new documents
☐ Prompt for document properties
☐ Prompt to save Normal template
☐ Save data only for forms (for current document only)
☑ Save AutoRecover info every: 10 minutes

- Imagine a word processing app.
- Assume two threads
  - One for editing a file
    - Allows the user to edit a file and save it.
  - One for saving a file automatically
    - Periodically saves an open file at background.
- The 2 threads call **`change()`** and **`save()`** on an open file concurrently.


File
changed
change()
save()
Editor
AutoSaver
run()
run()

- File
  - Has a boolean variable: “changed”
    - Initialized to be false.
  - change()
    - Changes the file’s content.
    - Assigns true to the variable “changed.”
  - save()
    - if(!changed) return;
    - if(changed)
      - Print out some message (e.g., time stamp, etc.)
      - Assign false to the variable “changed.”
- Editor (a Runnable) repeats:
  - Calls change() and save()
  - Sleeps for a second.
- AutoSaver (a Runnable) repeats:
  - Calls save()
  - Sleeps for two seconds.

# Desirable Result


Editor thread
File
AutoSaver thread
changed==false
change()
changed==true
save()
changed==false
save()
changed==false
return
change()
changed==true
save()
changed==false
save()
change==false
return

# HW 7

- Race conditions can occur if you do not guard the variable **`changed`** with a lock. Explain a potential race condition with a diagram like in a previous slide.
- Implement **`File`**, **`Editor`** and **`AutoSaver`** in a thread-safe manner
  - Define a **`ReentrantLock`** in File. Use the lock in **`change()`** and **`save()`**
    - c.f. **`deposit()`** and **`withdraw()`**, which use a lock to access a shared variable in the bank account example
    - Use try-finally blocks: Always do this in all subsequent HWs.
  - Create two extra threads and have them execute **`Editor`**’s **`run()`** and **`AutoSaver`**’s **`run()`**
    - Those threads acquire and release the lock in **`change()`** and **`save()`**

- Implement explicit thread termination in **Editor** and **AutoSaver** to terminate 2 extra threads.
- Have the main thread sleep for some time while **Editor** and **AutoSaver** are running.
  - Use **Thread.sleep()**
- Have the main thread terminate the two threads.
  - Define a flag variable **done** and **setDone()** in **Editor** and **AutoSaver**

```
class Editor implements Runnable{
  private boolean done = false;

  public void run(){
    while(true){
      if(done){
        System.out.println(”…");
        break;
      }
      aFile.change();
      aFile.save();
      Thread.sleep(1000);
    }

  public void setDone(){
    done = true; }   }
```

- Note that this sample code is not thread-safe.
  - Define a **ReentrantLock** in each of **Editor** and **AutoSaver** to guard a flag variable **done**.
    - Use try-finally blocks
    - Use balking in run()
      - Do not surround a “while” loop with lock() and unlock().

- Deadline: April 2 (Tue) midnight

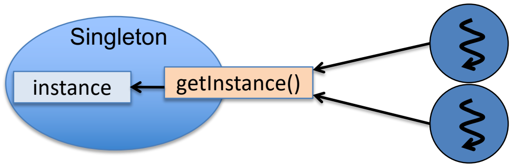
# Recap: Singleton Design Pattern

- Guarantee that a class has only one instance.
  - c.f. CS680 lecture note

```
public class Singleton{
  private Singleton(){};
  private static Singleton instance = null;

  // Factory method to return the singleton instance
  public static Singleton getInstance(){
     if(instance==null)
       instance = new Singleton();
     return instance;
  }
}
```

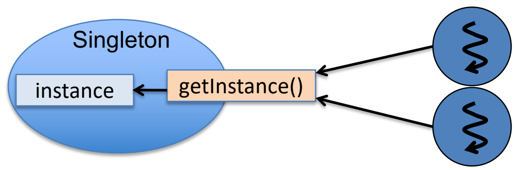
- This code is NOT thread-safe; race conditions can occur.



- When multiple threads call **getInstance()** concurrently, they share **instance**.

```
public class Singleton{
  private Singleton(){};
  private static Singleton instance = null;

  // Factory method to return the singleton instance
  public static Singleton getInstance(){
     if(instance==null)                  // Read    3 steps
       instance = new Singleton();       // Write   2 steps
     return instance;                    // Read    2 steps
  }
}
```



- 
```
public class Singleton{
  private Singleton(){};
  private static Singleton instance = null;
                         // Write logic. Requires 2 steps
                         // Thread safe }
```

- JVM completes all initial value assignments on all static data fields BEFORE using a class or creating class instances.
  - `instance` has been initialized before a thread(s) call `getInstance()`
  - This write logic is thread-safe.
    - No need to worry about race conditions here.

# Concurrent Singleton Design Pattern

- Guarantee that a class has only one instance.

- 
```
public class ConcurrentSingleton{
 private Singleton(){};
 private static Singleton instance = null;
 private static ReentrantLock lock = new ReentrantLock();

 // Factory method to create or return the singleton instance
 public static Singleton getInstance(){
     lock.lock();
     try{
       if(instance==null){ instance = new Singleton(); }
       return instance;
     }finally{
       lock.unlock();
     }
 }
}
```

# HW 8

- The Singleton class is not thread-safe.
  - Race conditions can occur if you do not guard the `instance` variable with a lock. Explain a potential race condition in which more than one instances are created.
    - Use a diagram like in a previous slide.
- Submit a thread-safe version of it (`ConcurrentSingleton`)
  - Define a lock in Singleton. Use the lock in `getInstance()`
    - Use try-finally blocks: Always do this in all subsequent HWs.
  - Create multiple extra threads and have them call `getInstance()`
    - Make sure that only one instance is created.
      - Use `System.out.println(Singleton.getInstance())`

- Deadline: April 2 (Tue) midnight

# Regular and Static Locks

-
  ```
  public class Foo{
       ReentrantLock lock = new ReentrantLock();
       static ReentrantLock sLock = new ReentrantLock(); }
  ```

- A regular lock is created and used on an *instance-by-instance* basis.
  - Different instances of `Foo` have different locks (i.e., different instances of `ReentrantLock`).

- A static lock is created and used on a *per-class* basis.
  - All instances of `Foo` share a single lock (`sLock`).

# Exercise: Regular and Static Locks

-
  ```
  public class Foo{
     private ReentrantLock        lock = new ReentrantLock();

     public      void a(){…}
     public      void b(){…}
     public      void syncA(){lock.lock(); … lock.unlock();}
     public      void syncB(){lock.lock(); … lock.unlock();}
  }
  ```

- `x = new Foo(); y = new Foo();`

- Two threads call…
  - x.a() and x.a(): no synchronization (no mutual exclusion) for the two threads
  - x.a() and x.b(): no synchronization
  - x.a() and x.syncA(): no synchronization
  - x.syncA() and x.syncA(): Synchronization (mutual exclusion)
  - y.syncA() and y.syncB(): Synchronization
  - x.syncA() and y.syncA(): No synchronization
  - x.syncA() and y.syncB(): No synchronization

-
  ```
  public class Foo{
     private ReentrantLock          lock = new ReentrantLock();
     private static ReentrantLock   sLock = new ReentrantLock();

     public       void a(){…}
     public       void b(){…}
     public       void syncA(){lock.lock(); … lock.unlock();}
     public       void syncB(){lock.lock(); … lock.unlock();}

     public static void sA(){…}
     public static void sB(){…}
     public static void sSyncA(){sLock.lock(); … sLock.unlock();}
     public static void sSyncB(){sLock.lock(); … sLock.unlock();} }
  ```

- `x = new Foo(); y = new Foo();`

- Two threads call…
  - x.a() and Foo.sA(): No synchronization for the two threads
  - x.syncA() and Foo.sA(): No synchronization
  - Foo.sA() and Foo.sA(): No synchronization
  - Foo.sA() and Foo.sB(): No synchronization
  - x.syncA() and Foo.sSyncA() No synchronization
  - Foo.sSyncA() and Foo.sSyncA(): Synchronization
  - Foo.sSyncA() and Foo.sSyncB(): Synchronization
  - x.sSyncA() and y.sSynchB(): Synchronization
    - This is not grammatically wrong, but write Foo.sSyncA() instead of x.sSyncA()

# Thread.sleep()

-
  ```
  Thread t = new Thread( new FooRunnable() );
  t.start();
  try{
       t.sleep(1000);
  }catch(InterruptedException e){...}
  ```

- It looks like an extra thread (*t*) will sleep.
- However, the main thread will actually sleep
  - because `sleep()` is a ***static method*** of Thread.
    - `Thread.sleep()`: Allows the *currently executing thread* to sleep (temporarily cease execution) for the specified number of milliseconds

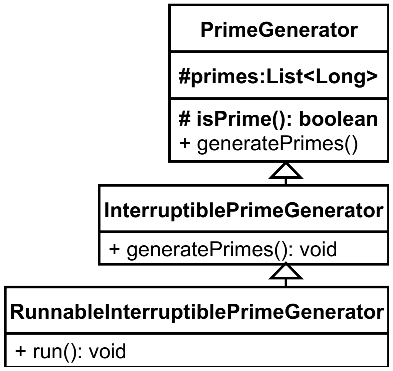
- DO NOT write `t.sleep(…)`. It's misleading and error-prone.
- ALWAYS WRITE `Thread.sleep(…).`
  - Make sure to do this in HW 7.

# RunnableInterruptiblePrimeGenerator

```
class InterruptiblePrimeGenerator extends PrimeGenerator {
  public void generatePrimes(){
    for (long n = from; n <= to; n++){
      if( Thread.interrupted() ){
        System.out.println("Stopped");
        this.primes.clear();
        break;
      }
      if( isPrime(n) ){ this.primes.add(n); } }}

class RunnableInterruptiblePrimeGenerator
  extends InterruptiblePrimeGenerator
  implements Runnable {

  public void run(){
    generatePrimes(); } }
```



# interrupt(), isInterrupted() and interrupted()

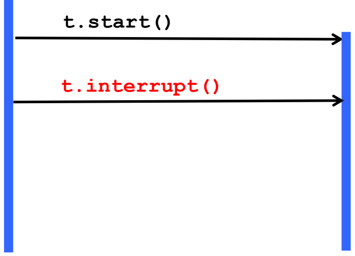
-
  ```
  public class Thread{
    public void interrupt();
    public boolean isInterrupted();
    public static boolean interrupted();
  ```
- Each thread (`Thread` instance) has the "interrupted" (boolean) state.
- `interrupt()`
  - Interrupts `this` thread and changes its "interrupted" state.

    -
      ```
      aThread = new Thread(...); aThread.start();
      aThread.interrupt();
      ```
- `isInterrupted()`
  - Returns true if `this` thread has been interrupted.

    -
      ```
      aThread = new Thread(…); aThread.start();
      if( aThread.isInterrupted() ){...}
      ```
  - Does not change the "interrupted" state of the thread.
- `interrupted()`
  - Returns true if the *currently-executed* thread has been interrupted.
  - Clears the "interrupted" state (true → false) if true is returned.

**Main thread** **Thread t**

```
gen = new RunnableInterruptiblePrimeGenerator(…)
t = new Thread(gen)
```



Executes run()
Generates prime nums

Thread.interrupted()==true
Clears the "interrupted" state.

Prints "stopped generating prime nums" and exits run()

```
for( long n = from; n <= to; n++ ){
    // Detect if another thread has interrupted. Balk if yes.
    if( Thread.interrupted() ){
      System.out.println("Stopped generating prime nums.");
      this.primes.clear();
      break; // balking
    }
    if( isPrime(n) ){ this.primes.add(n); } } }
```

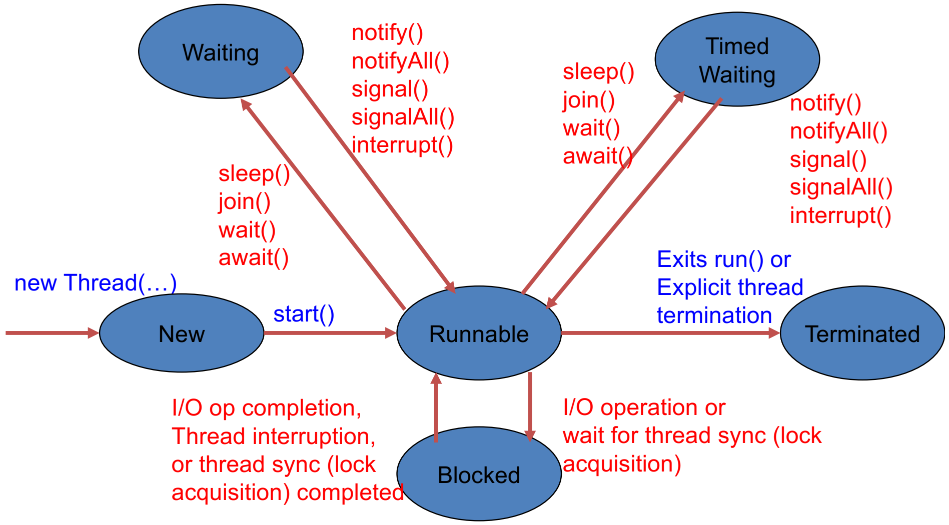
# Thread Interruption != Thread Termination

- `interrupt()` NEVER terminate a thread.
  - It simply change the "interrupted" state
    - to help/trigger a thread termination.

# What Happens When `interrupt()` is Called on a Thread?

- If the soon-to-be-terminated thread is in the Runnable state, `interruput()` changes its “interrupted” state to be true.
- If the soon-to-be-terminated thread is in the *Waiting* or *Blocked* state, it throws an `InterruptedException`.

# 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)

# `RunnableInterruptiblePrimeGenerator`

- In fact, `RunnableInterruptiblePrimeGenerator` is NOT thread-safe. Race conditions can occur.

```
class InterruptiblePrimeGenerator extends PrimeGenerator {
  public void generatePrimes(){
    for (long n = from; n <= to; n++){
      if( Thread.interrupted() ){          // 2 steps
        System.out.println("Stopped");
        this.primes.clear();
        break;
      }
      if( isPrime(n) ){ this.primes.add(n); } }}

class RunnableInterruptiblePrimeGenerator
  extends InterruptiblePrimeGenerator
  implements Runnable {

  public void run(){
    generatePrimes(); } }
```

# `Thread.interrupt()`

-
  ```
  public void interrupt(){
    ...
    synchronized(...){ // Acquire a lock in Thread
       ...
       interrupt0();    // native method (atomic)
       ...
    }
  }
  public static boolean interrupted(){
    return currentThread().isInterrupted(true);// native method
                                               //  (atomic)
   }
  ```
- `interrupt()` and `interrupted()` are thread-safe.
  - `isInterrupted()` is thread-safe as well.
  - c.f. Java source code
- However, ***client code*** of `interrupted()` is NOT guaranteed to be thread-safe.

# Solution: Locking and Balking

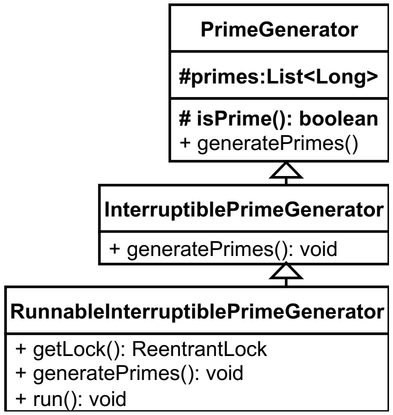
```
class RunnableInterruptiblePrimeGenerator
  extends InterruptiblePrimeGenerator
  implements Runnable {

  private final ReentrantLock lock = new ReentrantLock();

  public ReentrantLock getLock(){
    return lock;  }

  public void generatePrimes(){
    for (long n = from; n <= to; n++){
      lock.lock();
      if( Thread.interrupted() ){
        System.out.println("Stopped");
        this.primes.clear();
        break;
      }
      lock.unlock();
      if(isPrime(n)){this.primes.add(n);}}}

  public void run(){
    generatePrimes(); } }
```



PrimeGenerator

#primes:List<Long>

# isPrime(): boolean
+ generatePrimes()

InterruptiblePrimeGenerator

+ generatePrimes(): void

RunnableInterruptiblePrimeGenerator

+ getLock(): ReentrantLock
+ generatePrimes(): void
+ run(): void

- Main thread (client of `RunnableInterruptiblePrimeGenerator`)

```
– RunnableInterruptiblePrimeGenerator gen =
      new RunnableInterruptiblePrimeGenerator();
  Thread aThread = new Thread(gen); aThread.start();

  gen.getLock().lock();
  aThread.interrupt();
  gen.getLock().unlock();
```

- This code uses two locks.
  - One in `Thread`
  - One in `RunnableInterruptiblePrimeGenerator`

# HW 9

- Revise `RunnableInterruptiblePrimeGenerator.java` to be thread-safe.
  - c.f. HW 6, in which you work on a thread-safe version of `RunnableCancelablePrimeGenerator.java`
- Deadline: April 2 (Tue) midnight

# Explicit Thread Termination

- Flag-based
  - Pros:
    - Uses **1 lock (faster)**
  - Cons:
    - Program responsiveness may be lower.
      - if a flag-flipping (e.g. done==false → true) happens when a soon-to-be-terminated thread is in the Waiting or Blocked state.
- Interruption-based
  - Pros
    - Higher program responsiveness
      - interrupt() can immediately wake up a soon-to-be-terminated thread that is in the Waiting or Blocked state
  - Cons
    - Uses **2 locks (slower)**

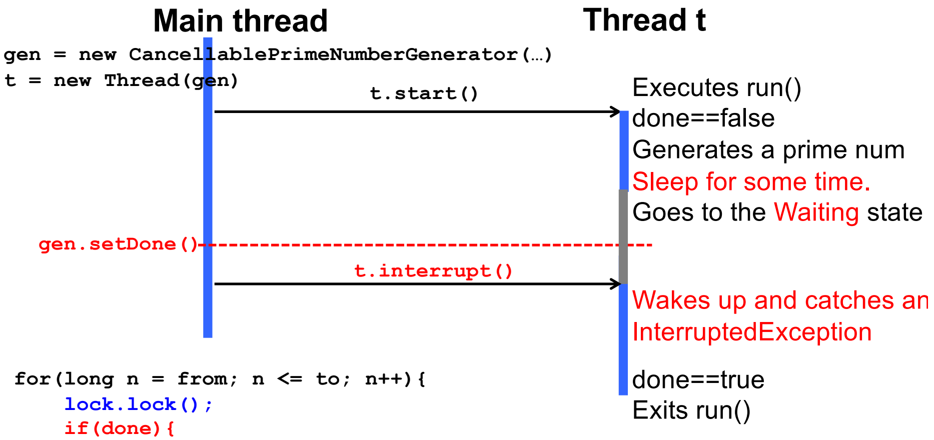
# Hybridization of the Two Approaches?

- Can we implement a responsive thread termination that uses only 1 lock?

# 2-Step Thread Termination (“Graceful” Thread Termination)

# 2-Step Thread Termination

- Primarily takes the flag-based approach.
  - A soon-to-be-terminated thread periodically checks a flag.
- Let the “terminator” thread call **`interrupt()`** after flipping the flag’s state (i.e., after calling **`setDone()`**)

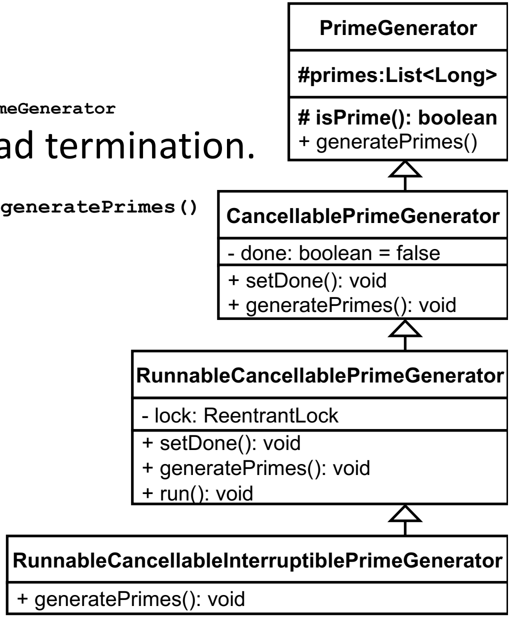


```
for(long n = from; n <= to; n++){
    lock.lock();
    if(done){
        System.out.println(“Stopped generating prime nums.”);
        this.primes.clear();
        break; }
    lock.unlock();
    if( isPrime(n) ){ this.primes.add(n); }
    try{
        Thread.sleep(3000);
    }catch(InterruptedException){
        continue; // OR break;
    } } } }
```

# HW 10

- Define `RunnableCancellableInterruptiblePrimeGenerator` to perform 2-step thread termination.
  - Re-define (or override) `generatePrimes()`

- Deadline: April 4 (Thu) midnight



PrimeGenerator
#primes:List<Long>
# isPrime(): boolean
+ generatePrimes()

CancellablePrimeGenerator
- done: boolean = false
+ setDone(): void
+ generatePrimes(): void

RunnableCancellablePrimeGenerator
- lock: ReentrantLock
+ setDone(): void
+ generatePrimes(): void
+ run(): void

RunnableCancellableInterruptiblePrimeGenerator
+ generatePrimes(): void

# 2-Step Thread Termination is Effective if…

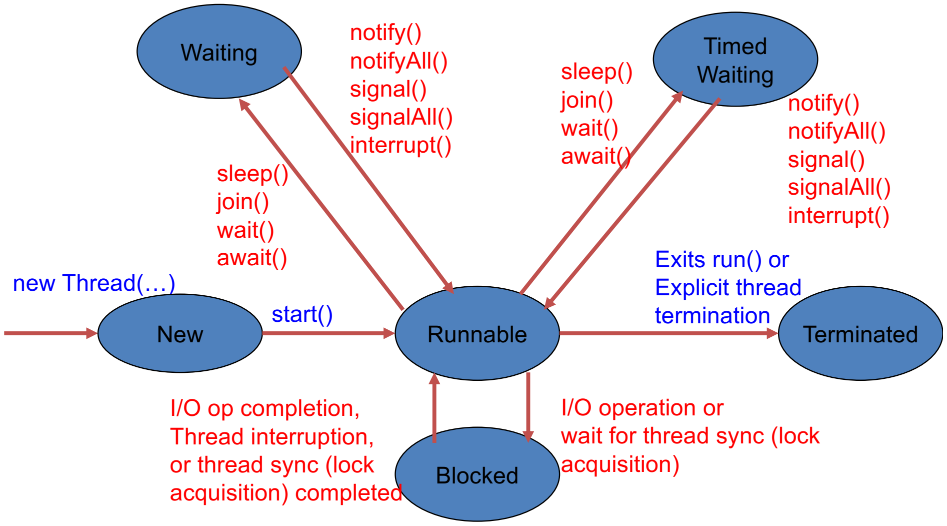
- A soon-to-be-terminated thread may be in the Waiting or Blocked state when a "terminator" thread tries to terminate it.
  - Performing an I/O operation.
    - e.g., reading/writing data from/to a file, waiting for an incoming data on a socket, sending data to a remote app.
  - Waiting for a lock acquisition
    - Has called lock() on a lock, but the lock is not available yet.
  - Has called sleep(), join(), etc.

# What Happens When `interrupt()` is Called on a Thread?

- If a soon-to-be-terminated thread is in the Runnable state, `interruput()` changes its "interrupted" state to be true.

- If the soon-to-be-terminated thread is in the *Waiting* or *Blocked* state, it raises an `InterruptedException`.

# 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)

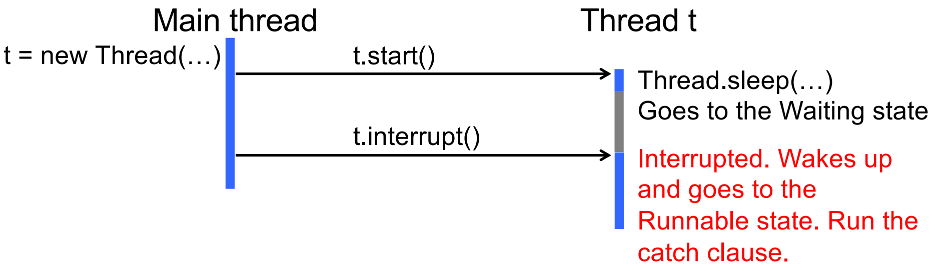
# InterruptedException

- Some methods in Java API throws `InterruptedException`.
  - They can respond to a thread interruption by throwing an `InterruptedException`.
  - `Thread.sleep()`
  - `Thread.join()`
  - `ReentrantLock.lockInterruptibly()`
  - `BlockingQueue.put()/take()`
  - `Condition.await()`
  - I/O operations
  - These methods can be long-running and interruptible.

# Thread.sleep()

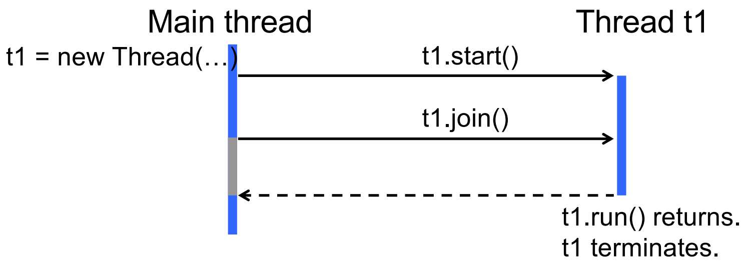
- `sleep()` lets the *currently-executed thread* to sleep for a specified time period.
- `interrupt()` interrupts a sleeping thread.
  - Wakes up the thread and force `sleep()` to throw an `InterruptedException`.

-
  ```
  try{
      Thread.sleep(60000);
  }catch(InterruptedException e){
      // Write thread termination (shutdown) logic here.
  }
  ```


Main thread
Thread t
t = new Thread(…)
t.start()
Thread.sleep(…)
Goes to the Waiting state
t.interrupt()
Interrupted. Wakes up and goes to the Runnable state. Run the catch clause.

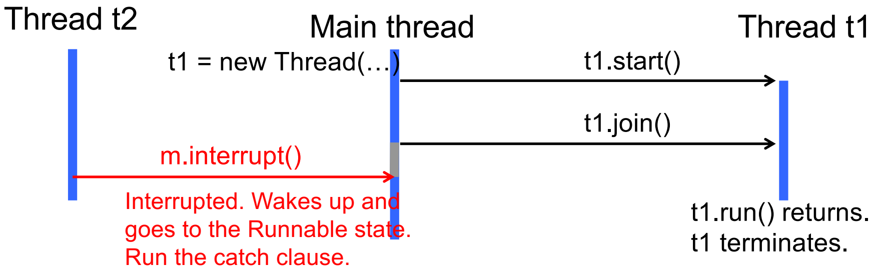
# Thread.join()

- `join()` lets the *currently-executed thread* to wait/sleep until another thread terminates (i.e., until another thread returns `run()`).
- `interrupt()` can interrupt a waiting/sleeping thread.
  - Force join() to throw an `InterruptedException`.



# Thread.join()

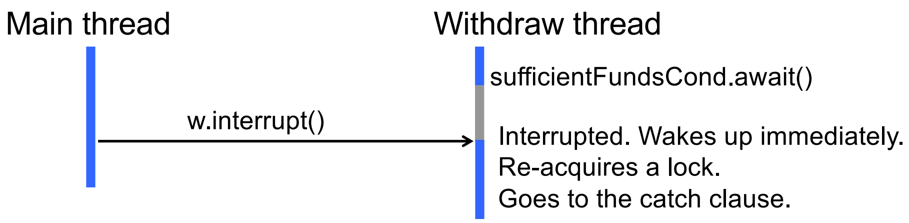
- `join()` lets the *currently-executed thread* to wait/sleep until another thread terminates (i.e., until another thread returns `run()`).
- `interrupt()` can interrupt a waiting/sleeping thread.
  - Force join() to throw an `InterruptedException`.



# `Condition.await()`

- `await()` lets the currently-executed thread wait/sleep until another thread wakes it up with `signal()`/`signalAll()`.
- `interrupt()` can interrupt a waiting/sleeping thread.
  - Allows `await()` to acquire a lock and forces it to throw an `InterruptedException`

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



Main thread

Withdraw thread

sufficientFundsCond.await()

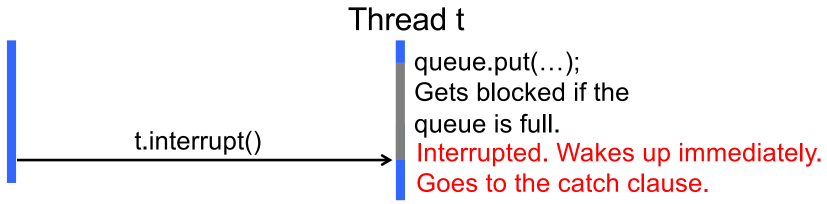
w.interrupt()

Interrupted. Wakes up immediately.
Re-acquires a lock.
Goes to the catch clause.

```
withdraw(double amount){
    lock.lock();
    while(balance =< 0){
        try{
            // waiting for the balance to exceed 0
            sufficientFundsCondition.await();
        }catch(InterruptedException e){
            //Do something; e.g., balk with a
            //"break" statement.
        }
    }
    ...}
```

# `BlockingQueue`

- `interface BlockingQueue<E> extends Queue<E>`
  - Adds A Queue that additionally supports operations that
    - wait for the queue to become non-empty when retrieving an element
    - wait for space to become available in the queue when storing an element.
- Several impls: `ArrayBlockingQueue`, `LinkedBlockingQueue`, etc.
  - `put()` and `take()` are *blocking* methods.
    - `put()`: Add an element to a queue as the last element.
    - `take()`: Get the first element in the queue.
  - They can respond to a thread interruption by throwing an `InterruptedException`.



Thread t

queue.put(…);
Gets blocked if the
queue is full.

t.interrupt()

Interrupted. Wakes up immediately.
Goes to the catch clause.

# Thread Termination

- Thread creation is a no brainer.
- Thread termination requires your careful attention.
  - No methods available in Thread to directly terminate threads like `terminate()`.
    - Do: 2-step termination
  - Why not?
    - Different programmers/apps need different termination policies.
      - Notify on-going thread termination to other threads?
      - Raise exception(s) in addition to `InterruptException`?
      - What to do for the data maintained by a thread being terminated?
    - Java allows you to flexibly craft your own termination policy.

# Where did the `Synchronized` Keyword go?

- Java still has the **`synchronized`** keyword.

  -
    ```
    public synchronized void foo(){
              // The entire method body is atomic.
    }
    ```

  -
    ```
    public void foo(){
              // non-atomic code here
              synchronized(this){
                      // atomic code here
              }
              // non-atomic code here }
    ```
  - Implicit locking
    - No need to create a `ReentrantLock` and call `lock()` and `unlock()`.
  - When a thread enters a synchronized method/block, it tries to acquire the (implicit) lock that **`this`** instance maintains.
    - Instance-by-instance locking
  - Code gets tricky/dirty to use multiple locks in a single class.

- Explicit locking

  -
    ```
    ReentrantLock aLock = new ReentrantLock()
    public void foo(){
         aLock.lock();
         // atomic code
         aLock.unlock(); }
    ```
  - Arbitrary locking scope.
  - Clean code even if a class uses multiple locks.
  - Extra functionalities
    - e.g., getQueueLength(): returns the # of waiting threads.
    - tryLock(): acquires a lock only if it is not held by another thread.
  - The catch is… it’s VERY easy to forget calling unlock().
    - Must call unlock() in a finally clause.

- Implicit locking with the “synchronized” keyword
  – A thread can call notify() and notifyAll() even if it has not acquired a lock.
    - An IllegalMonitorStateException is thrown.

- Explicit locking
  – This error/bug never occurs.

    -
      ```
      ReentrantLock lock = new ReentrantLock();
      Condition cond = lock.newCondition();
      lock.lock();
      …
      cond.SignalAll();
      ```