Computer System Design & Application

计算机系统设计与应用A

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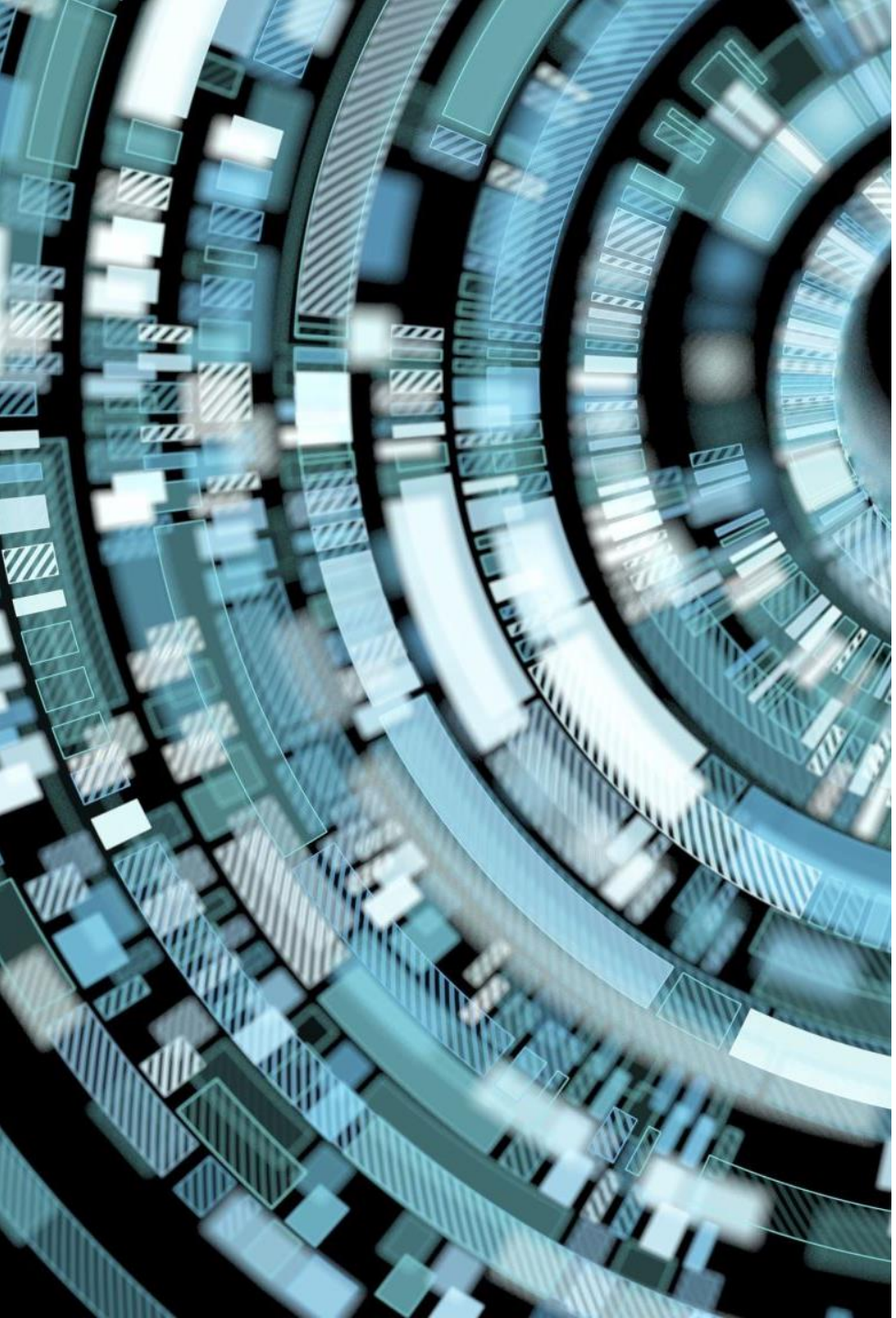
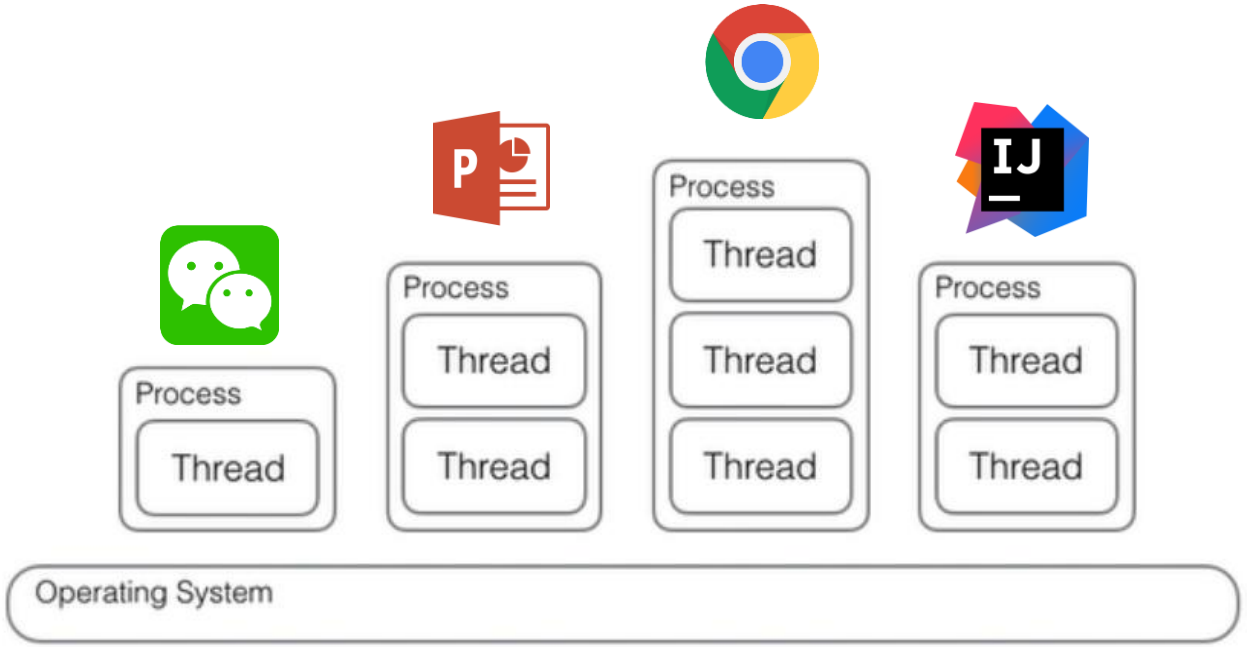


Lecture 7

- Multithreading Overview
- Creating & Starting Threads
- Thread Safety
- Concurrent Collections

Process vs Thread

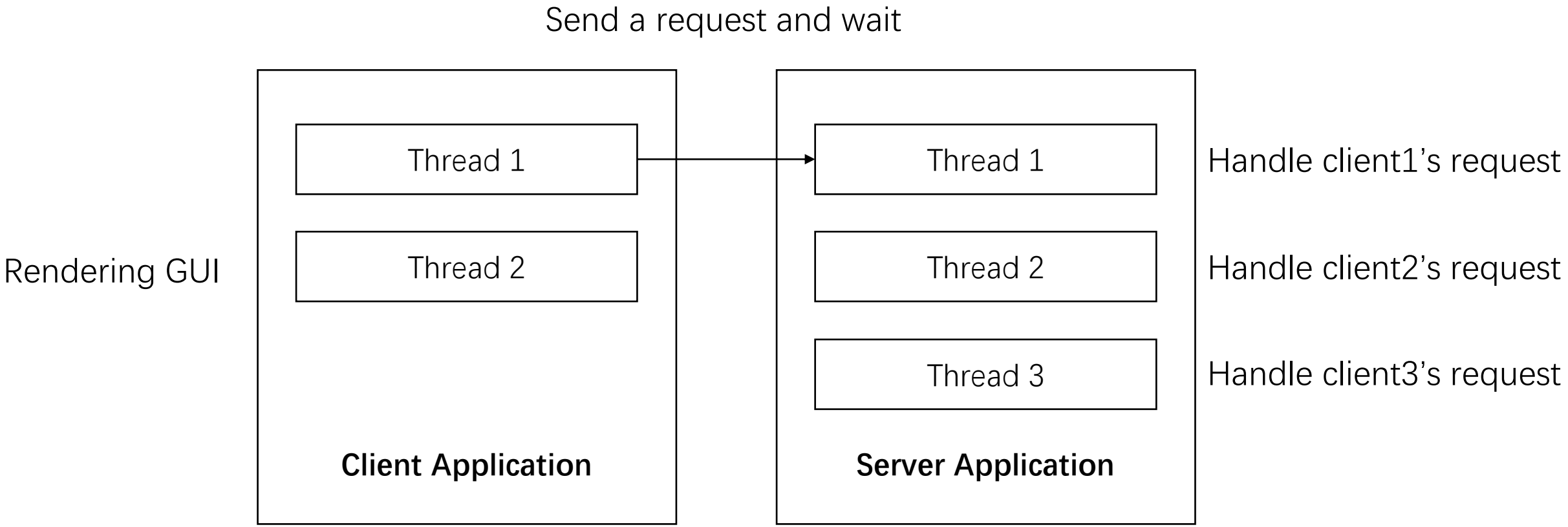
- **Process (进程)**
  - Executing a program starts a process (a running/active program)
  - OS allocates separate memory spaces for different processes
- **Thread (线程)**
  - A process can have multiple threads (at least 1 thread)
  - Threads within a process share the memory and resources of that process.

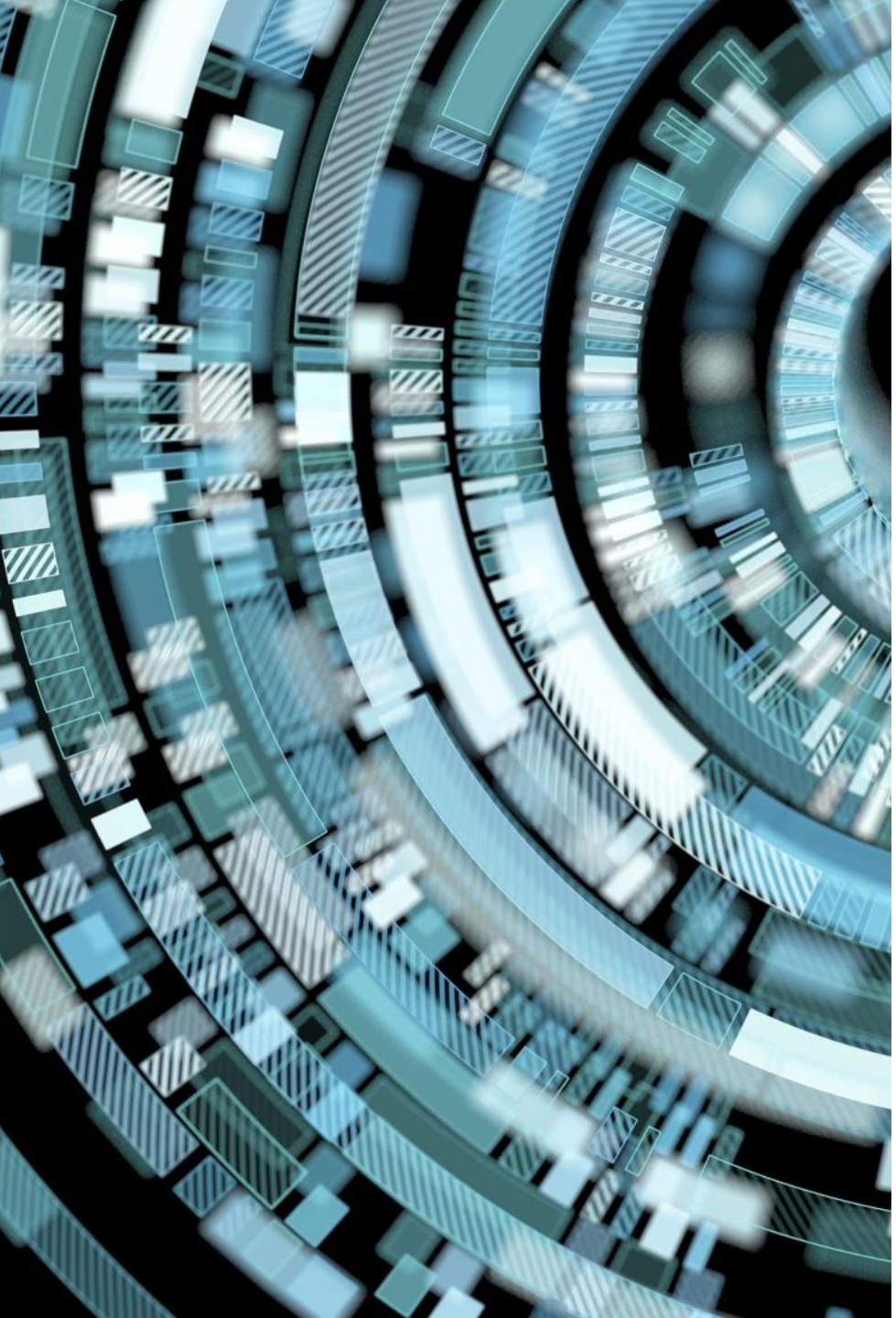


Multithreading

- In Java, Multithreading refers to executing two or more threads simultaneously for maximum utilization of the CPU.
- Each thread defines a separate path of execution
- The threads are independent, so it does not block the user to perform multiple operations at the same time
- If an exception occurs in a single thread, it does not affect other threads.

Multithreading





Lecture 7

- Multithreading Overview
- Creating & Starting Threads
- Thread Safety
- Concurrent Collections

Multithreading in Java

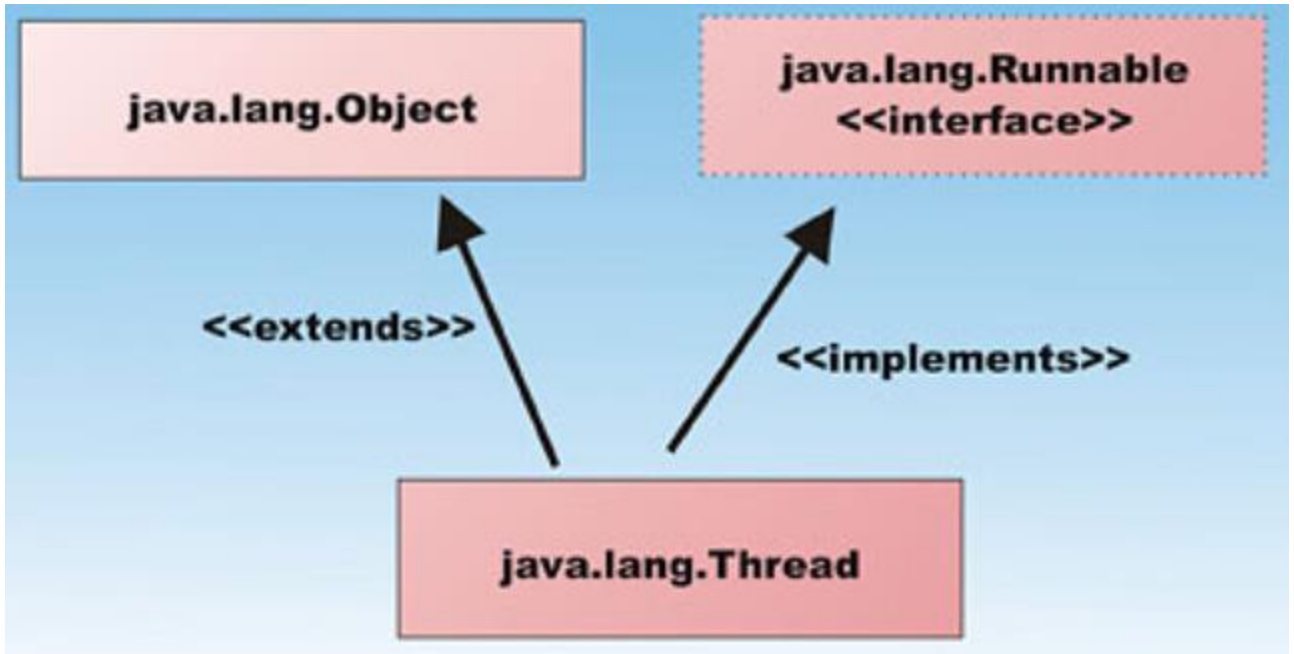
- JVM runs (mostly) as a single process
- The `main` thread is created automatically when our Java program is started
- The `main` thread has the ability to create additional threads

```
public class Concurrency {
    public static void main(String[] args){
        System.out.println(Thread.currentThread().getName());
    }
}
```

Output "main"

Creating & Starting Threads

- Approach 1: Extending the `Thread` class **(not recommended)**
- Approach 2: Implementing the `Runnable` interface **(preferred)**



The Thread Class

```
public class Thread
extends Object
implements Runnable
```

- One way to create a new thread of execution is to declare a class to be a subclass of `Thread`
- This subclass should override the `run` method of `Thread`: specify what this thread does inside `run`.
- An instance of the subclass can then be allocated and started

```java
public class CatThread extends Thread{
    @Override
    public void run() {
        System.out.println("I'm a cat.");
    }
}
```

```java
public class Concurrency {
    public static void main(String[] args){
        Thread cat = new CatThread();
        cat.start();
    }
}
```

1. How many threads? 2. why start()?

Using Thread

```
public class CatThread extends Thread{
    int cnt = 0;

    public void run(){
        while(cnt<10){
            System.out.printf("My class: Cat  |  My thread: %s  %d\n",
                    Thread.currentThread().getName(), ++cnt);
            try{
                Thread.sleep( millis: 1000);
            }catch (InterruptedException e){
                e.printStackTrace();
            }
        }
    }
}
```

- Print a string 10 times
- 1s interval between each print
- Also print the current thread's name at the same time

Using Thread (cont.)

```java
public class CatMain {
    public static void main(String[] args) throws InterruptedException {
        Thread cat = new CatThread();
        cat.start();

        int cnt=0;
        while(cnt<10){
            System.out.printf("My class: Main  |  My thread: %s:  %d\n",
                    Thread.currentThread().getName(), ++cnt);
            Thread.sleep( millis: 1000);
        }
    }
}
```

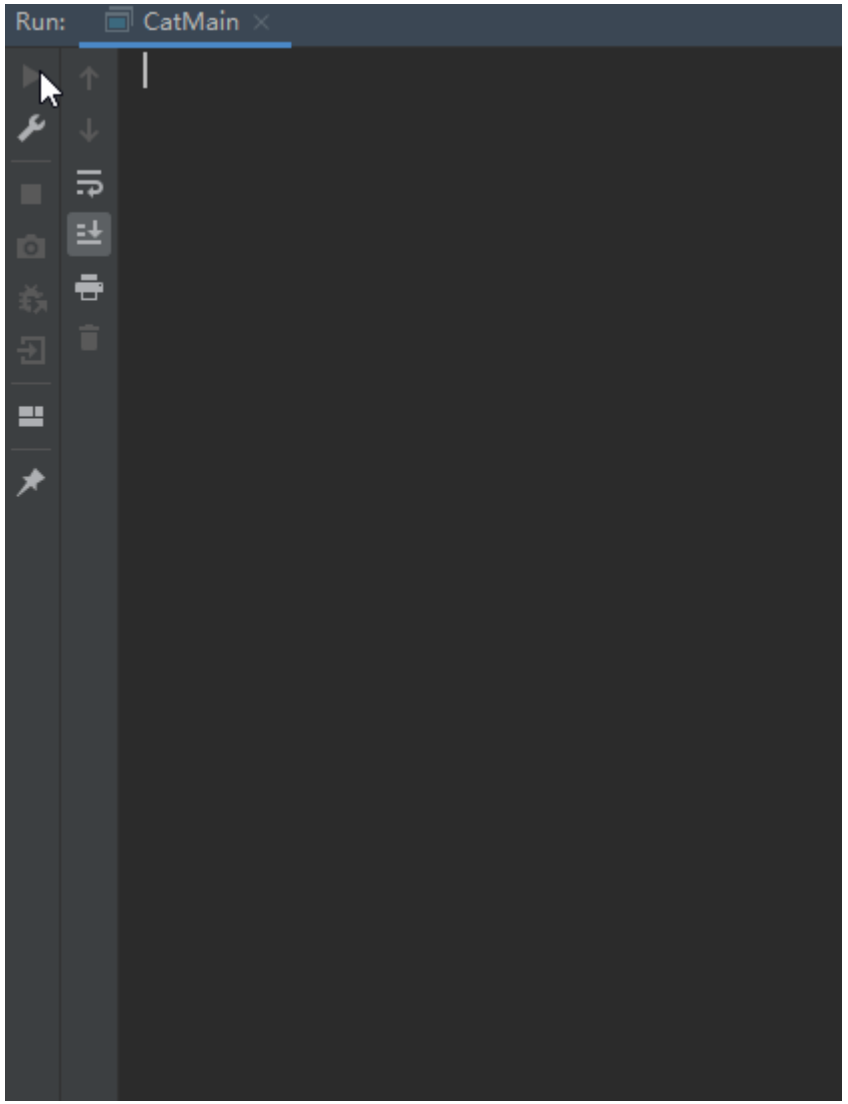
What will happen?

- Print the current thread's name for 10 times
- 1s interval between each print

Using Thread (cont.)

The print operations for the Cat thread and the main thread are executed simultaneously

- Try execute the same program multiple times. Do we always get the same results?
- Try change the sleep duration. What will happen?



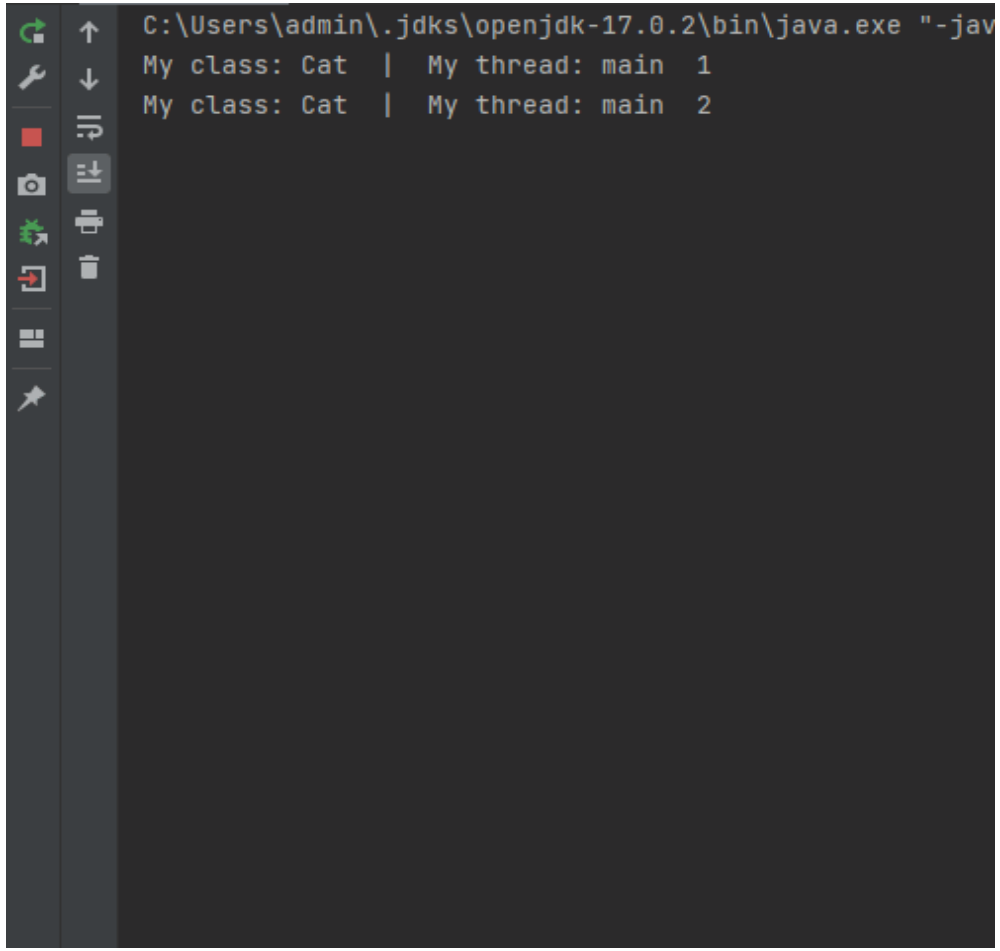
Using Thread (cont.)

```java
public class CatThread extends Thread{
    int cnt = 0;

    public void run(){
        while(cnt<10){
            System.out.printf("My class: Cat  |  My thread: %s  %d\n",
                    Thread.currentThread().getName(), ++cnt);
            try{
                Thread.sleep( millis: 1000);
            }catch (InterruptedException e){
                e.printStackTrace();
            }
        }
    }
}
```

```java
public class CatMain {
    public static void main(String[] args) throws InterruptedException {
        Thread cat = new CatThread();
        cat.start();

        int cnt=0;
        while(cnt<10){
            System.out.printf("My class: Main  |  My thread: %s:  %d\n",
                    Thread.currentThread().getName(), ++cnt);
            Thread.sleep( millis: 1000);
        }
    }
}
```

Why start() instead of run()?

Why `start()` instead of `run()`?




```
Thread cat = new CatThread();
//cat.start();
cat.run();
```

Observation

1. Things are executed sequentially instead of simultaneously
2. There is even **no** Cat thread!

- run() executes like a normal method in the current thread
- start() indeed creates a new thread then calls run()

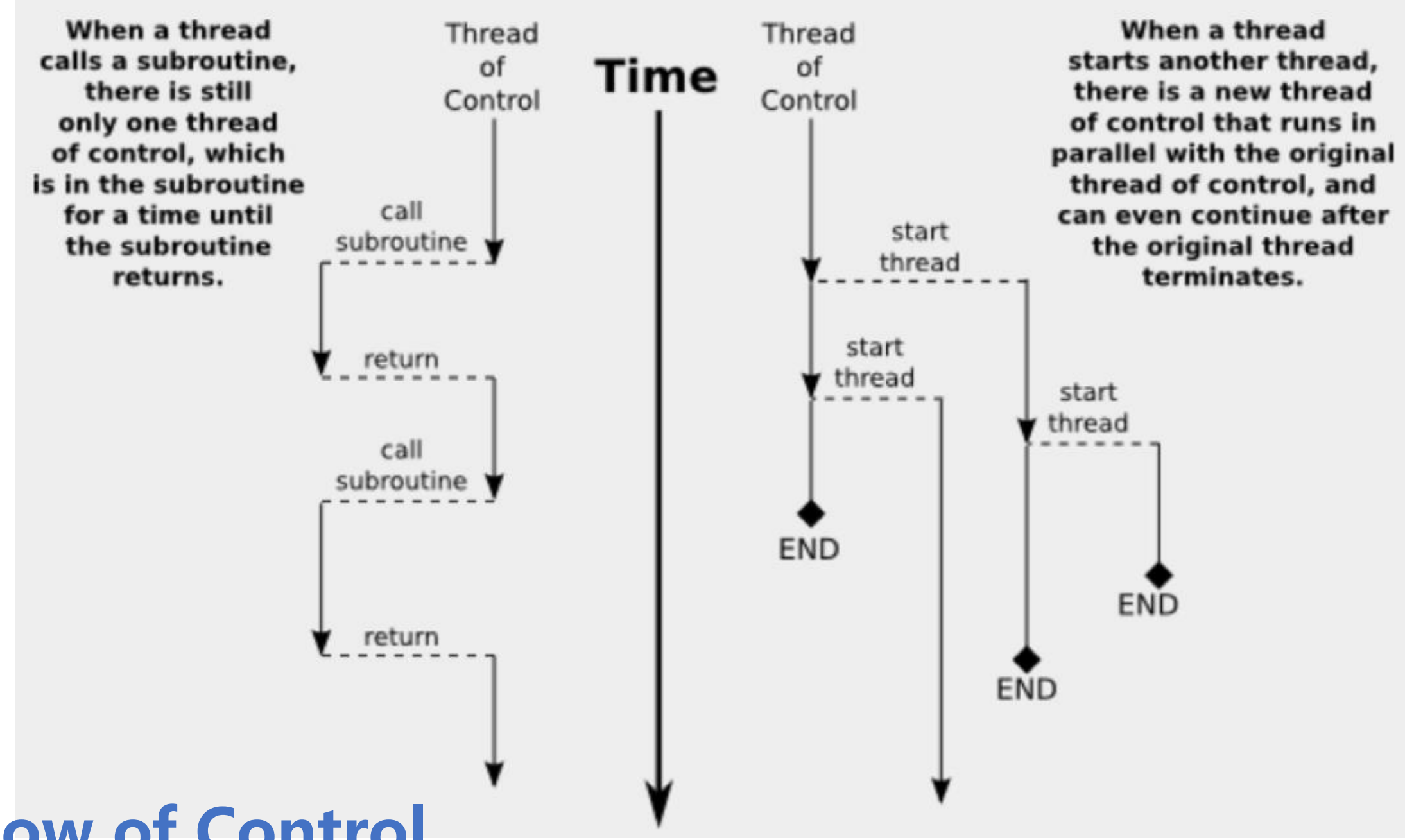
Using Thread (cont.)

Why start()?

```
public class CatMain {
    public static void main(String[] args) throws InterruptedException {
        Thread cat = new CatThread();
        cat.start();

        int cnt=0;
        while(cnt<10){
            System.out.printf("My class: Main  |  My thread: %s:  %d\n",
                    Thread.currentThread().getName(), ++cnt);
            Thread.sleep( millis: 1000);
        }
    }
}
```

start() is non-blocking!
Don't have to wait for it before executing the subsequent operations

Flow of Control



The `Runnable` Interface

- The `Runnable` interface should be implemented by any class whose instances are intended to be executed by a thread (`Thread` class also does so)
- To implement `Runnable`, a class must implement the abstract method `run()`

```
@FunctionalInterface
public interface Runnable {
    When an object implementing interface Runnable is used to create a thread, starting the thread
    causes the object's run method to be called in that separately executing thread.
    The general contract of the method run is that it may take any action whatsoever.
    See Also: Thread.run()
    public abstract void run();
}
```

Implementing Runnable

1. Using Class

```
public class RunnableThread implements Runnable{
    public void run(){
        System.out.println("This is a runnable.");
    }
}
```

```
Runnable runnable1 = new RunnableThread();
```

2. Using Anonymous Class

```
Runnable runnable2 = new Runnable() {
    @Override
    public void run() {
        System.out.println("This is a runnable.");
    }
};
```

3. Using Lambda Expressions

```
Runnable runnable3 = () -> System.out.println("This is a runnable");
```

Starting a Thread with a Runnable

- Thread has a constructor that takes a Runnable

`Thread(Runnable target)`
Allocates a new `Thread` object.

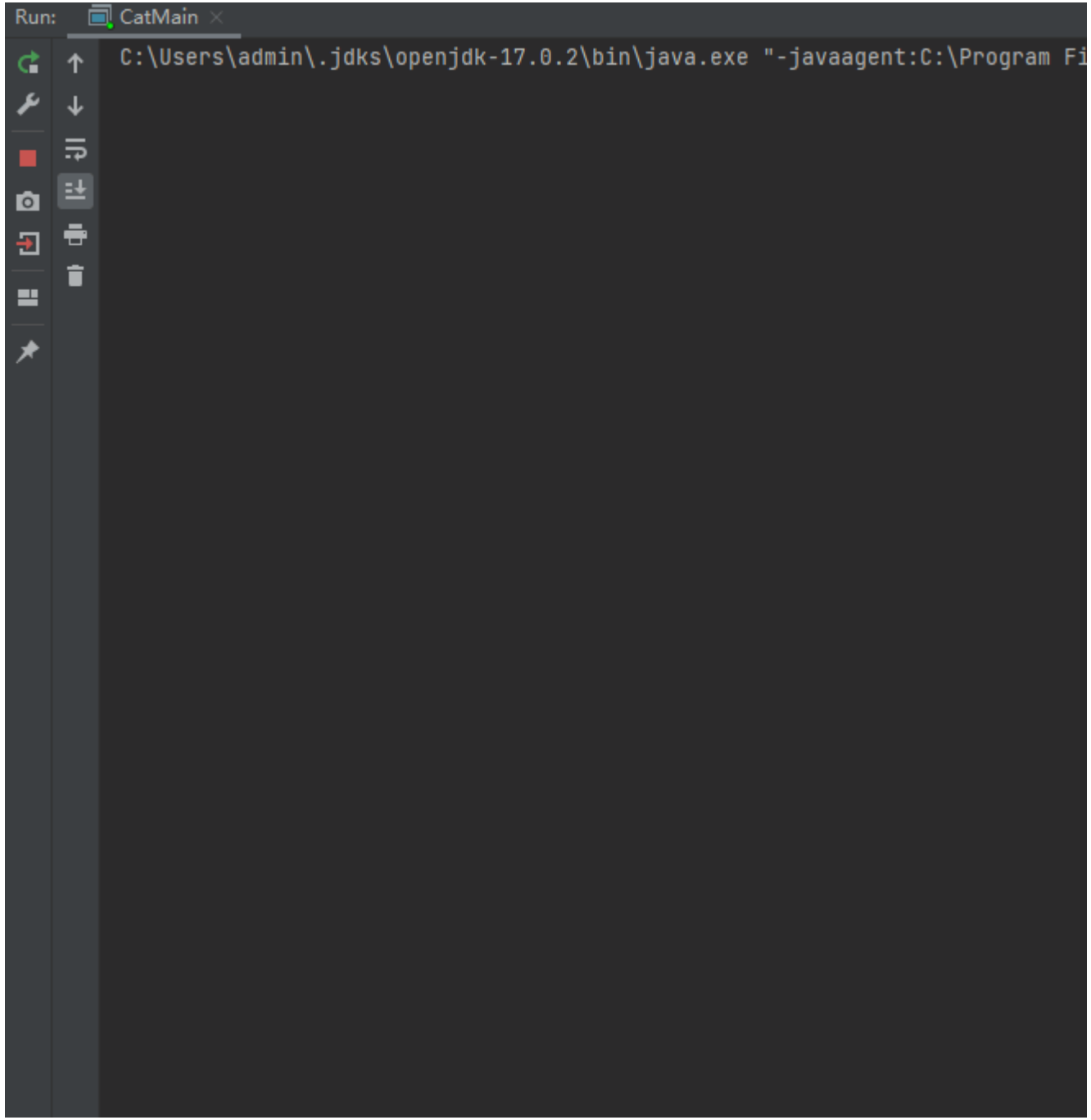
- To have the run() method executed by a thread, pass an instance of a class, anonymous class or lambda expression that implements the Runnable interface to a Thread constructor

```
Runnable runnable = () -> System.out.println(Thread.currentThread().getName());

Thread runnableThread = new Thread(runnable);
runnableThread.start();
```

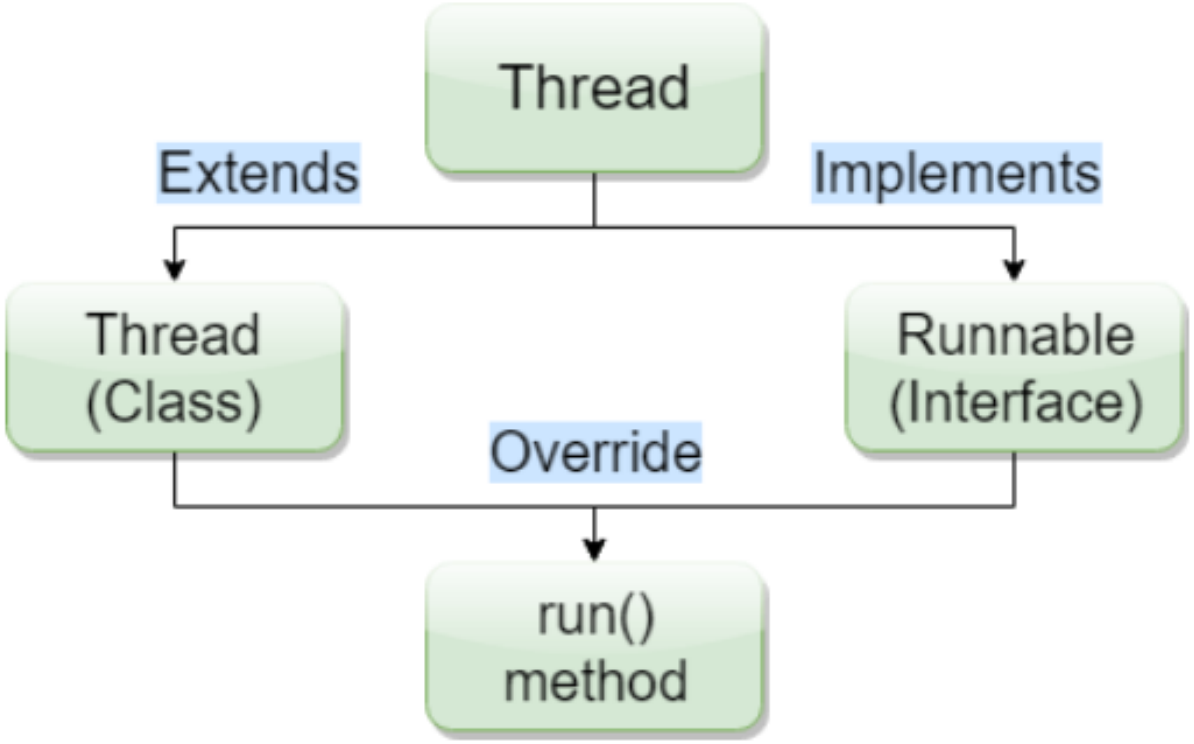
Subclass vs Runnable

```java
public static void main(String[] args) throws InterruptedException {
    // Cat thread (subclassing)
    Thread cat = new CatThread();
    cat.start();

    // Dog thread (runnable)
    Runnable runnable = ()-> {
        int cnt = 0;
        while(cnt<10) {
            System.out.printf("My class: Anonymous Dog  |  My thread: %s:  %d\n",
                    Thread.currentThread().getName(), ++cnt);
            try {
                Thread.sleep( millis: 600);
            } catch (InterruptedException e) {
                e.printStackTrace();
            }
        }
    };
    Thread dog = new Thread(runnable);
    dog.start();

    // Main thread
    int cnt=0;
    while(cnt<10){
        System.out.printf("My class: Main  |  My thread: %s:  %d\n",
                Thread.currentThread().getName(), ++cnt);
        Thread.sleep( millis: 1000);
    }
}
```

Subclass vs Runnable



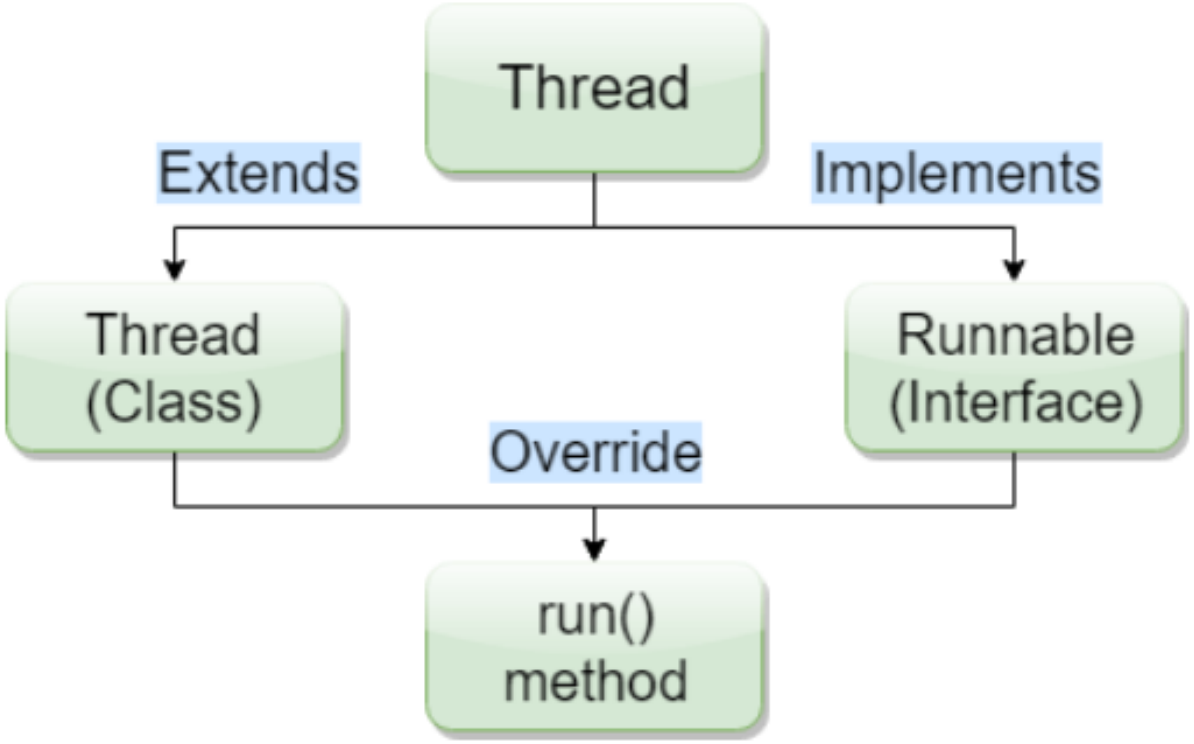
Subclass vs Runnable



Practical POV

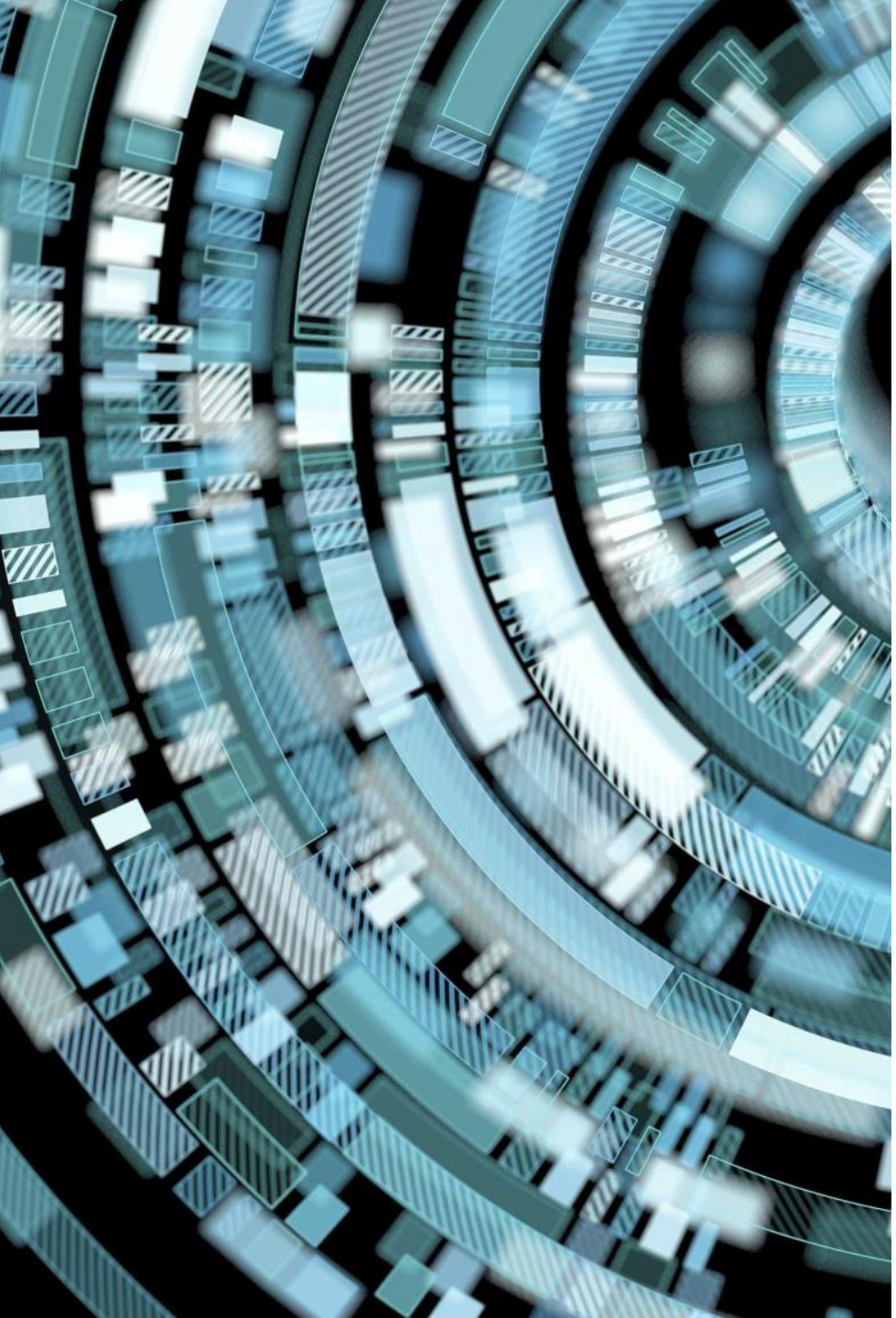
- Java doesn't support multiple inheritances.
- If a class extends Thread, it cannot extend other classes
- If a class implements Runnable, it can still extend other classes

Subclass vs Runnable



Design POV

- In OOP, extending a class generally means adding new functionality and modifying/improving behaviors
- But we're not really improving a thread's behavior, we're just giving it something to run (task)
- Implementing Runnable separates the task from the Thread object that executes the task



Lecture 7

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- Concurrent Collections

Example: shared resource

```
public class DogThread implements Runnable{
    private int bones = 10;

    public void run(){
        while (bones > 0 ){
            System.out.println(Thread.currentThread().getName()
                    + ": Dog eats bone " + (bones--));
            try {
                Thread.sleep( millis: 1000);
            } catch (InterruptedException e) {
                e.printStackTrace();
            }
        }
    }
}
```

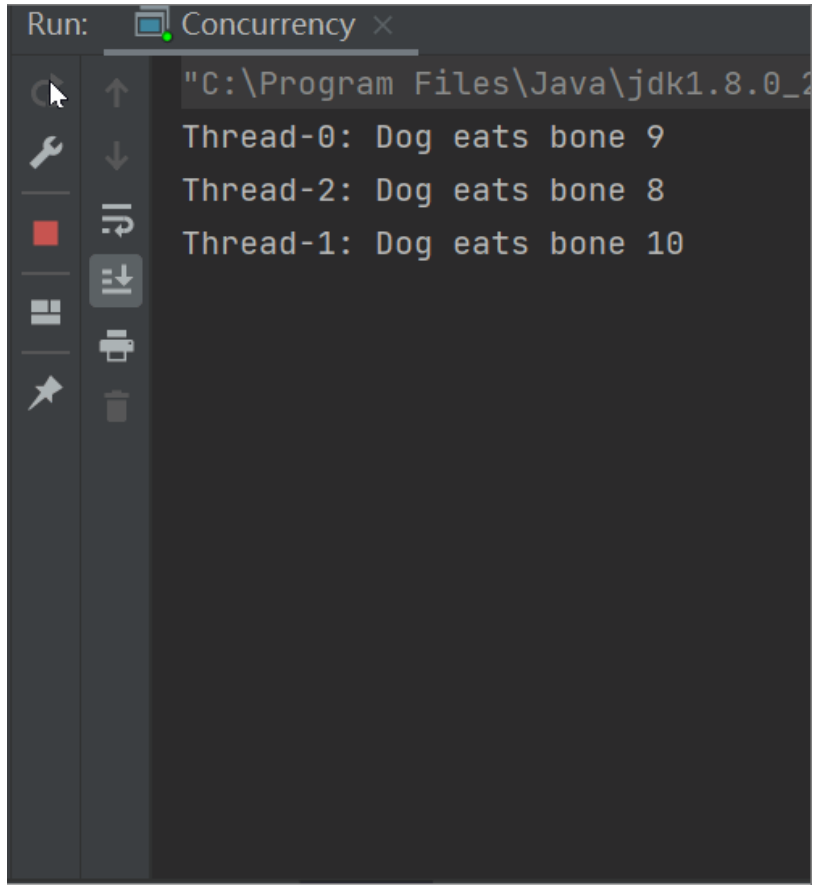
Inside main()

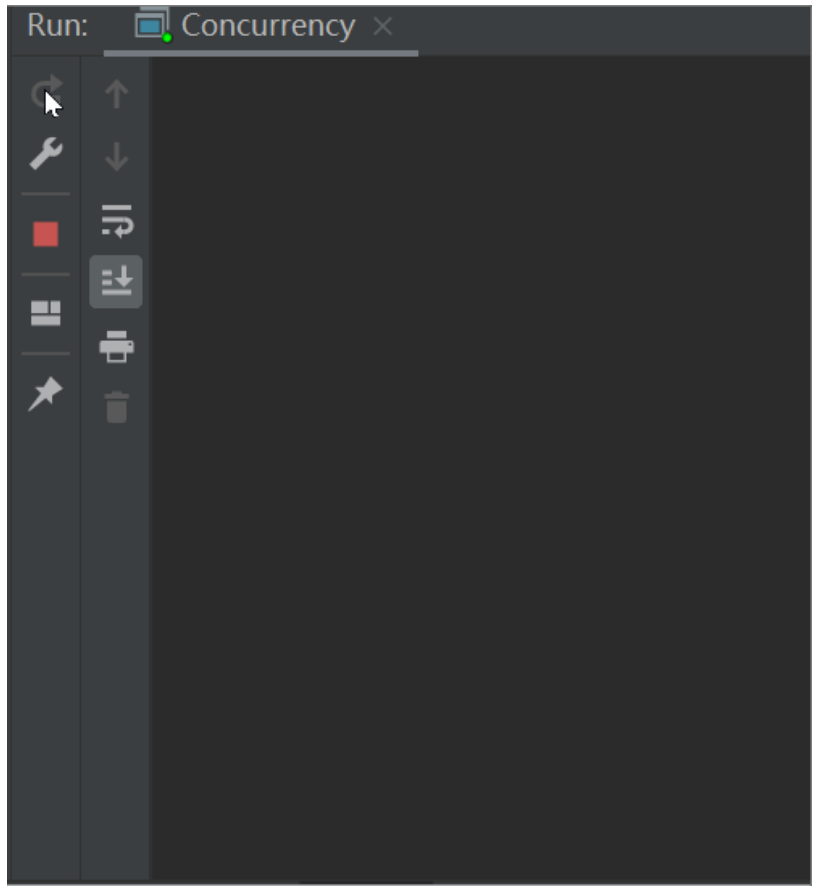
```
Runnable dog = new DogThread();
new Thread(dog).start();
new Thread(dog).start();
new Thread(dog).start();
```

What if we extend Thread?

Thread dog1 = new DogThread();
Thread dog2 = new DogThread();
Thread dog3 = new DogThread();

Example: shared resource





The same bone has been eaten by multiple dogs

-1 bone?

Example: shared resource

What we want

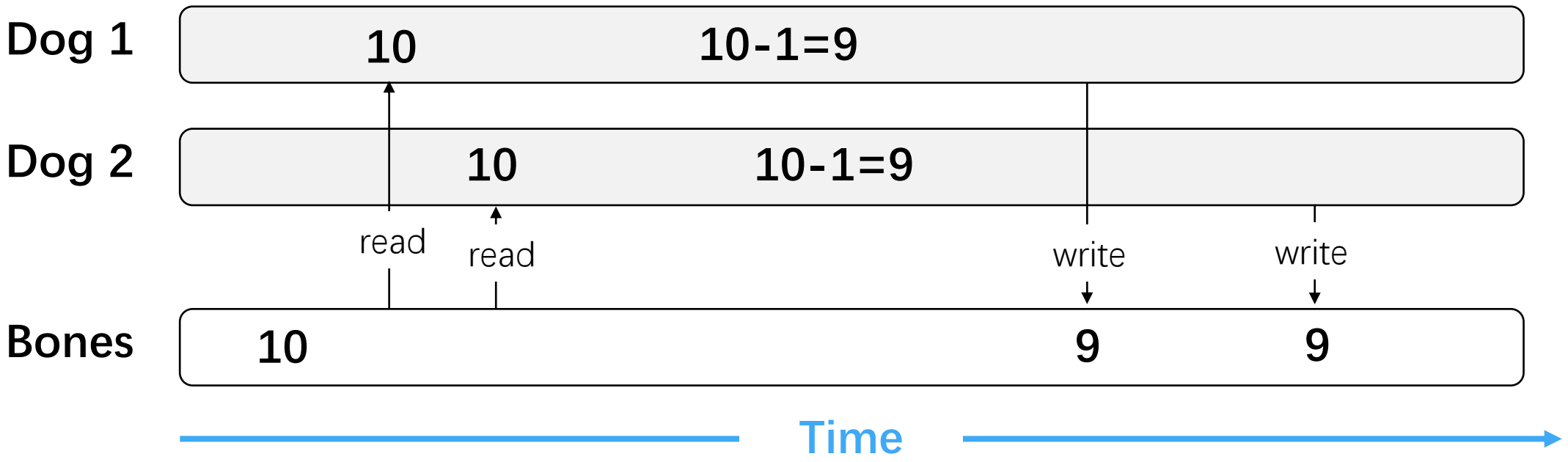
What we get

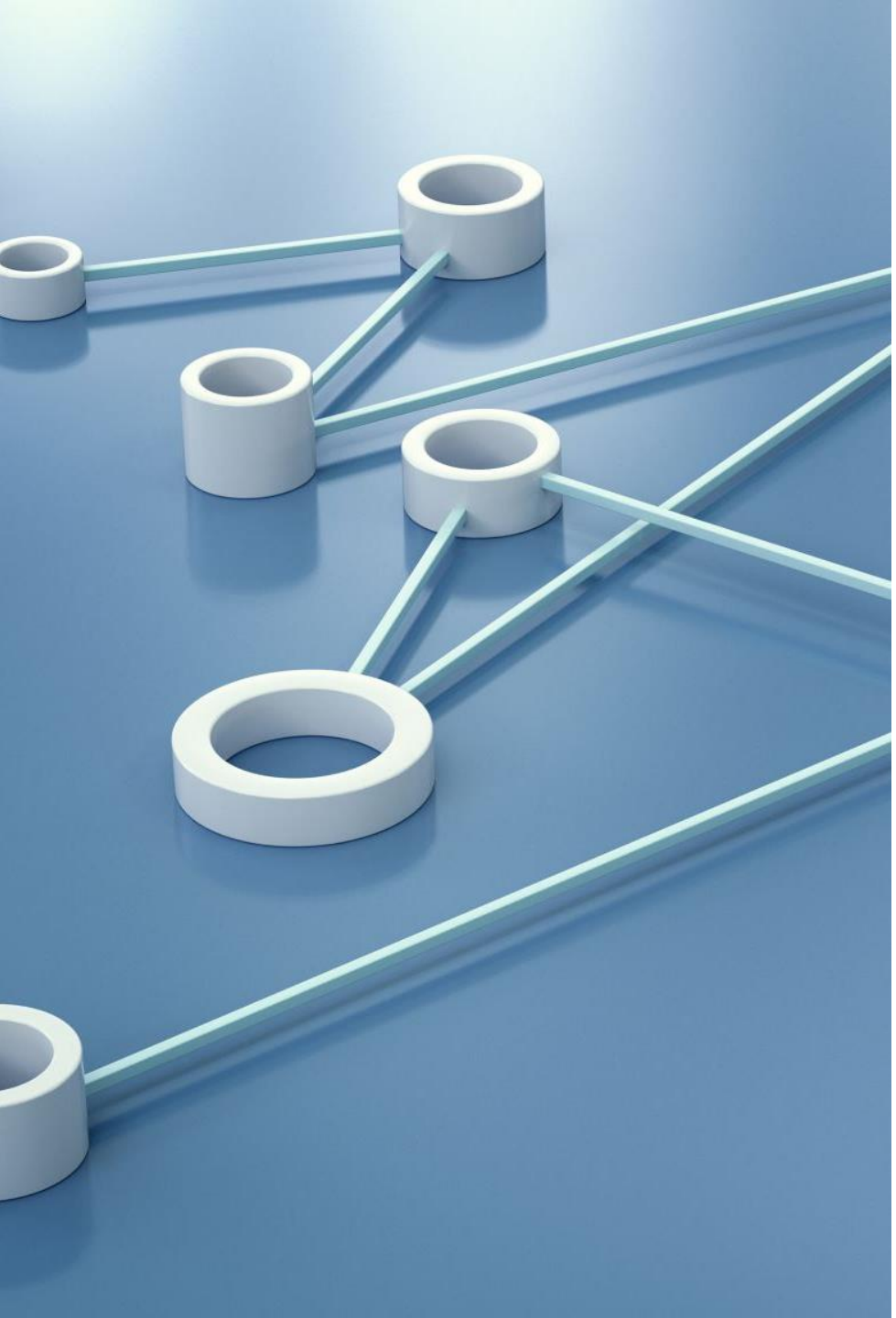
Race Condition

- A concurrency problem/bug
- Multiple threads compete for a shared resource (race)
- The final results depend on which thread gets the resource first (non-deterministic)

Critical Section

- The part of the program which accesses the shared resource
- A critical section is executed by multiple threads, and the sequence of execution for the threads makes a difference in the result





Synchronization in Java

- The synchronization mechanism ensures that only one thread can access the critical section (shared resource) at a given time

- Java supports
  - The `synchronized` keyword
  - The `Concurrency` API (`java.util.concurrent`), introduced in Java 5

Using the `synchronized` Keyword

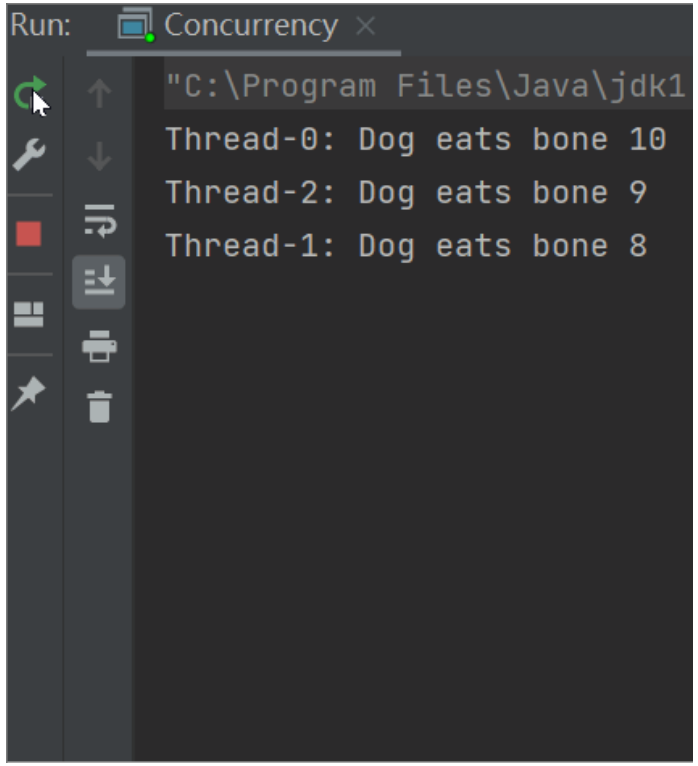
- A synchronized block is wrapped using the `synchronized` keyword
  - A code block inside a method (同步代码块)
  - A method (同步方法)

- All synchronized blocks synchronized on the same object can only have one thread executing inside them at the same time.
- All other threads attempting to enter the synchronized block are blocked until the thread inside the synchronized block exits the block.

Synchronized Methods

```java
public class DogThread implements Runnable{
    private int bones = 10;
    private boolean hasBone = true;

    public synchronized void eat(){
        if(bones <= 0){
            hasBone = false;
        } else{
            System.out.println(Thread.currentThread().getName()
                    + ": Dog eats bone " + (bones--));
        }
    }

    public void run(){
        while (hasBone){
            eat();
            try {
                Thread.sleep( millis: 1000);
            } catch (InterruptedException e) {
                e.printStackTrace();
            }
        }
    }
}
```

```java
Runnable dog = new DogThread();
new Thread(dog).start();
new Thread(dog).start();
new Thread(dog).start();
```



Synchronized Methods

```java
public class DogThread implements Runnable{
    private int bones = 10;
    private boolean hasBone = true;

    public synchronized void eat(){
        if(bones <= 0){
            hasBone = false;
        } else{
            System.out.println(Thread.currentThread().getName()
                    + ": Dog eats bone " + (bones--));
        }
    }

    public void run(){
        while (hasBone){
            eat();
            try {
                Thread.sleep( millis: 1000);
            } catch (InterruptedException e) {
                e.printStackTrace();
            }
        }
    }
}
```

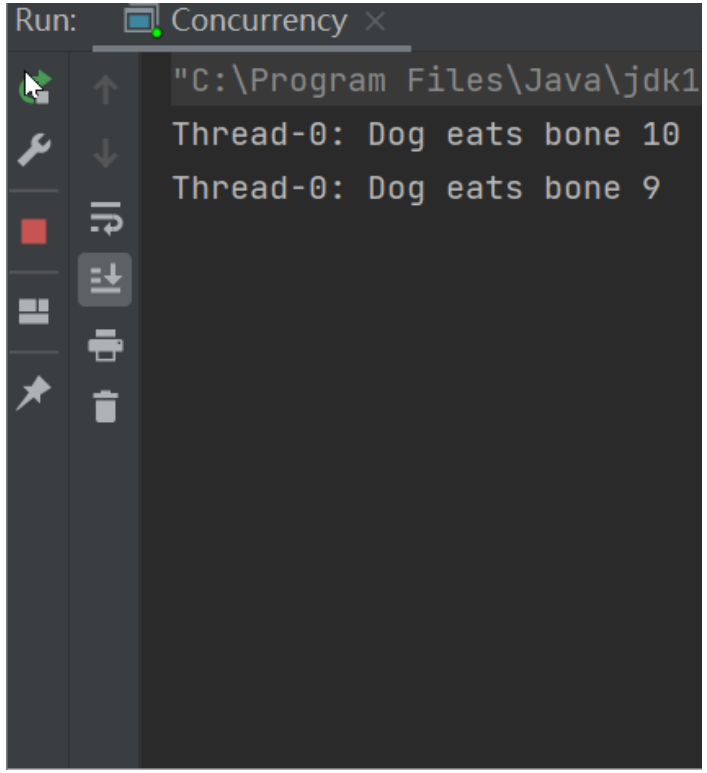
```java
Runnable dog = new DogThread();
new Thread(dog).start();
new Thread(dog).start();
new Thread(dog).start();
```

- A synchronized instance method in Java is synchronized on the instance (object) owning the method
- When one thread is executing a synchronized method for an object, all other threads that invoke any synchronized methods for the same object block until the first thread is done with the object.

Can we synchronize the `run()` method?

```java
public class DogThread implements Runnable{
    private int bones = 10;
    private boolean hasBone = true;

    public void eat(){
        if(bones <= 0){
            hasBone = false;
        } else{
            System.out.println(Thread.currentThread().getName()
                    + ": Dog eats bone " + (bones--));
        }
    }

    public synchronized void run(){
        while (hasBone){
            eat();
            try {
                Thread.sleep( millis: 1000);
            } catch (InterruptedException e) {
                e.printStackTrace();
            }
        }
    }
}
```

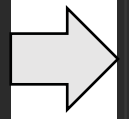
```java
Runnable dog = new DogThread();
new Thread(dog).start();
new Thread(dog).start();
new Thread(dog).start();
```



Synchronized Code Block

- Synchronized block synchronizes only part of the method
- A synchronized block takes an object in parentheses, which is called a monitor object.
- Only one thread can execute inside a Java code block synchronized on the same monitor object.

```
public synchronized void eat(){
    if(bones <= 0){
        hasBone = false;
    } else{
        System.out.println(Thread.currentThread().getName()
                + ": Dog eats bone " + (bones--));
    }
}
```



```
public void eat(){
    synchronized(this) {
        if (bones <= 0) {
            hasBone = false;
        } else {
            System.out.println(Thread.currentThread().getName()
                    + ": Dog eats bone " + (bones--));
        }
    }
}
```

Synchronized Code Block

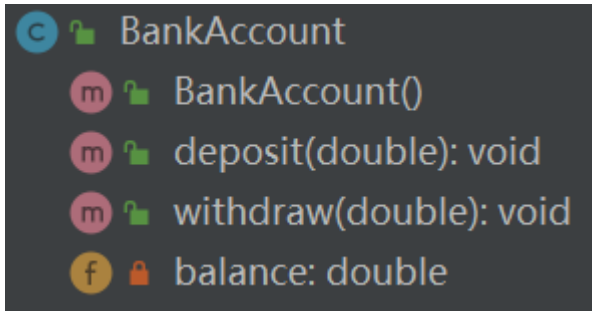
- Synchronized block can synchronize only part of the method
- c1 and c2 are independent variables, which can be updated concurrently
- Synchronizing inc1() and inc2() creates unnecessary blocking. Instead, synchronizing blocks improves concurrency

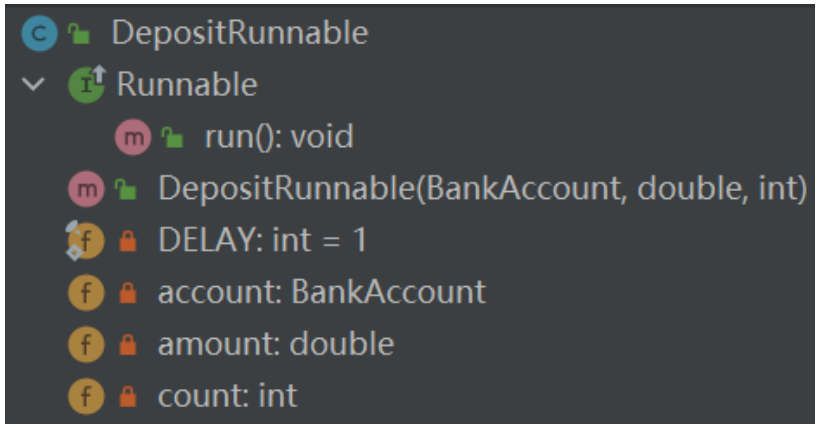
```
public class SyncDemo {

    private long c1 = 0;
    private long c2 = 0;

    private Object lock1 = new Object();
    private Object lock2 = new Object();

    public void inc1() {
        // 20 lines of code omitted...
        synchronized(lock1) {
            c1++;
        }
    }

    public void inc2() {
        // 30 lines of code omitted...
        synchronized(lock2) {
            c2++;
        }
    }
}
```

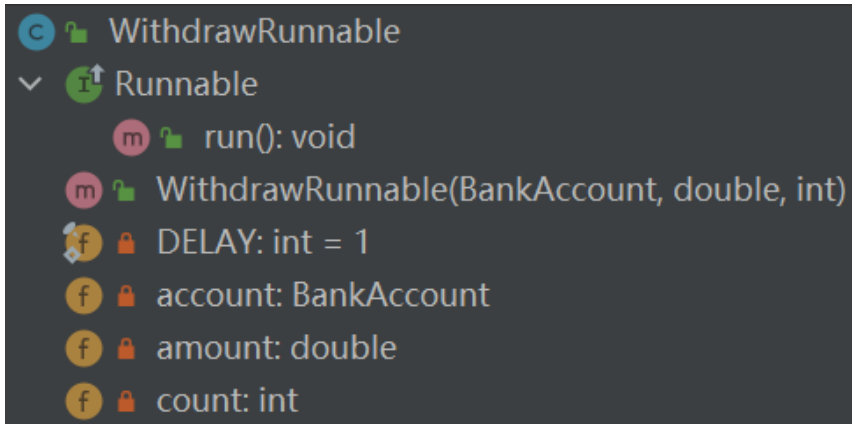
Using `Lock` in the `Concurrency` API

- Java 5 added a new Java package `java.util.concurrent`, which contains a set of classes that makes it easier to develop concurrent (multithreaded) applications in Java
- The Java `Lock` interface, `java.util.concurrent.locks.Lock`, represents a concurrent lock which can be used to guard against race conditions inside critical sections.
- The `Lock` interface provides more options than a `synchronized` block

A more practical problem: Bank Account Management








```
public void run() {
   try {
      for (int i = 1; i <= count; i++) {
         account.deposit( amount );
         Thread.sleep( DELAY );
      }
   } catch (InterruptedException exception) {}
}
```

```
public void run() {
   try {
      for (int i = 1; i <= count; i++) {
         account.withdraw( amount );
         Thread.sleep( DELAY );
      }
   } catch (InterruptedException exception) {}
}
```

Using Lock

- Lock is used to control the threads that want to manipulate a shared resource
- Since Lock is an interface, we cannot create an instance of Lock directly; we should create an instance of a class that implements the Lock interface
- Java provides several implementations of Lock; ReentrantLock is the most used one

```
Lock lock = new ReentrantLock();
```

Using Lock

- To lock the Lock instance, invoke its `lock()` method
- To unlock the Lock instance, invoke its `unlock()` method

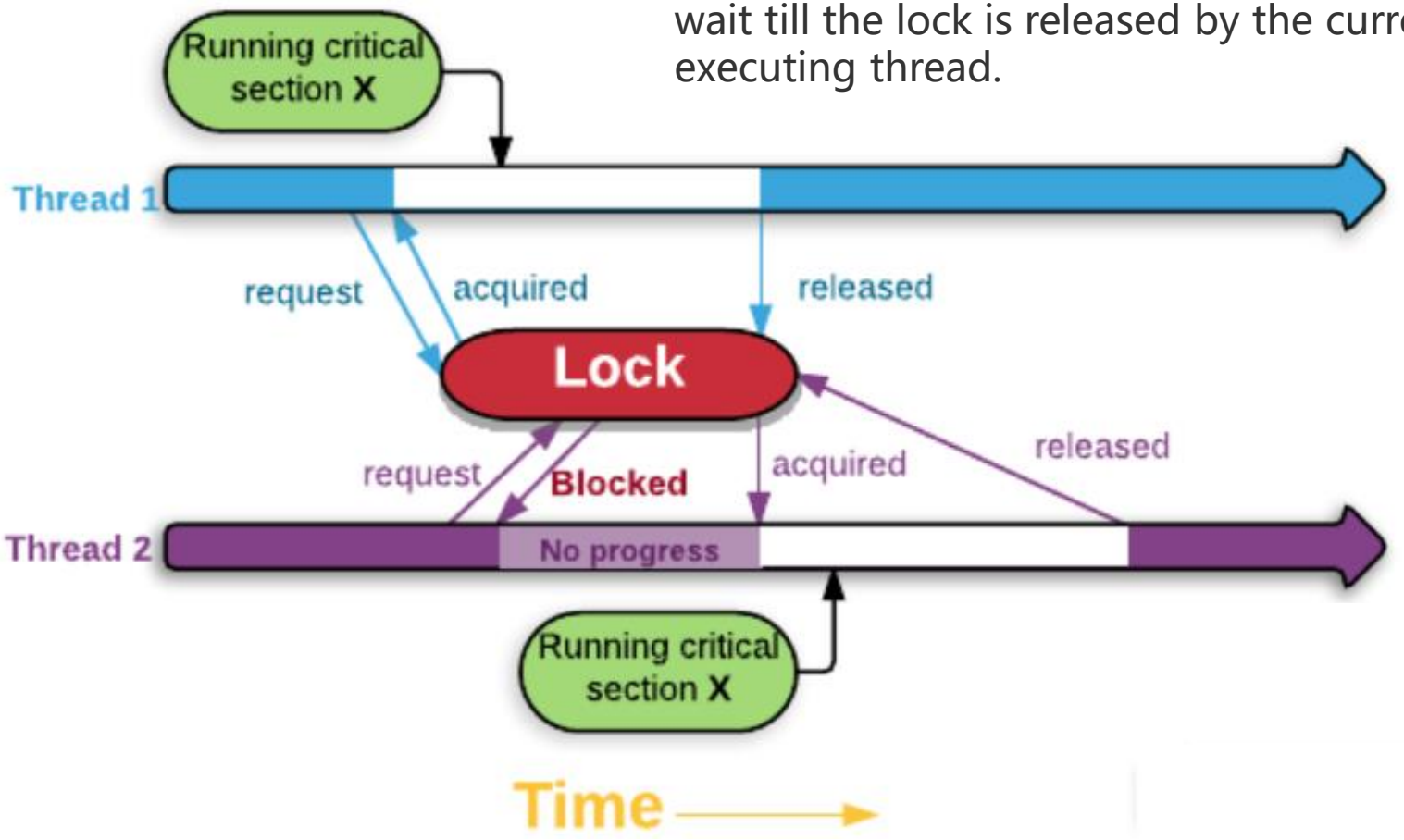
```
public class BankAccount {

   private Lock balanceChangeLock;
   . . .
   public BankAccount() {

      balanceChangeLock = new ReentrantLock();
      . . .
   }
}
```

```
balanceChangeLock.lock();
Manipulate the shared resource.
balanceChangeLock.unlock();
```

- When the Lock instance is locked, any other thread calling lock() will be blocked until the thread that locked the lock calls unlock().
- When unlock() is called, the Lock is unlocked so other threads can lock it.

Mutual Exclusion of Critical Section

- As long as a thread owns a lock, no other thread can acquire the same lock.
- The other threads will block when they attempt to acquire the lock. The blocked threads will wait till the lock is released by the currently executing thread.



https://www.logicbig.com/tutorials/core-java-tutorial/java-multi-threading/java-intrinsic-locks.html

Potential Flaw?

```
balanceChangeLock.lock();
Manipulate the shared resource.
balanceChangeLock.unlock();
```

- What will happen if the code between `lock()` and `unlock()` throws an exception?
  - The call `unlock()` never happen
  - The current thread continues to hold the lock, and no other thread can acquire it

Avoid Exceptions lock a Lock forever

- To overcome this problem, place unlock() in a `finally` clause

```
public void deposit (double amount) {
    balanceChangeLock.lock();
    try {
        System.out.print("Depositing " + amount);
        double newBalance = balance + amount;
        System.out.println(", new balance is " + newBalance);
        balance = newBalance;
    } finally {
        balanceChangeLock.unlock();
    }
}
```

- The finally block *always* executes when the try block exits.
- This ensures that the finally block is executed even if an unexpected exception occurs

Deadlock

- Thread A acquires a lock and then waits for thread B to do some essential work.
- Thread B is currently waiting to acquire the same lock in order to do the essential work

Interviewer: “Explain deadlock to us and we’ll hire you.”

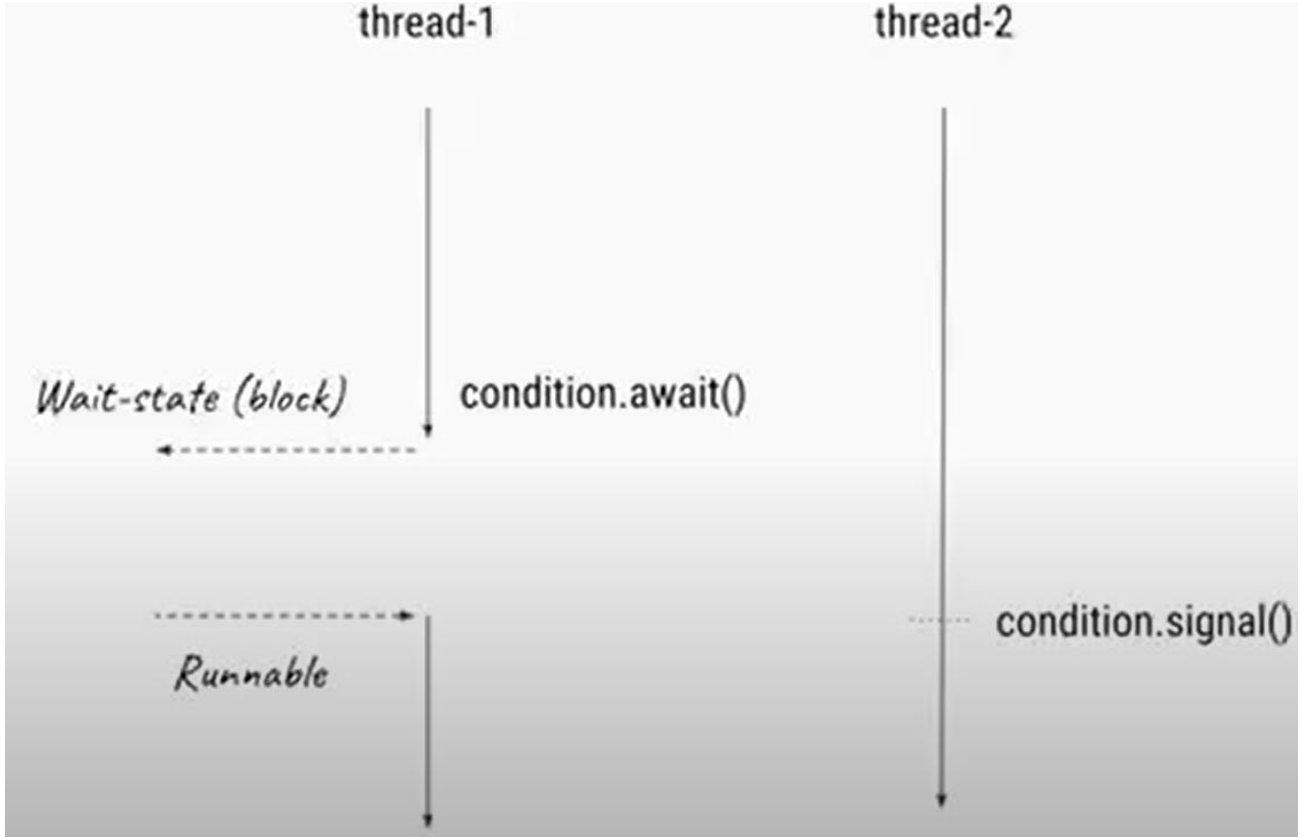
Me: “Hire me and I’ll explain it to you.”

Deadlock

- To disallow negative balance during withdraw, we can wait for other threads to deposit money
- Other threads calling deposit() are blocked and waiting for withdraw() to unlock() the resource
- But withdraw() is waiting for deposit() to execute so that balance becomes enough for withdrawal.

```
public void withdraw(double amount)
{
   balanceChangeLock.lock();
   try
   {
      while (balance < amount)
      {
         Wait for the balance to grow.
      }
      . . .
   }
   finally
   {
      balanceChangeLock.unlock();
   }
}
```

Avoiding Deadlocks



- The `Condition` interface (`java.util.concurrent.locks`) provides a thread ability to suspend its execution, until the given condition is true.
- Condition allows a thread
  - To temporarily release a lock so that another thread can proceed
  - To regain the lock later when the condition is satisfied

Using `Condition`

- Each condition object belongs to a specific lock object.
- We could obtain a condition object with the `newCondition()` method of the `Lock` interface

- A Condition object is necessarily bound to a Lock
- It is customary to give the condition object a name that describes the condition that you want to test

```
public class BankAccount {
    private Lock balanceChangeLock;
    private Condition sufficientFundsCondition;
    . . .
    public BankAccount() {
        balanceChangeLock = new ReentrantLock();
        sufficientFundsCondition = balanceChangeLock.newCondition();
        . . .
    }
}
```

Using `Condition await()`

- For a condition to take effect, we need to implement an appropriate test (i.e., condition)
- For as long as the test/condition is not fulfilled, call the `await()` method on the condition object (hence the loop)
- Calling `await()` on a condition object makes the current thread wait and allows another thread to acquire the lock object.

When calling await, the current thread becomes disabled and lies dormant until some other thread invokes the signal() or signalAll() method for this Condition

```
public void withdraw(double amount)
{
   balanceChangeLock.lock();
   try
   {
      while (balance < amount)
      {
         sufficientFundsCondition.await();
      }
      . . .
   }
   finally
   {
      balanceChangeLock.unlock();
   }
}
```

Using `Condition signalAll()`

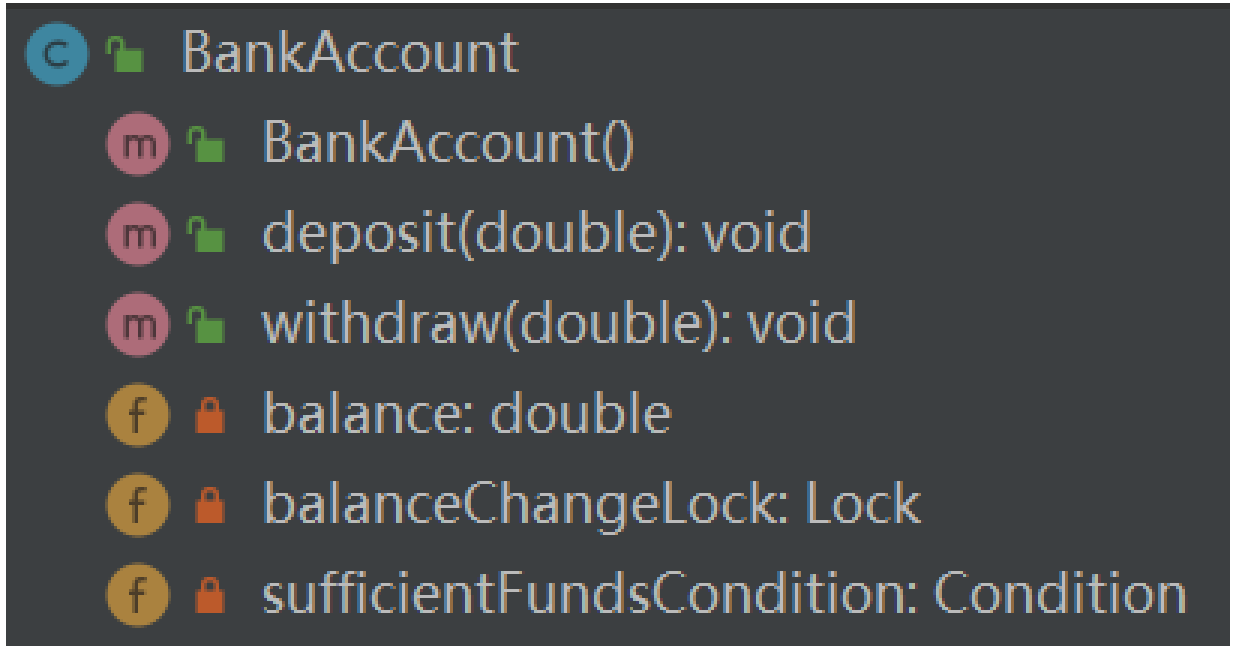
The call to signalAll() notifies all the waiting threads that sufficient funds may be available, and that it is worth testing the loop condition again

- To unblock, another thread must execute the `signalAll()` method on the same condition object
- The `signalAll()` method unblocks all threads waiting on the condition, which then compete with each other that is waiting for the lock object.
- Eventually, one of them will gain access to the lock, and it will exit from the `await()` method.

```
public void deposit(double amount)
{
   balanceChangeLock.lock();
   try
   {
      . . .
      sufficientFundsCondition.signalAll();
   }
   finally
   {
      balanceChangeLock.unlock();
   }
}
```

To Put it Altogether

```java
public class BankAccount {
   private double balance;
   private Lock balanceChangeLock;
   private Condition sufficientFundsCondition;

   /**
      Constructs a bank account with a zero balance.
   */
   public BankAccount() {
      balance = 0;
      balanceChangeLock = new ReentrantLock();
      sufficientFundsCondition = balanceChangeLock.newCondition();
   }
```

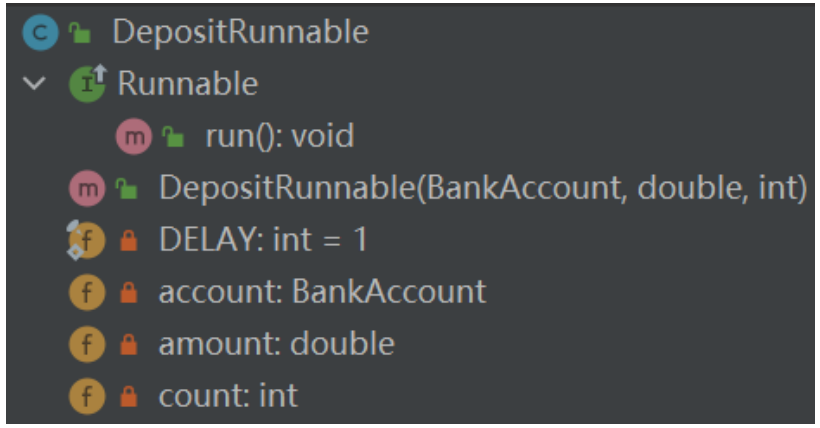


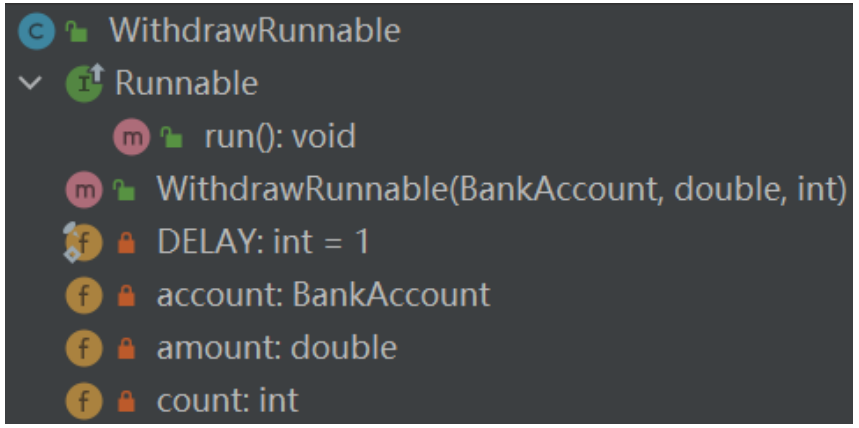
To Put it Altogether

```
public void withdraw (double amount) throws InterruptedException {
    balanceChangeLock.lock();
    try {
        while (balance < amount) {
            sufficientFundsCondition.await();
        }
        System.out.print( "Withdrawing " + amount );
        double newBalance = balance - amount;
        System.out.println( ", new balance is " + newBalance );
        balance = newBalance;
    } finally {
        balanceChangeLock.unlock();
    }
}
```

```
public void deposit (double amount) {
    balanceChangeLock.lock();
    try {
        System.out.print( "Depositing " + amount );
        double newBalance = balance + amount;
        System.out.println( ", new balance is " + newBalance );
        balance = newBalance;
        sufficientFundsCondition.signalAll();
    } finally {
        balanceChangeLock.unlock();
    }
}
```

To Put it Altogether



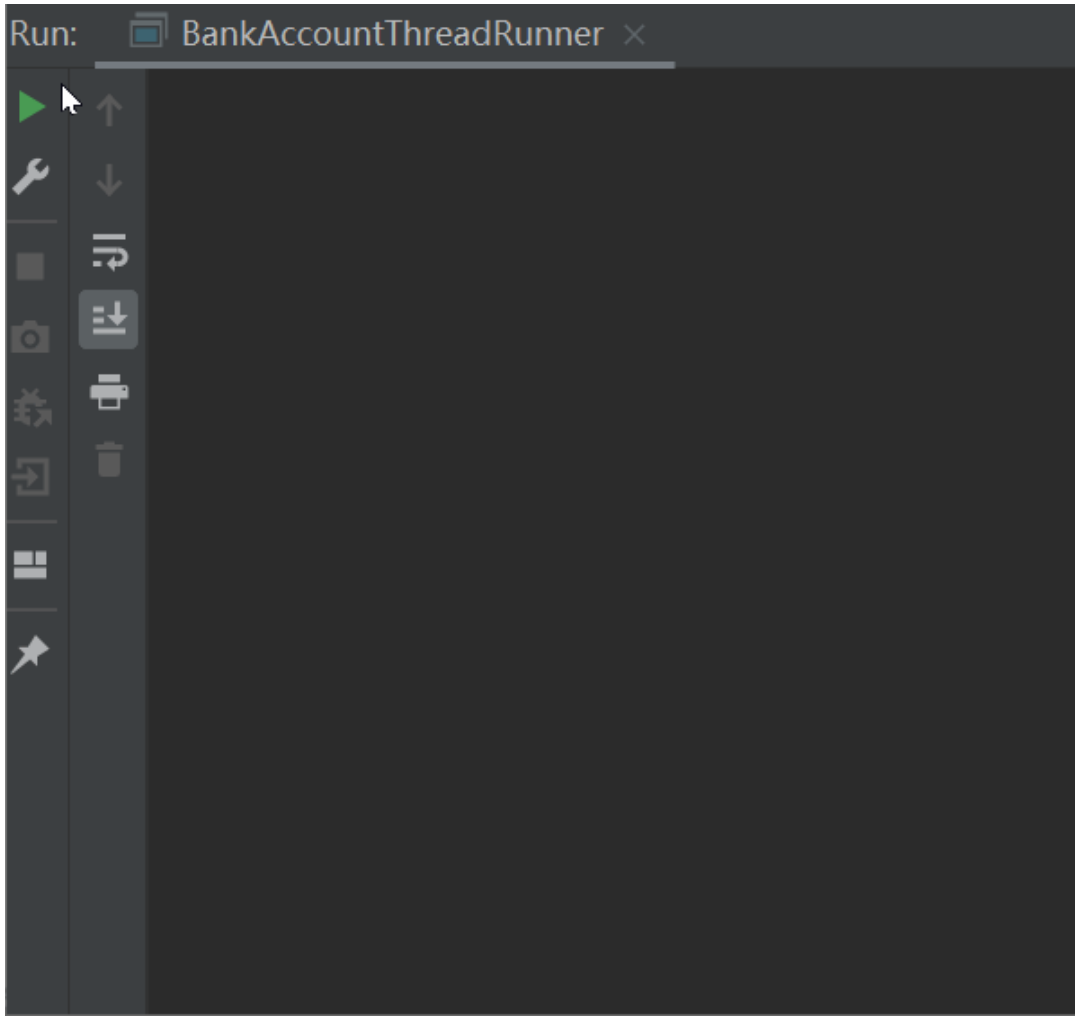



```
public void run() {
   try {
      for (int i = 1; i <= count; i++) {
         account.deposit( amount );
         Thread.sleep( DELAY );
      }
   } catch (InterruptedException exception) {}
}
```

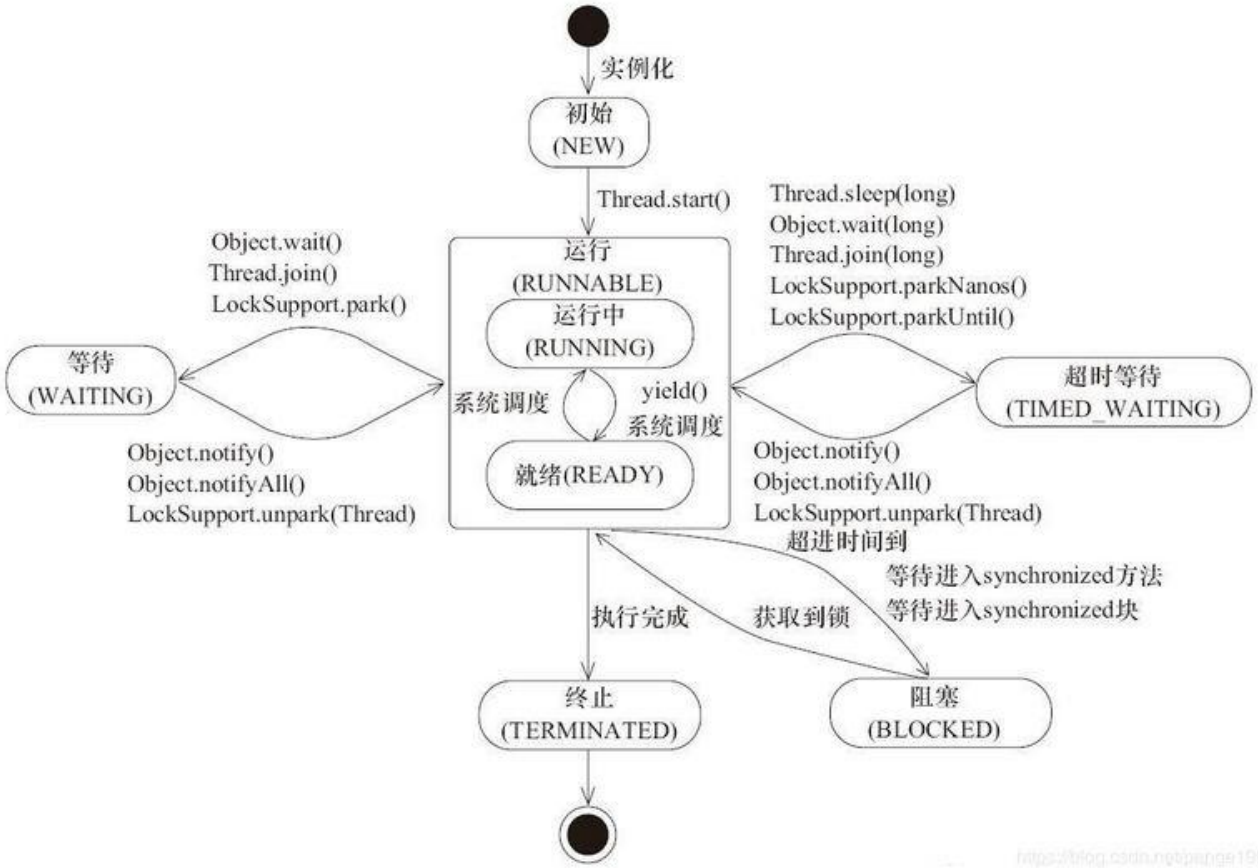
```
public void run() {
   try {
      for (int i = 1; i <= count; i++) {
         account.withdraw( amount );
         Thread.sleep( DELAY );
      }
   } catch (InterruptedException exception) {}
}
```

To Put it Altogether

```
public class BankAccountThreadRunner {
    public static void main (String[] args) {
        BankAccount account = new BankAccount();
        final double AMOUNT = 100;
        final int REPETITIONS = 100;
        final int THREADS = 100;

        for (int i = 1; i <= THREADS; i++) {
            DepositRunnable d =
                new DepositRunnable( account, AMOUNT, REPETITIONS );
            WithdrawRunnable w =
                new WithdrawRunnable( account, AMOUNT, REPETITIONS );

            Thread dt = new Thread(d);
            Thread wt = new Thread(w);

            dt.start();
            wt.start();
        }
    }
}
```



Thread States

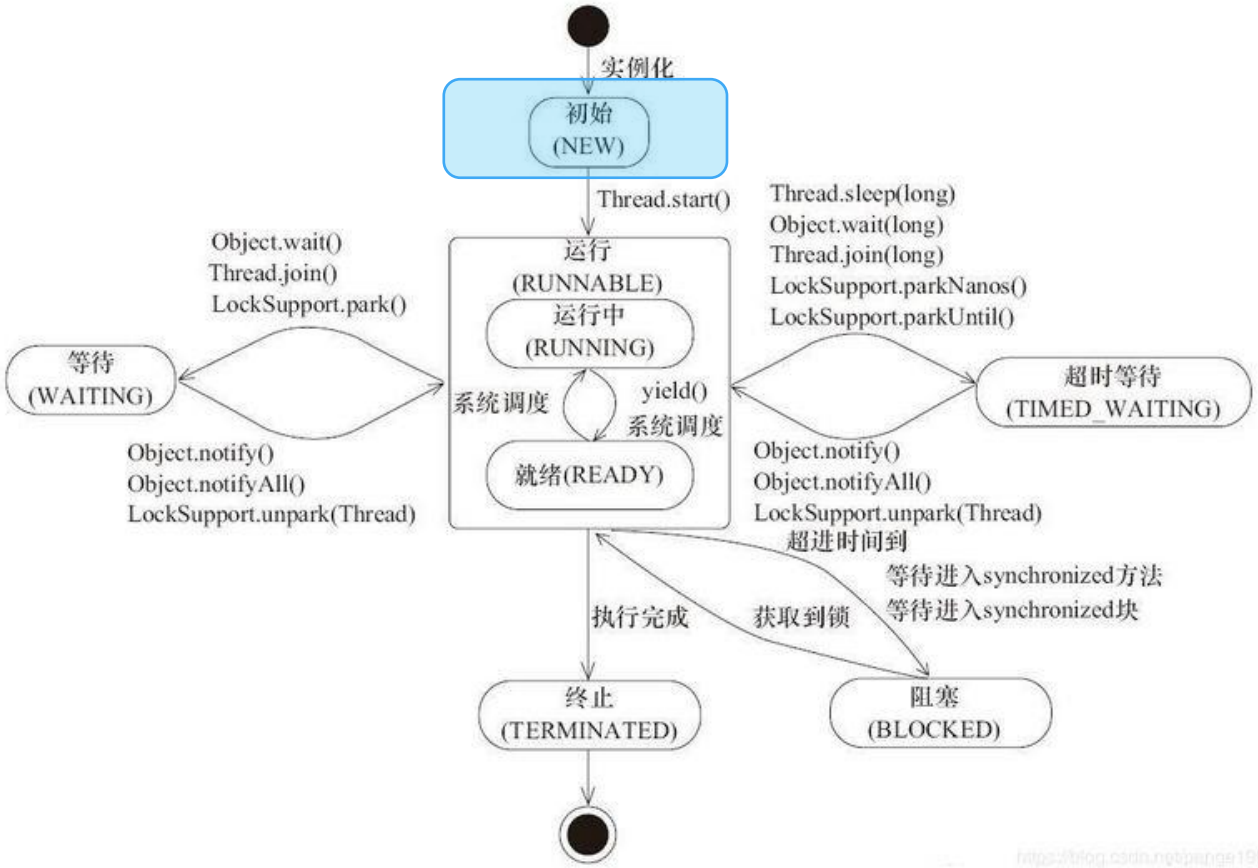


A thread can be in one of the following states (Enum `Thread.State`):

- NEW
- RUNNABLE
- BLOCKED
- WAITING
- TIMED_WAITING
- TERMINATED

https://developpaper.com/six-states-and-switching-of-java-thread/

Thread States

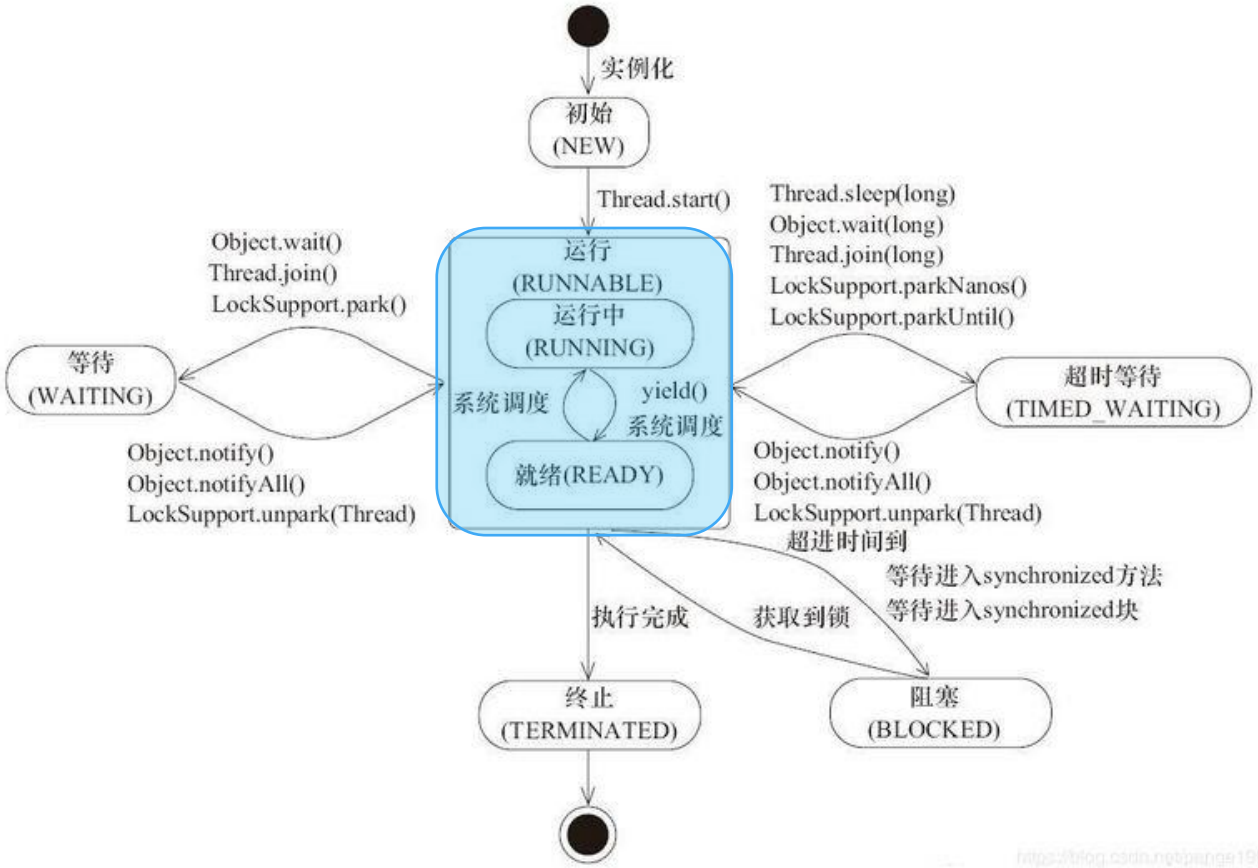


https://developpaper.com/six-states-and-switching-of-java-thread/

NEW

- When you create a thread with `new` (e.g., `new Thread(r)`), it enters this initial NEW state
- At this state, the program has NOT started executing code

Thread States

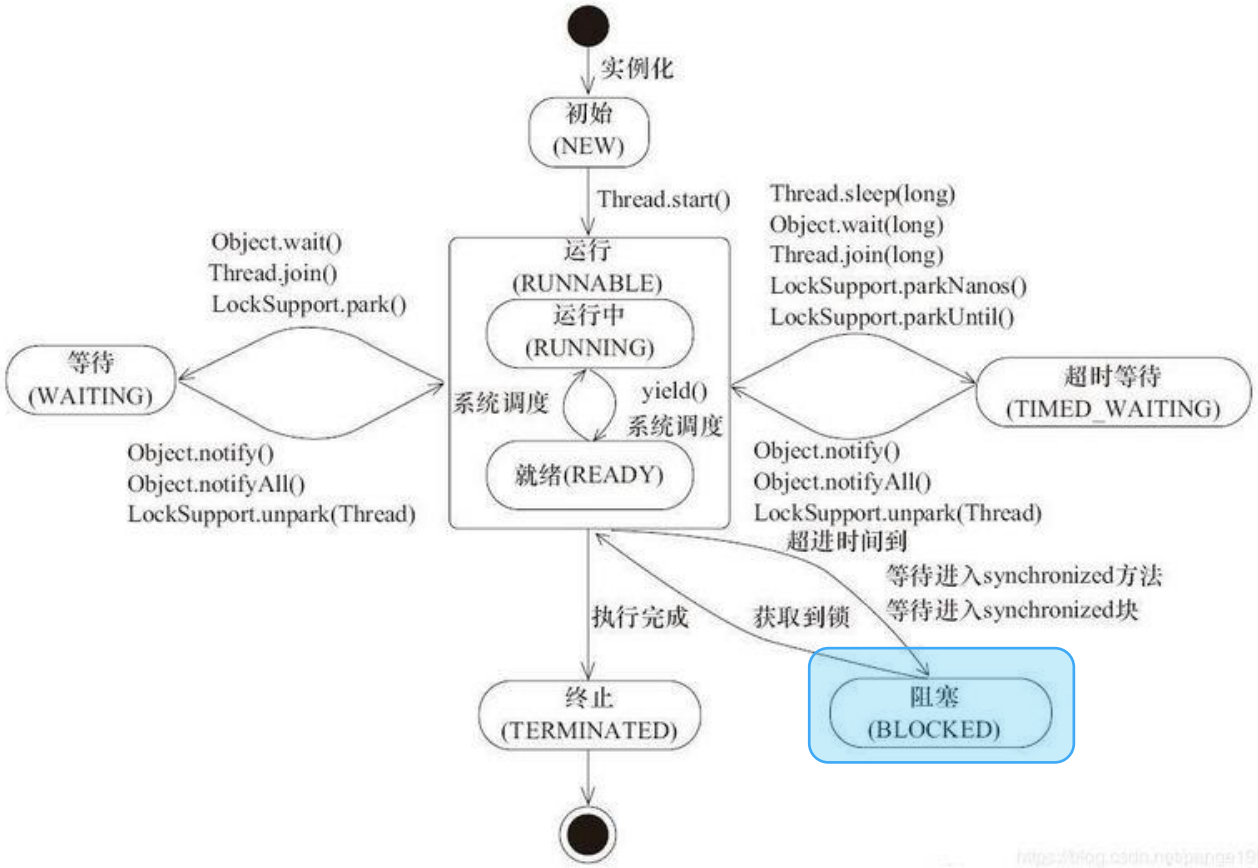


https://developpaper.com/six-states-and-switching-of-java-thread/

RUNNABLE

- Ready to run (`Thread.start()`)
- Nothing prevents the thread from "running" except the availability of a CPU to run on (or in other words waiting for other threads (currently executing) to complete its execution and execute itself).

Thread States

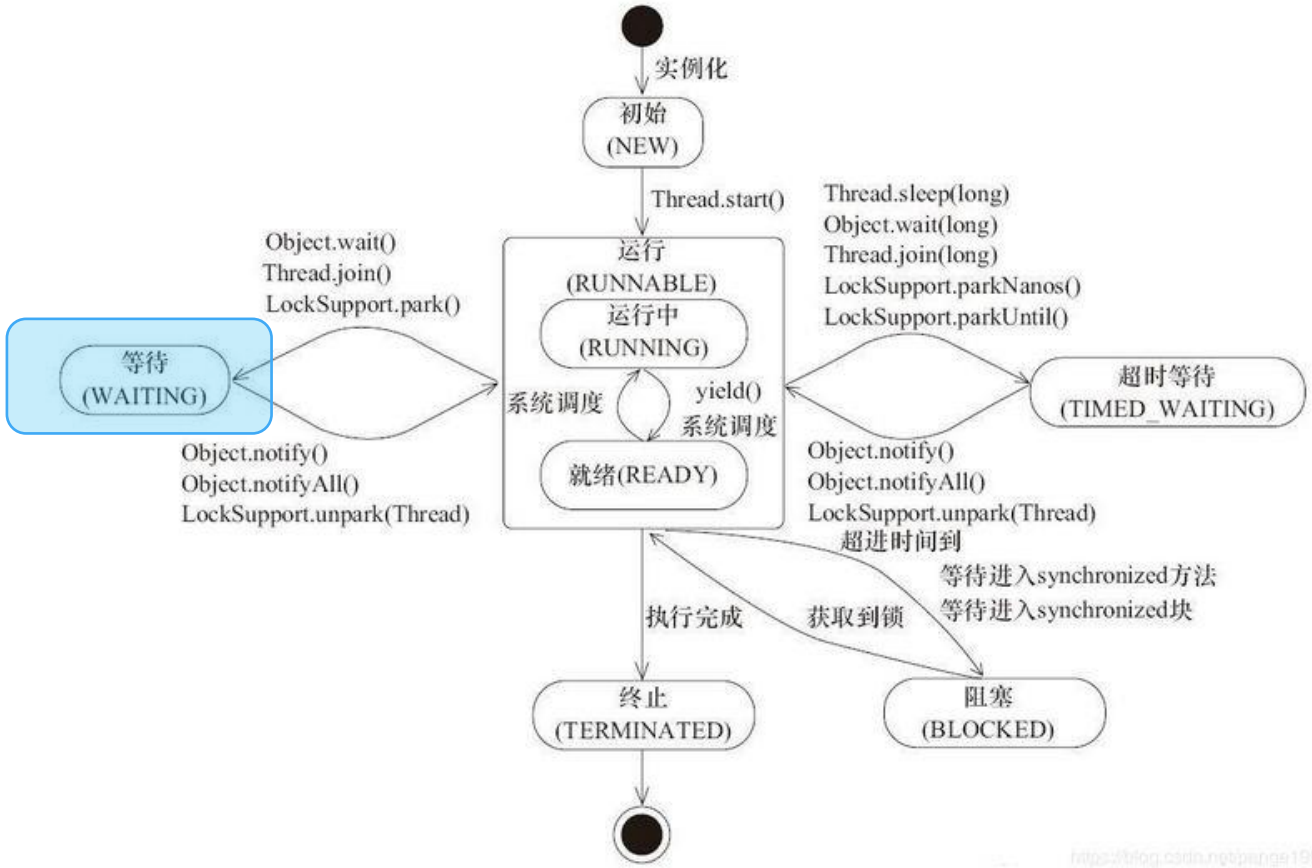


BLOCKED

- When a thread tries to acquire an intrinsic object lock (synchronized keyword) that is currently held by another thread, it becomes blocked.
- The thread is unblocked when all other threads have released the lock

https://developpaper.com/six-states-and-switching-of-java-thread/

Thread States

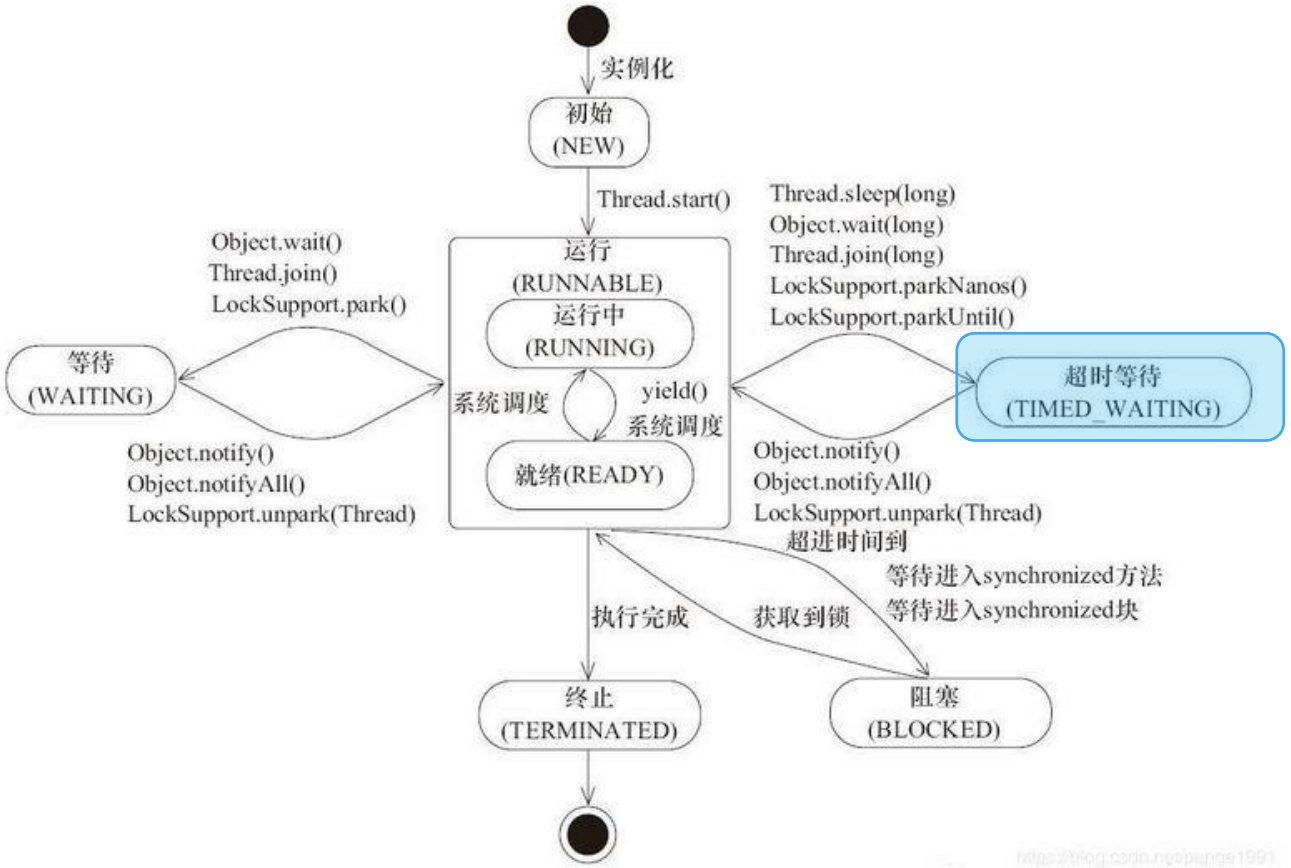


https://developpaper.com/six-states-and-switching-of-java-thread/

WAITING

- In the WAITING state, a thread is waiting for a signal from another thread.
- This happens typically by calling `Object.wait()`, or `Thread.join()`.
- The thread will then remain in this state until another thread calls `Object.notify()`, `Object.notifyAll()`, or dies.

Thread States

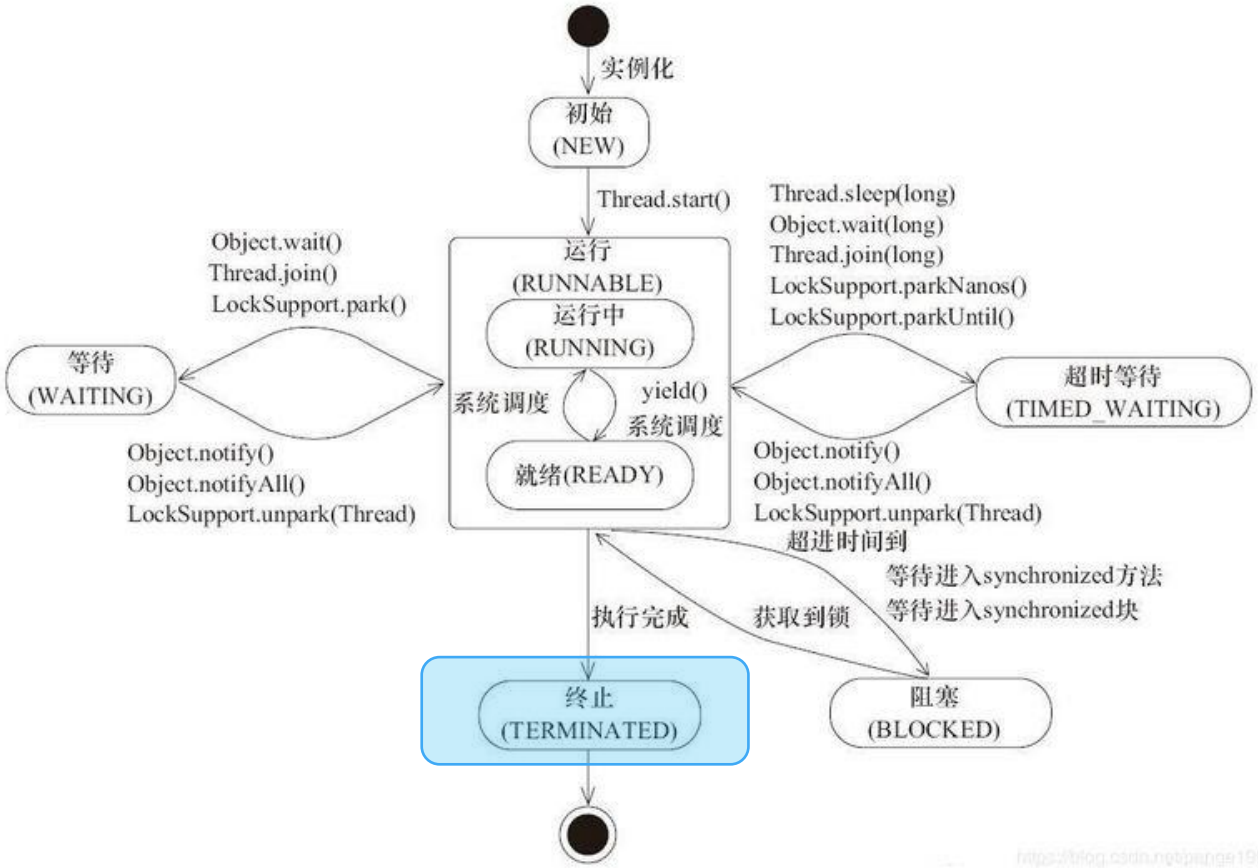


TIMED_WAITING

- Several methods support timeout
- Calling them causes the thread to enter TIMED_WAITING state

https://developpaper.com/six-states-and-switching-of-java-thread/

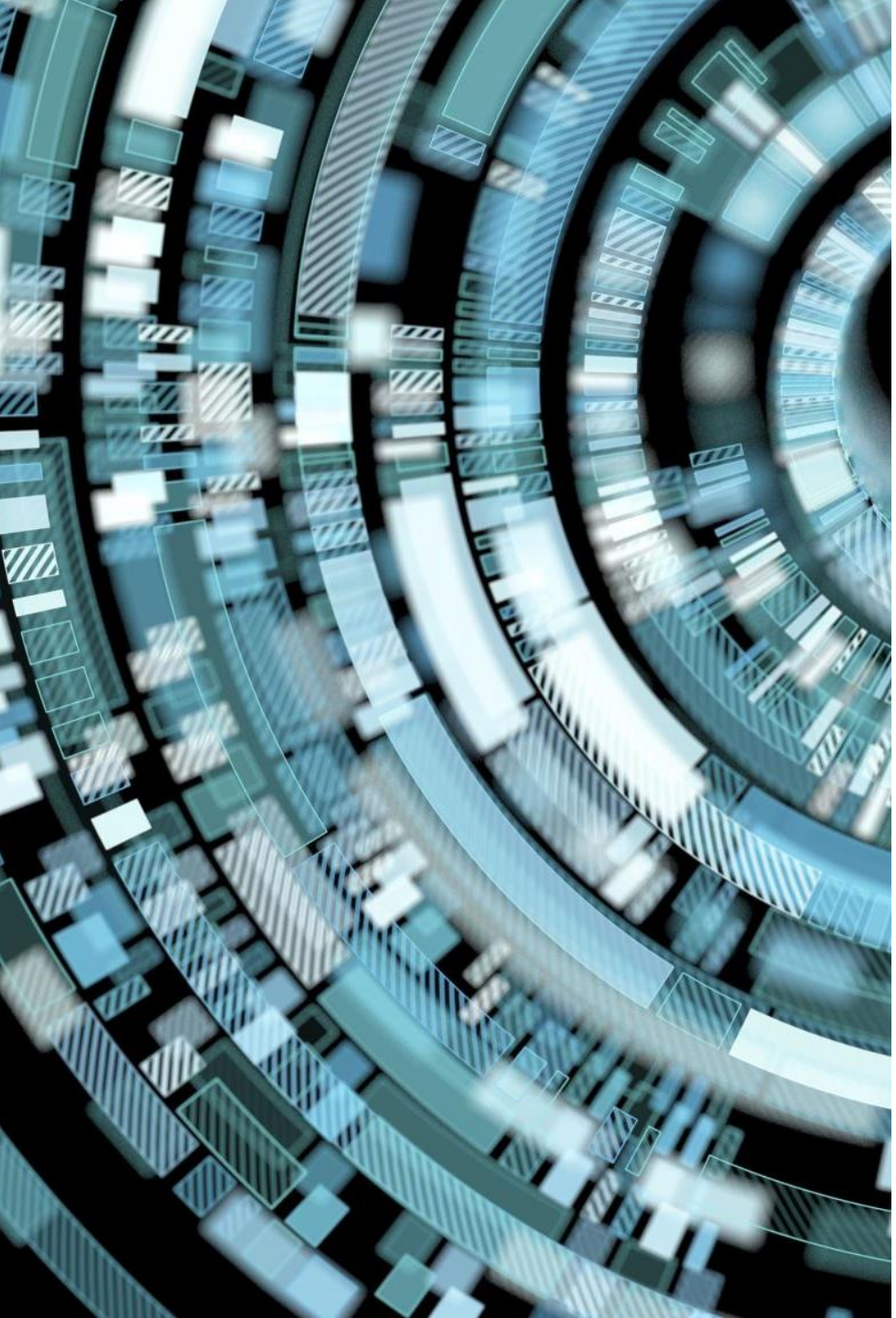
Thread States



TERMINATED

- The `run()` method exits normally
- The `run()` method dies abruptly because of an uncaught exception

https://developpaper.com/six-states-and-switching-of-java-thread/



Lecture 7

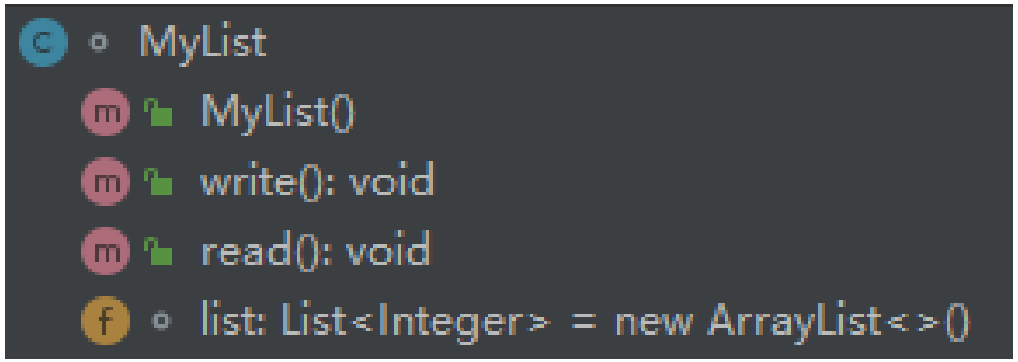
- Multithreading Overview
- Creating & Starting Threads
- Thread Safety
- Concurrent Collections

Concurrency for Java Collection

- All collection classes (e.g., `ArrayList`, `HashMap`, `HashSet`, `TreeSet`, etc.) in `java.util` are not thread-safe (except for `Vector` and `Hashtable`) . Why?
- Synchronization can be expensive
  - Vector and Hashtable are the two collections exist early and are designed for thread-safety from the start. However, they quickly expose poor performance
  - New collections (List, Set, Map, etc) provide no concurrency control to provide maximum performance in single-threaded applications

https://www.codejava.net/java-core/collections/understanding-collections-and-thread-safety-in-java

Example: fail-fast iterators




```java
public MyList(){
    for(int i=0;i<100;i++){
        list.add(i);
    }
}
```

```java
public void read(){
    Thread thread = new Thread(()->{
        Iterator<Integer> iter = list.iterator();
        while(iter.hasNext()){
            System.out.println(iter.next());
        }
    });
    thread.start();
}
```

```java
public void write(){
    Thread thread = new Thread(()->{
        for(int i=100; i<200; i++){
            list.add(i);
        }
    });
    thread.start();
}
```

Example: fail-fast iterators

```java
public static void main(String[] args) {
    MyList list = new MyList();
    list.read();
    list.write();
}
```

```
20
21
22
23
24
Exception in thread "Thread-0" java.util.ConcurrentModificationException
    at java.util.ArrayList$Itr.checkForComodification(ArrayList.java:909)
    at java.util.ArrayList$Itr.next(ArrayList.java:859)
    at IteratorFailFastTest$2.run(IteratorFailFastTest.java:32) <1 intern
```

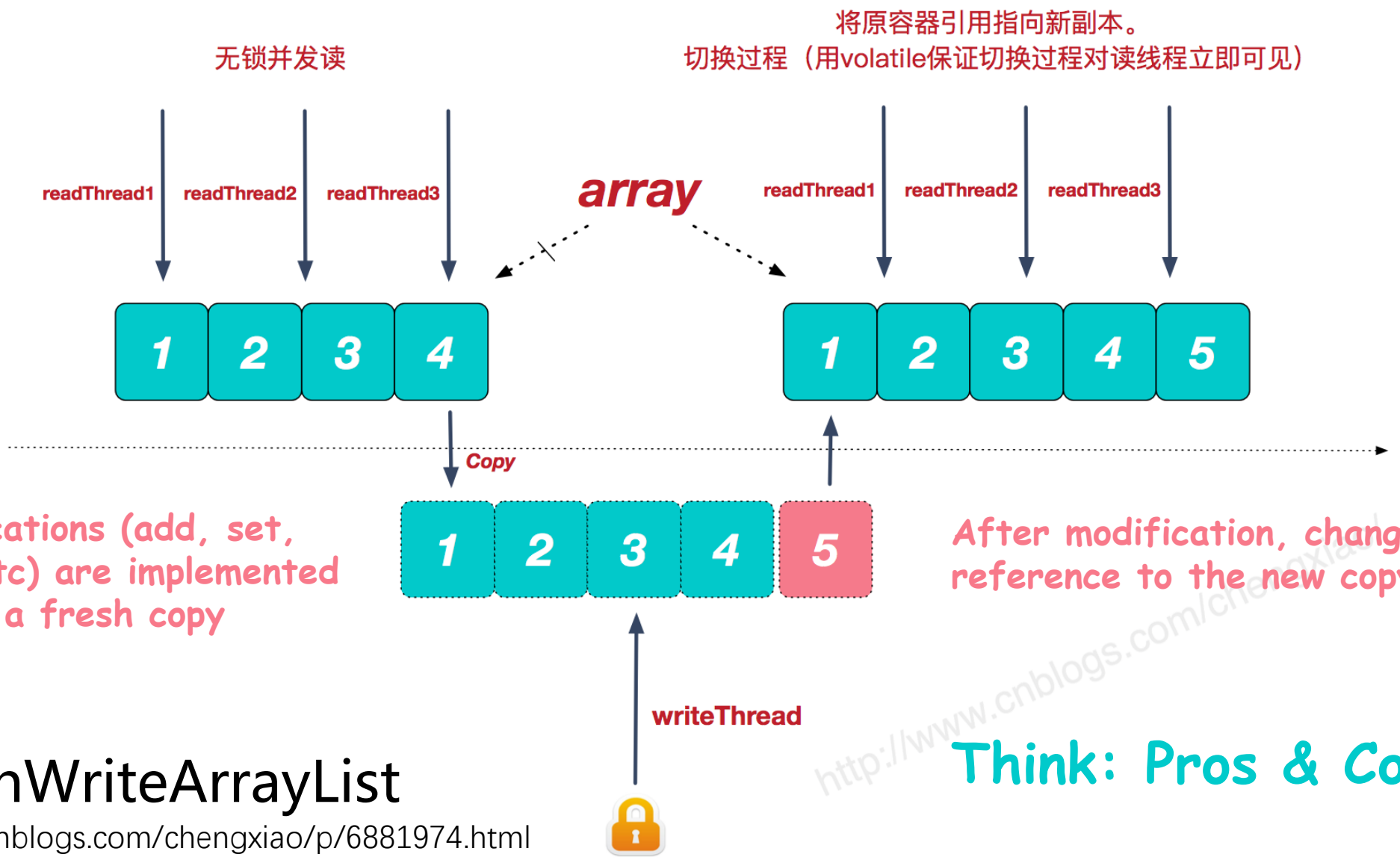
- Concurrent modification may lead to unexpected behavior and inconsistent results
- Fail-fast iterator prevents this by failing quickly, so that we can find and diagnose bugs early
- We should not rely on fail-fast iterator; instead, we should avoid dangerous concurrent operations

Concurrent Collections in Java

- Introduced in Java 5 in `java.util.concurrent` package
- 3 categories w.r.t. thread-safety mechanism
  - Copy-on-Write collections
  - Compare-and-Swap collections (CAS)
  - Collections using Lock

Copy-on-Write Collections

- Behaviors: sequential writes and concurrent reads
  - Reads do not block
  - Writes do not block reads, but only one write can occur at once
- Under the hood: copy-on-write collections store values in an immutable array; any change to the value of the collection results in a new array being created to reflect the new values
- Example classes
  - `CopyOnWriteArrayList`
  - `CopyOnWriteArraySet`



CopyOnWriteArrayList

https://www.cnblogs.com/chengxiao/p/6881974.html

CopyOnWriteArrayList

- CopyOnWriteArrayList implements the List interface (i.e., it has all typical behaviors of a List)
- CopyOnWriteArrayList is considered as a thread-safe alternative to ArrayList with some differences (checkout the official documentation or https://www.codejava.net/java-core/concurrency/java-concurrent-collection-copyonwritearraylist-examples)
  - `iterator()` is non-fail fast / fail safe

Fail-fast vs. Fail-safe Iterator

```java
List<Integer> list = new ArrayList<>(List.of(1,2,3,4));
Iterator<Integer> itr = list.iterator();
while (itr.hasNext()) {
    Integer no = itr.next();
    System.out.println(no);
    if (no == 3)
        // ConcurrentModificationException
        list.add(5);
}
```

```
1
2
3
Exception in thread "main" java.util.ConcurrentModificationException Create breakpoint
    at java.base/java.util.ArrayList$Itr.checkForComodification(ArrayList.java:1013)
    at java.base/java.util.ArrayList$Itr.next(ArrayList.java:967)
    at multithreading.FailSafeExample.main(FailSafeExample.java:26)
```

Fail-fast vs. Fail-safe Iterator

The "snapshot" style iterator method uses a reference to the state of the array at the point that the iterator was created.

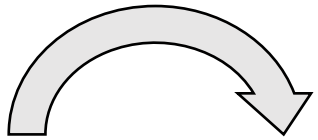
```
CopyOnWriteArrayList<Integer> list
        = new CopyOnWriteArrayList<>(new Integer[] { 1, 2, 3, 4 });
Iterator<Integer> itr = list.iterator();
while (itr.hasNext()) {
    Integer no = itr.next();
    System.out.println(no);
    if (no == 3)
        // No exception since it has created a separate copy
        //  Yet list doesn't grow since itr belongs to the old copy
        list.add(5);
}
```

Print: 1 2 3 4

Compare-And-Swap (CAS) Collections

- CAS: a technique used when designing concurrent algorithms

1. Make a local copy of the variable value (old value)



2. Calculate the new value

CAS (variable address, old value, new value)

3. Check if variable equals to the old value. if so, set variable to the new value; otherwise, retry (i.e., the variable must have been changed by another thread)

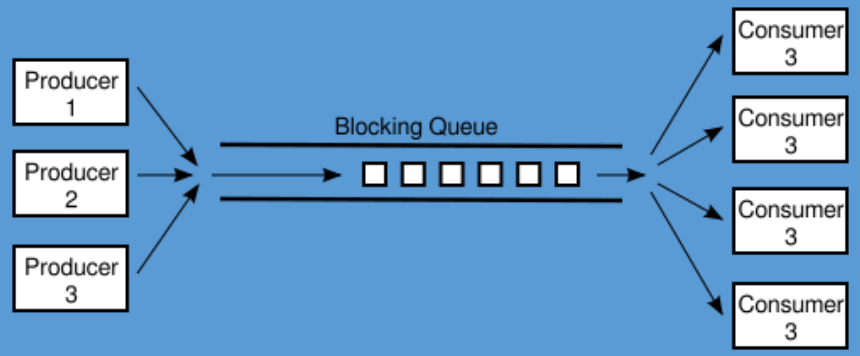
- Example classes: `ConcurrentLinkedQueue, ConcurrentSkipListMap`

Collections using Lock

- This mechanism divides the collection into parts that can be separately locked, giving improved concurrency

- Example classes
  - Most implementations of BlockingQueue
  - ConcurrentHashMap

BlockingQueue



- A blocking queue causes a thread to block when
  - Adding an element to a queue that is full
  - Removing an element when the queue is empty
- Blocking queues are useful for coordinating work of multiple threads
  - Producer threads can periodically deposit intermediate results into a blocking queue
  - Consumers threads can remove the intermediate results and process them further
- Blocking queues automatically balances the workload
  - If producers run slower than consumers, consumers block while waiting for the results
  - If producers run faster, the queue blocks until consumers catch up

Image resources:
https://math.hws.edu/eck/cs124/javanotes7/c12/s3.html

```java
public static void main(String[] args) {
    BlockingQueue<Integer> queue = new LinkedBlockingQueue<>(5);
    Random random = new Random();

    Runnable producer = ()->{
        while(true){
            try {
                //queue.add(1);
                queue.put(1);
                System.out.println("Put 1, " + queue);
                Thread.sleep(random.nextInt(100));
            } catch (InterruptedException e) {
                e.printStackTrace();
            }

        }
    };

    Runnable consumer = ()->{
        while(true){
            try {
                //queue.remove();
                queue.take();
                System.out.println("Take 1, " + queue);
                Thread.sleep(random.nextInt(100));
            } catch (InterruptedException e) {
                e.printStackTrace();
            }

        }
    };

    new Thread(producer).start();
    new Thread(consumer).start();

}
```

```
Take 1, []
Put 1, [1]
Put 1, [1, 1]
Put 1, [1, 1, 1]
Take 1, [1, 1]
Put 1, [1, 1, 1]
Take 1, [1, 1]
Put 1, [1, 1, 1]
Put 1, [1, 1, 1, 1]
Take 1, [1, 1, 1]
Put 1, [1, 1, 1, 1]
Take 1, [1, 1, 1]
Take 1, [1, 1]
Put 1, [1, 1, 1]
Put 1, [1, 1, 1, 1]
Put 1, [1, 1, 1, 1, 1]
Take 1, [1, 1, 1, 1]
```

Coordinate smoothly within queue capacity

- Try make the producer sleeps longer
- Try make the consumer sleeps longer
- Try replace put() with add(), replace take() with remove()

Summary of BlockingQueue methods

	Throws exception	*Special value*	*Blocks*	*Times out*
Insert	`add(e)`	`offer(e)`	`put(e)`	`offer(e, time, unit)`
Remove	`remove()`	`poll()`	`take()`	`poll(time, unit)`
Examine	`element()`	`peek()`	*not applicable*	*not applicable*

1. **Throws Exception**:
   If the attempted operation is not possible immediately, an exception is thrown.
2. **Special Value**:
   If the attempted operation is not possible immediately, a special value is returned (often true / false).
3. **Blocks**:
   If the attempted operation is not possible immediately, the method call blocks until it is.
4. **Times Out**:
   If the attempted operation is not possible immediately, the method call blocks until it is, but waits no longer than the given timeout. Returns a special value telling whether the operation succeeded or not (typically true / false).

ConcurrentHashMap

- ConcurrentHashMap added one Segment Array on top of HashMap
- Each index of the Segment array represents complete HashMap, and is guarded by a lock for put operation.

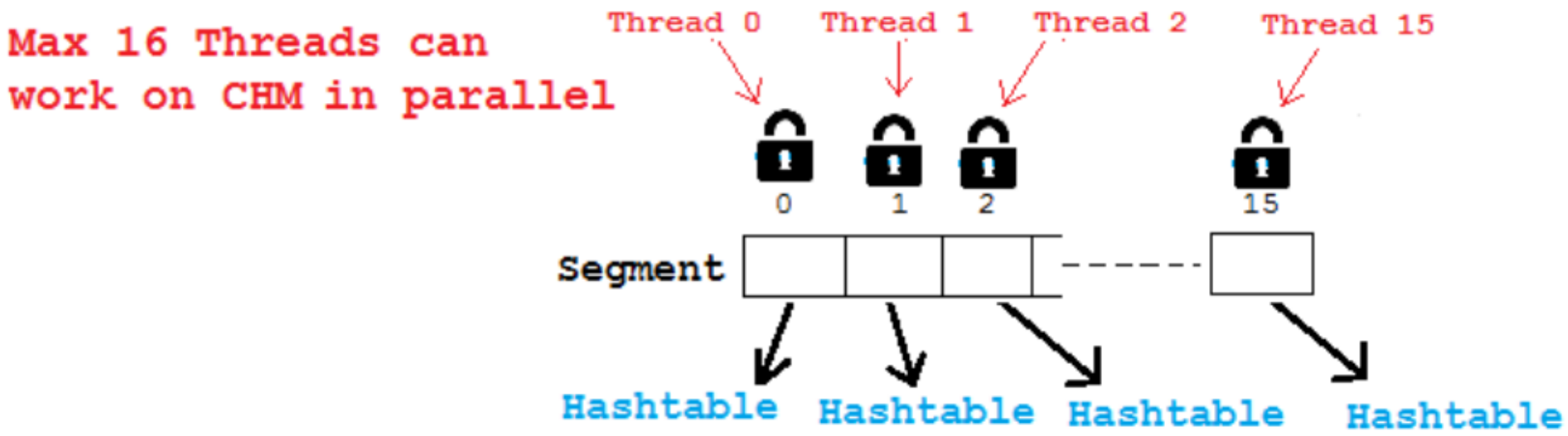
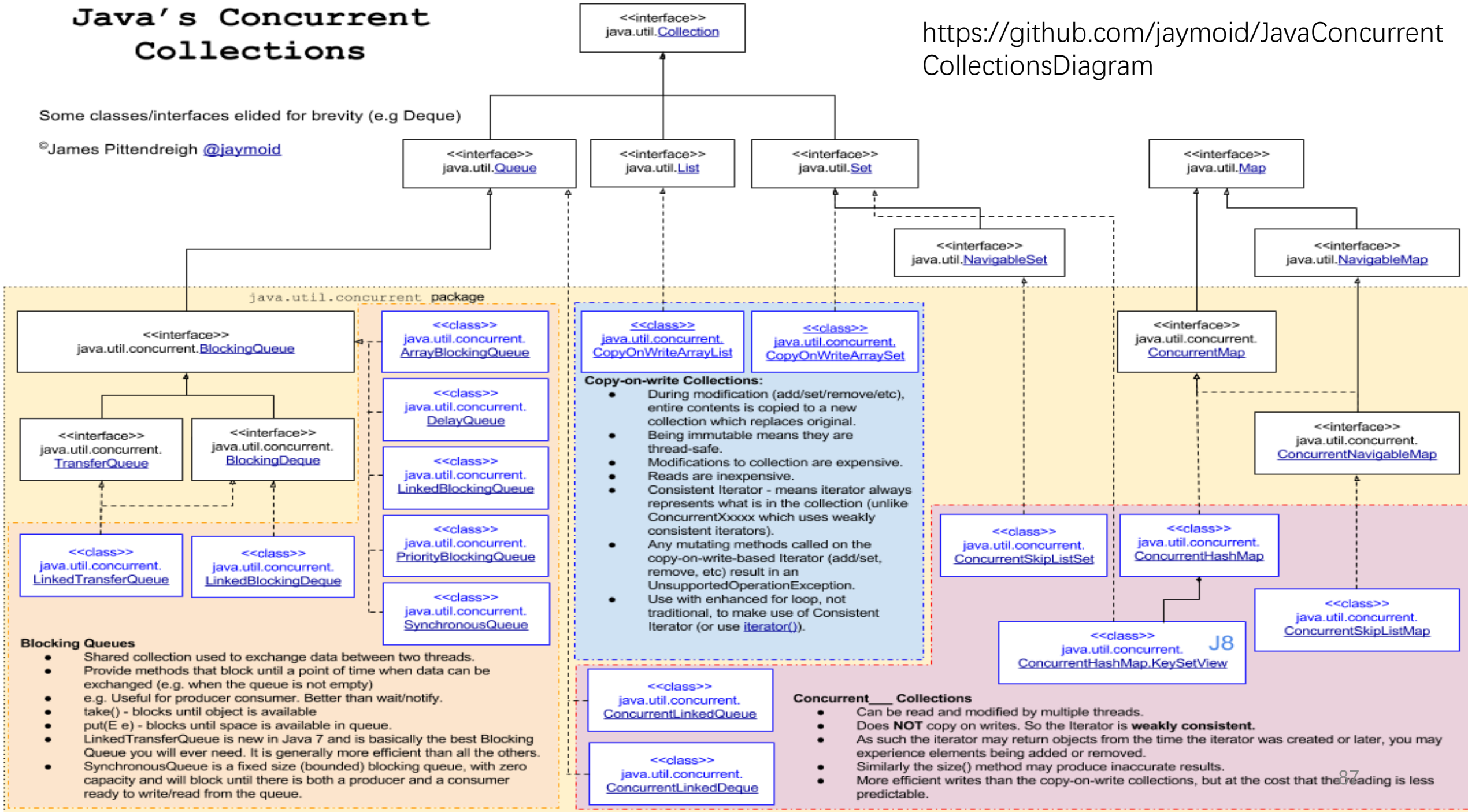


Image source: https://javabypatel.blogspot.com/2016/09/concurrenthashmap-interview-questions.html

Java's Concurrent Collections

https://github.com/jaymoid/JavaConcurrentCollectionsDiagram

Some classes/interfaces elided for brevity (e.g Deque)



Next Lecture

- Network Programming