Computer System Design & Application

计算机系统设计与应用A

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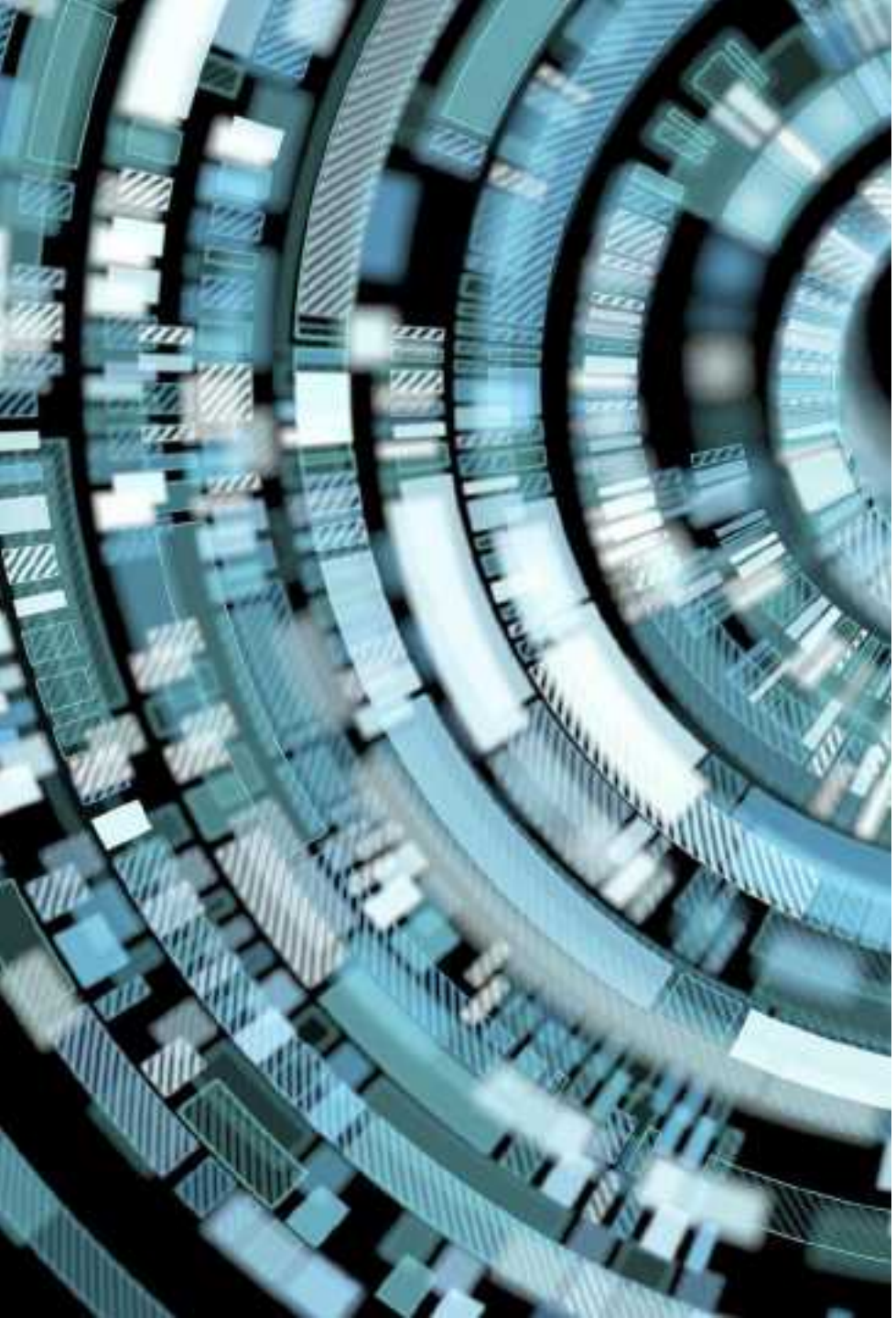
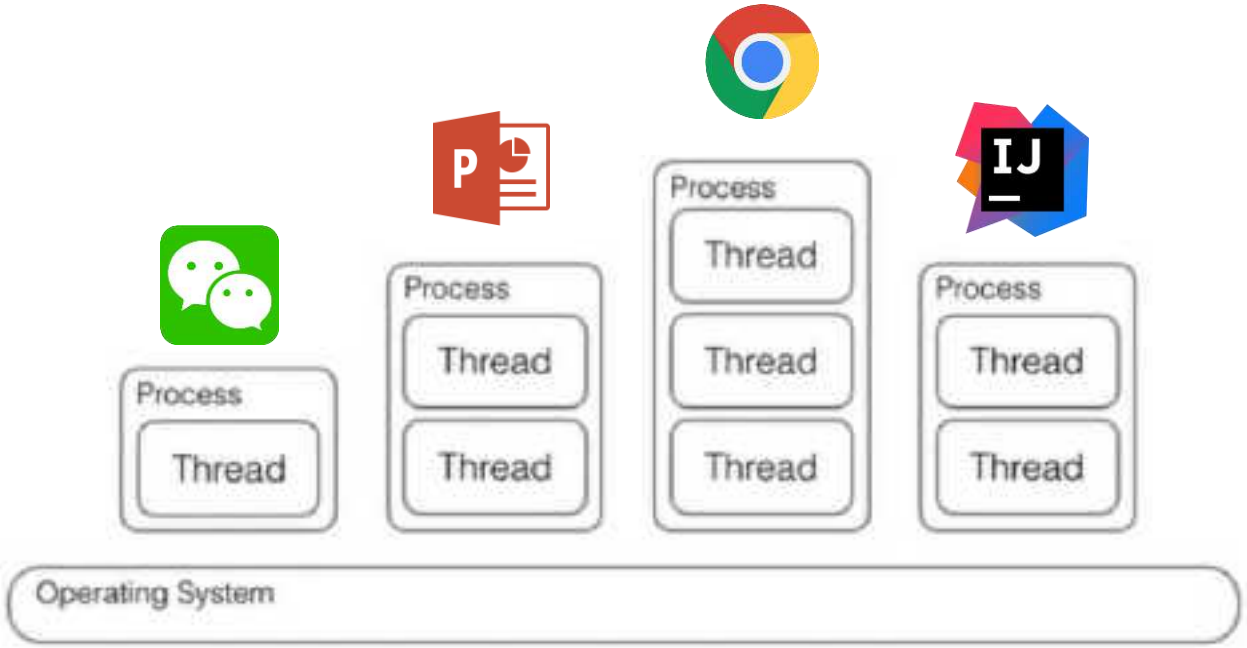


Lecture 8

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

Process vs Thread

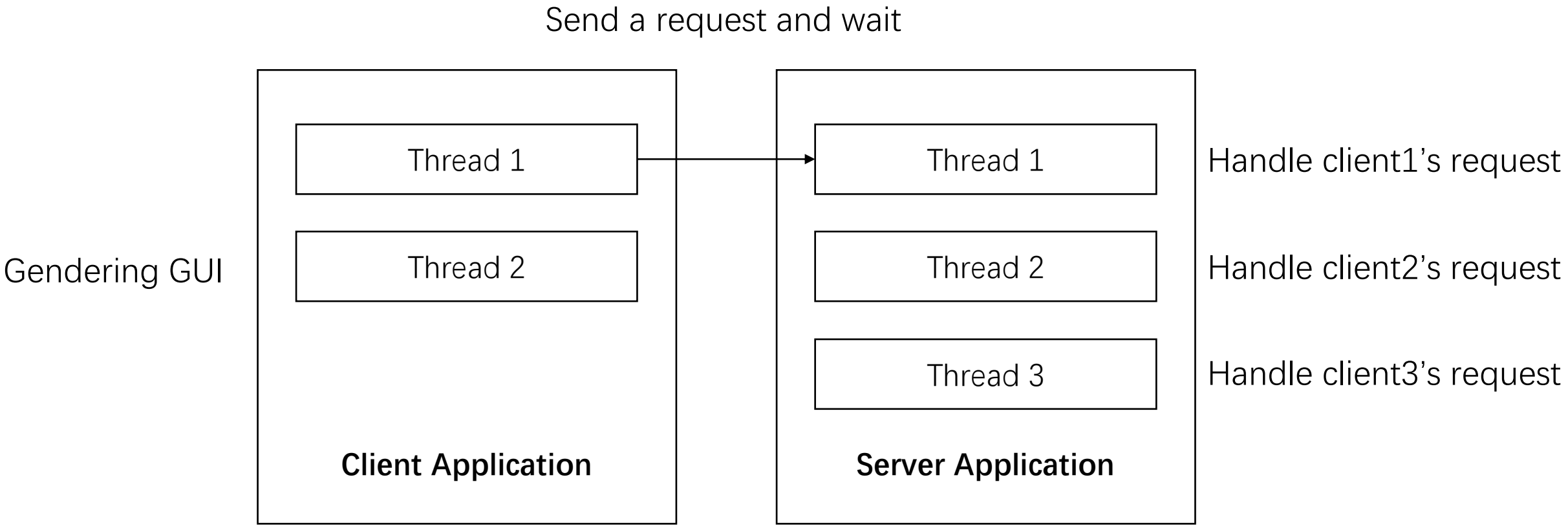
- **Process (进程)**
  - Executing a program starts a process (a running/active program)
  - OS allocates separate memory spaces for different processes
- **Thread (线程)**
  - A process can have multiple threads (at least 1 thread)
  - Threads within a process share the memory and resources of that process.



Multithreading

- In Java, Multithreading refers to a process of 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

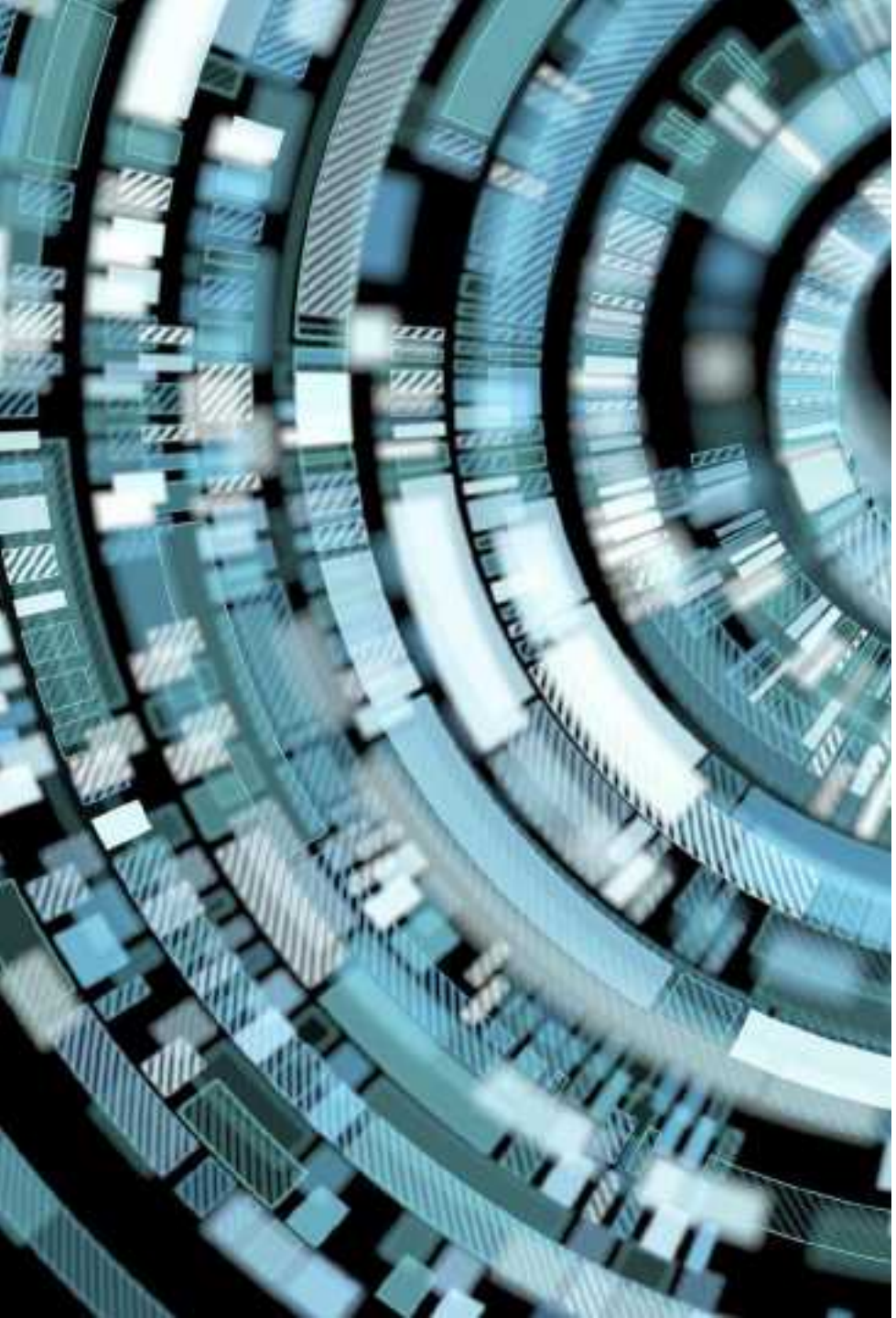


Multithreading in Java

- The `main` thread is created automatically when our Java program is started

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

Output "main"



Lecture 8

- Multithreading Overview
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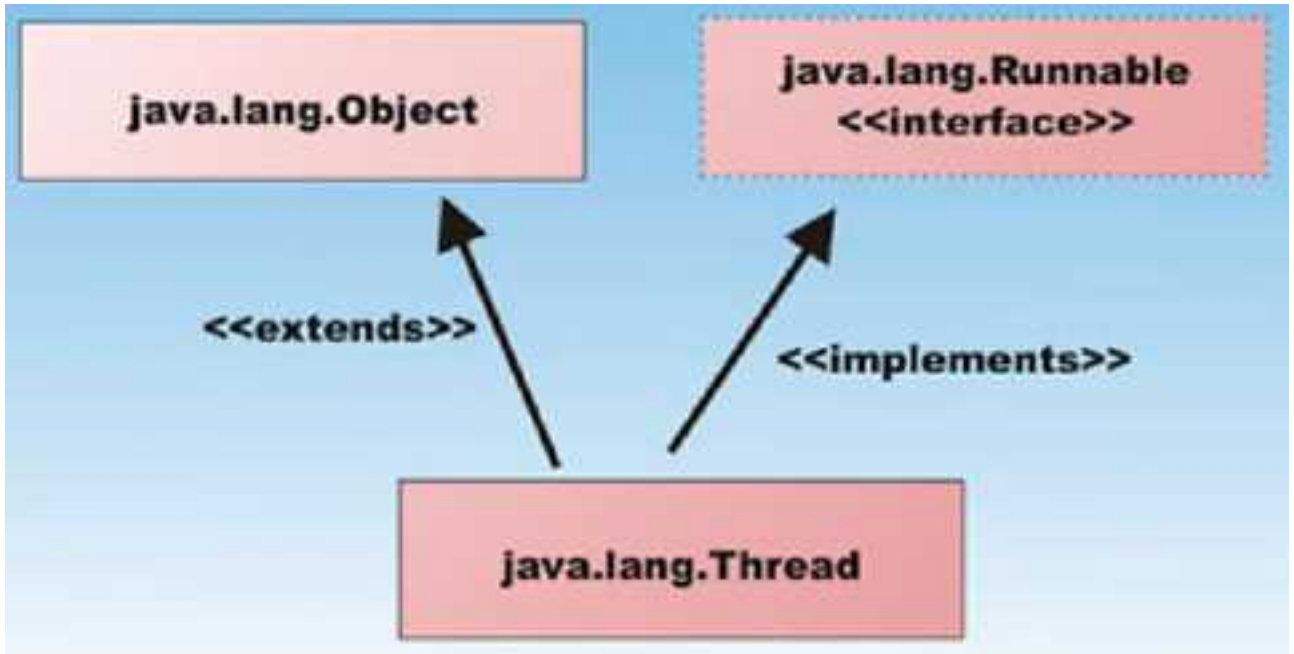
Creating & Starting Threads

- Approach 1: Extending the `Thread` class
- 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 class 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

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

    @Override
    public void run() {
        while (cnt<10){
            System.out.println(Thread.currentThread().getName()
                    + ": I'm a cat " + (++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

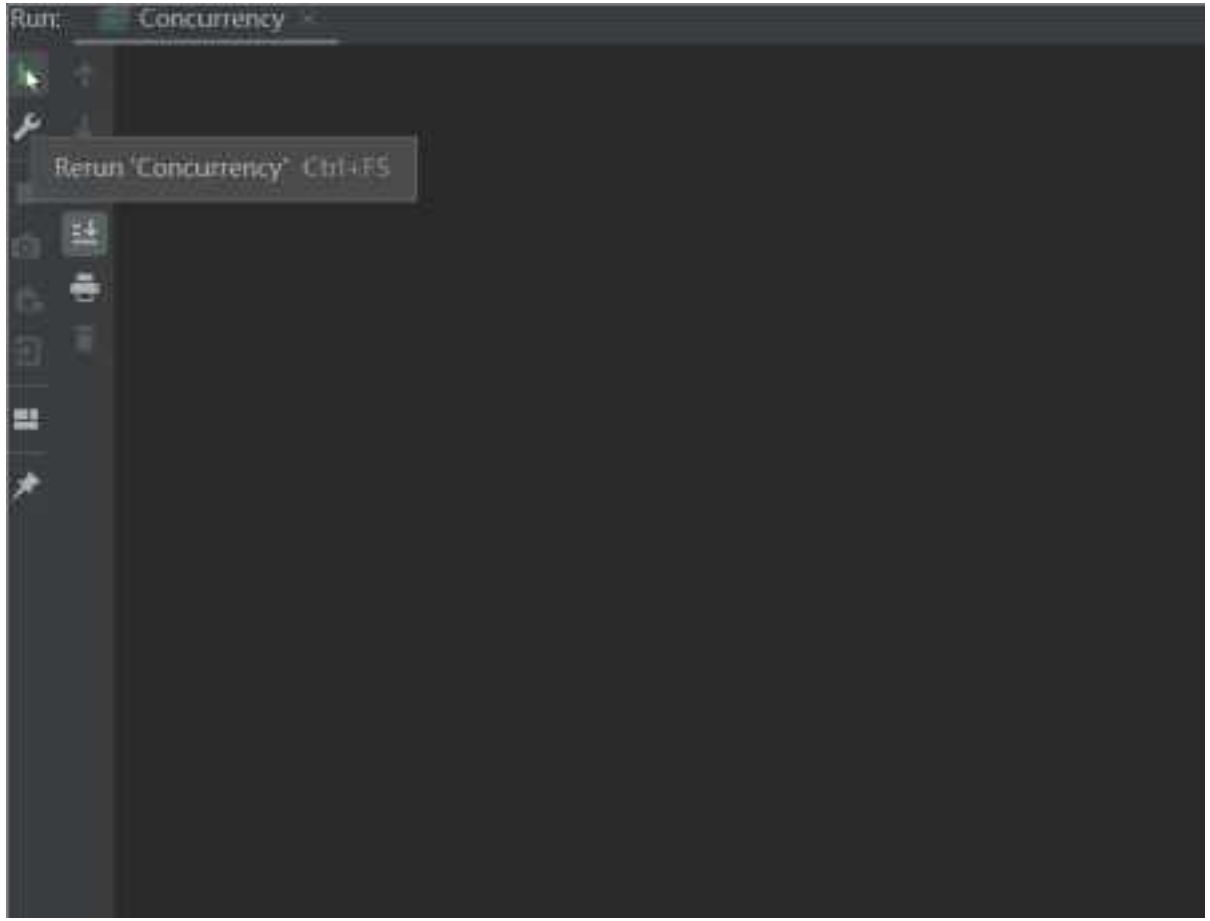
Using Thread (cont.)

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

        int cnt = 0;
        while(cnt<10){
            System.out.println(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

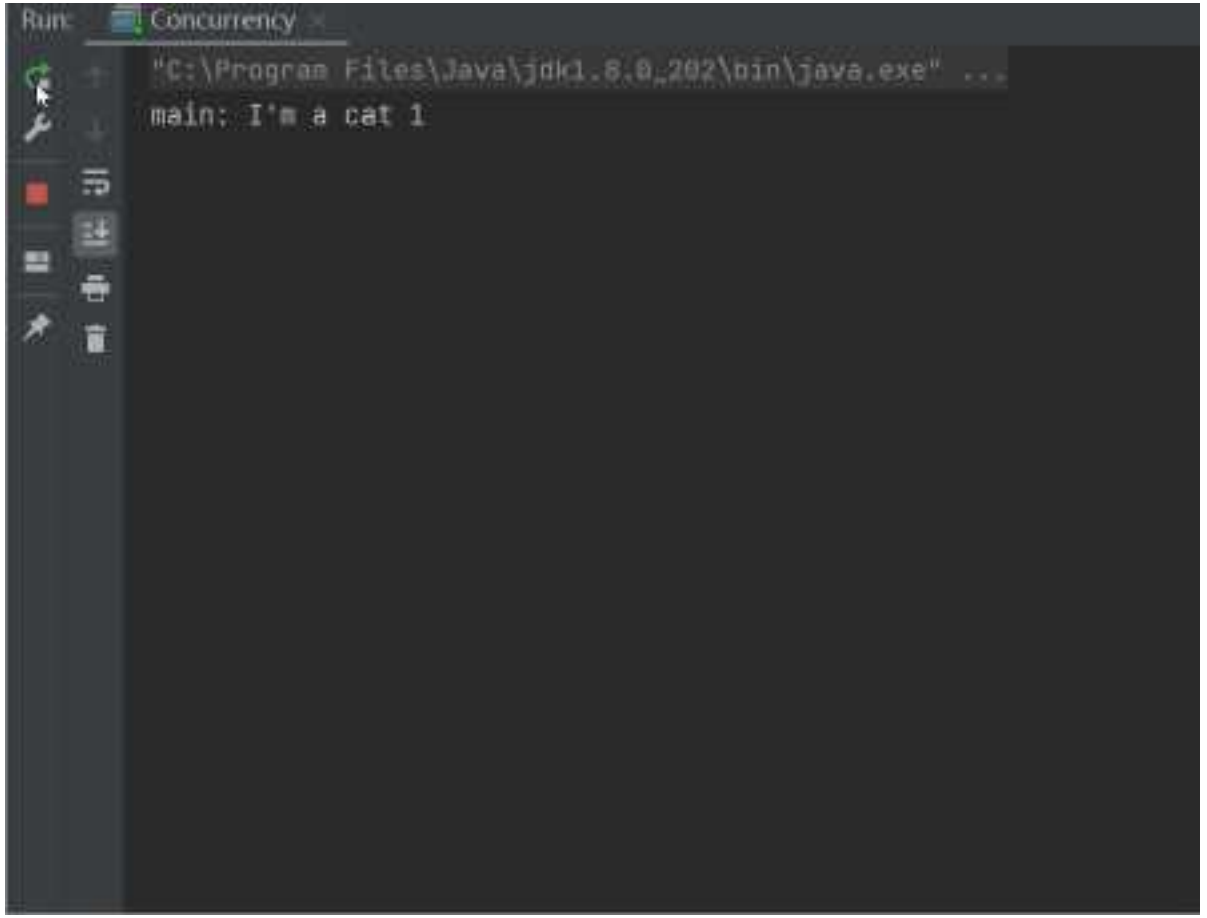
Using Thread (cont.)

Why start()?

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

        int cnt = 0;
        while(cnt<10){
            System.out.println(Thread.currentThread().getName() + (++cnt));
            Thread.sleep( millis: 1000);
        }
    }
}
```

Non-blocking!
Don't have to wait for it before executing the subsequent operations

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



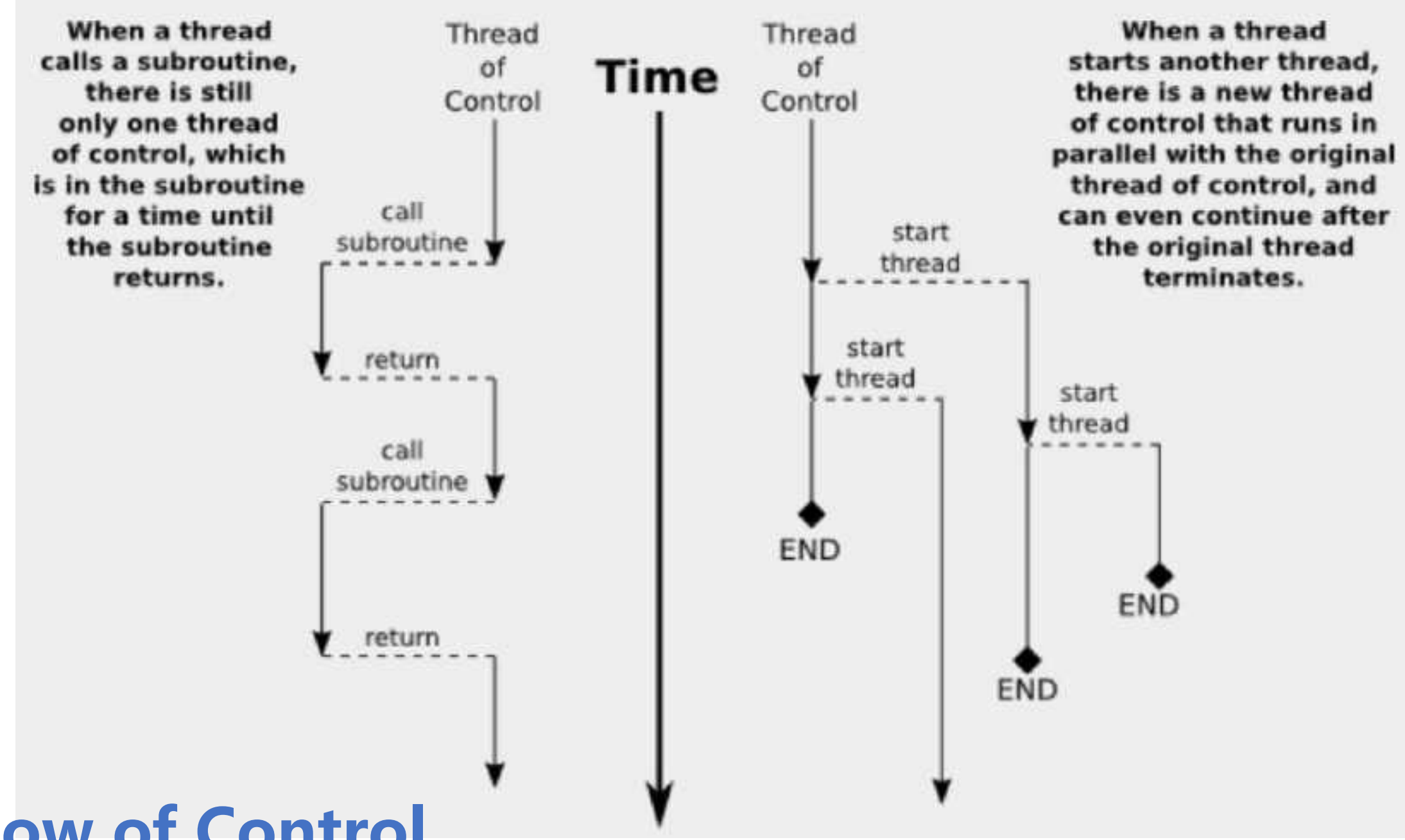

```
Thread cat = new CatThread();
//cat.start();
cat.run();
```

Observation

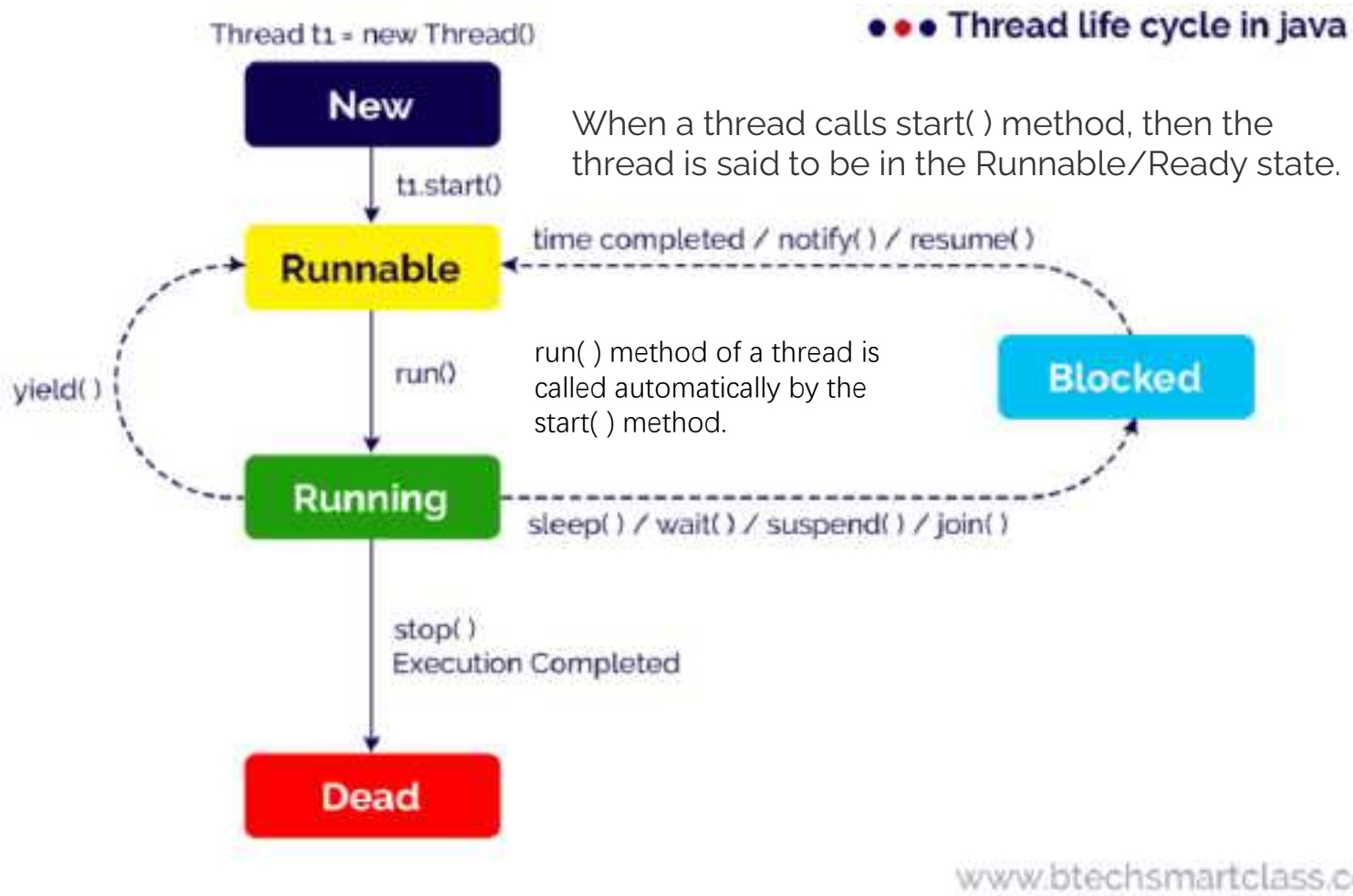
1. Things are executed sequentially instead of simultaneously
2. There is even **no** Cat thread!

- run() executes like a normal method
- start() executes certain native code to start a new thread

Flow of Control



Thread States & Lifecycle



When a thread calls start( ) method, then the thread is said to be in the Runnable/Ready state.

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()`

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

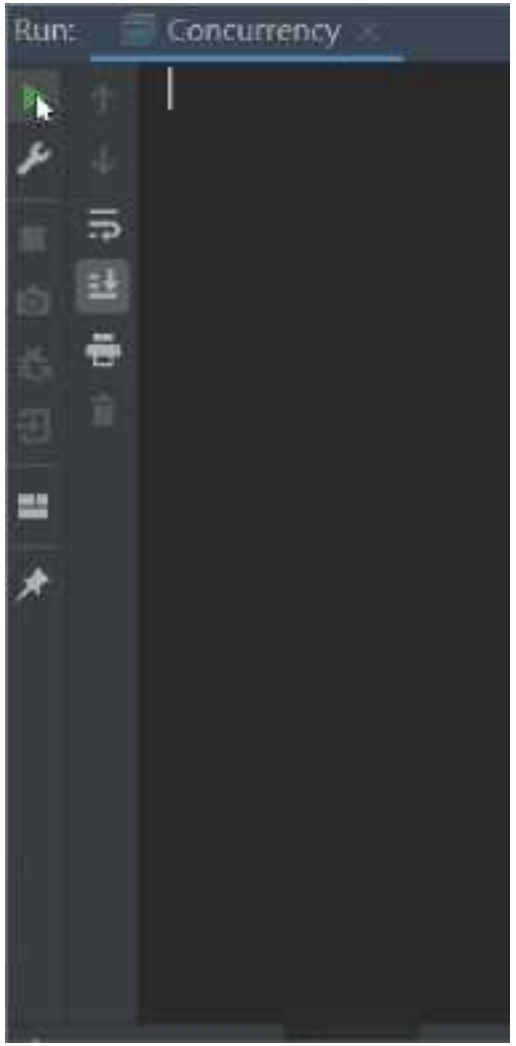
- Thread has a constructor that takes a Runnable

- 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

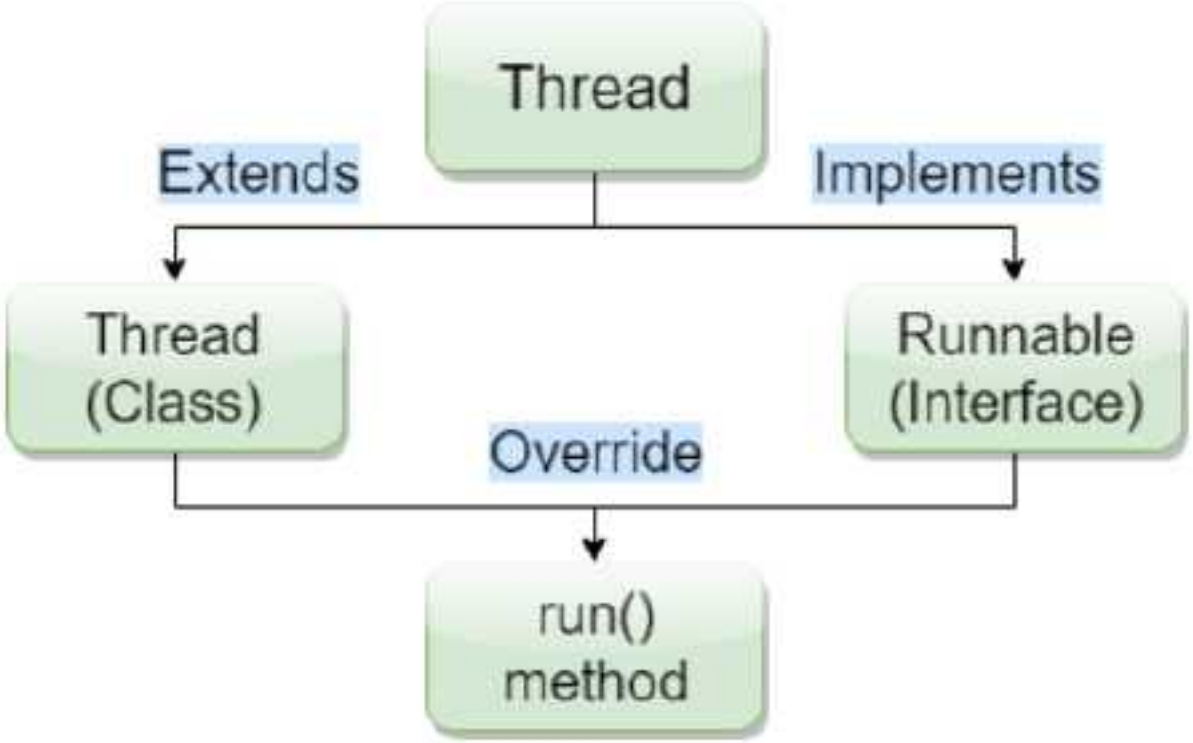
```
Runnable runnable = () -> System.out.println(Thread.currentThread().getName());

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

Subclass vs Runnable

```
public static void main(String[] args) throws InterruptedException {

    // Cat thread (Subclassing)
    Thread cat = new CatThread();
    cat.start();

    // Dog thread (Runnable)
    Runnable runnable = new DogThread();
    Thread dog = new Thread(runnable);
    dog.start();

    // Main
    int cnt = 0;
    while(cnt<10){
        System.out.println(Thread.currentThread().getName() + (++cnt));
        Thread.sleep( millis: 1000);
    }
}
```



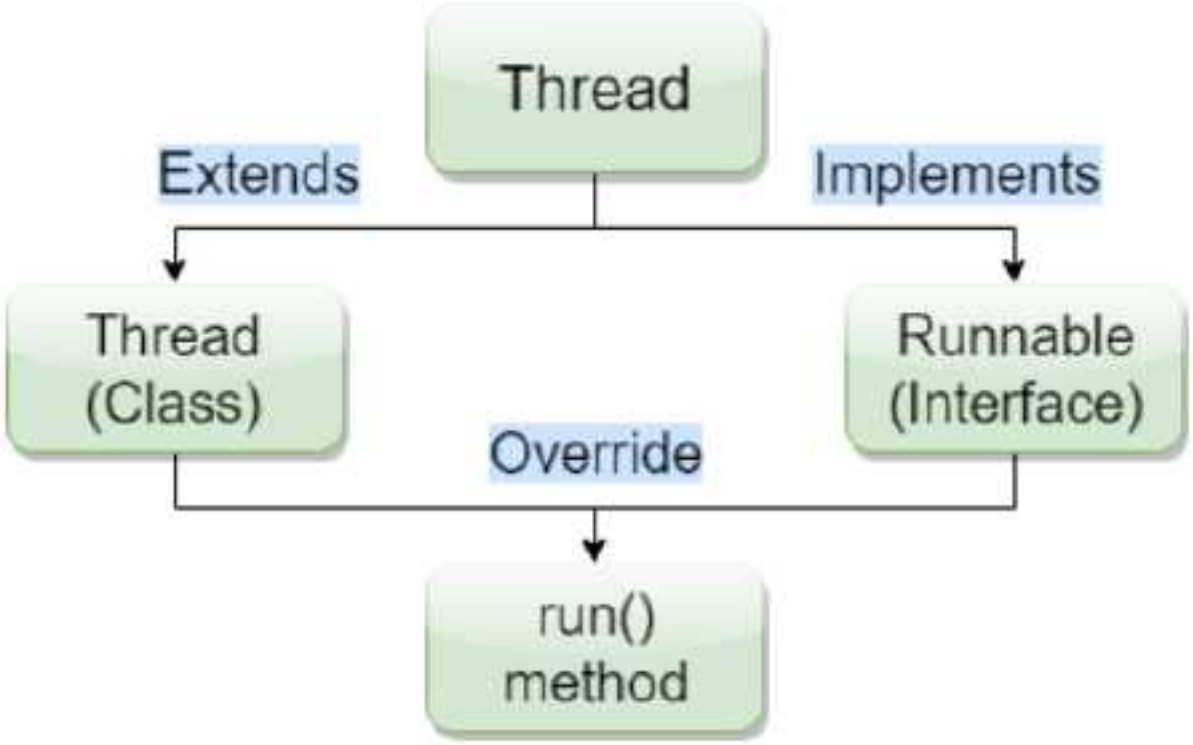
Subclass vs Runnable



Practical POV

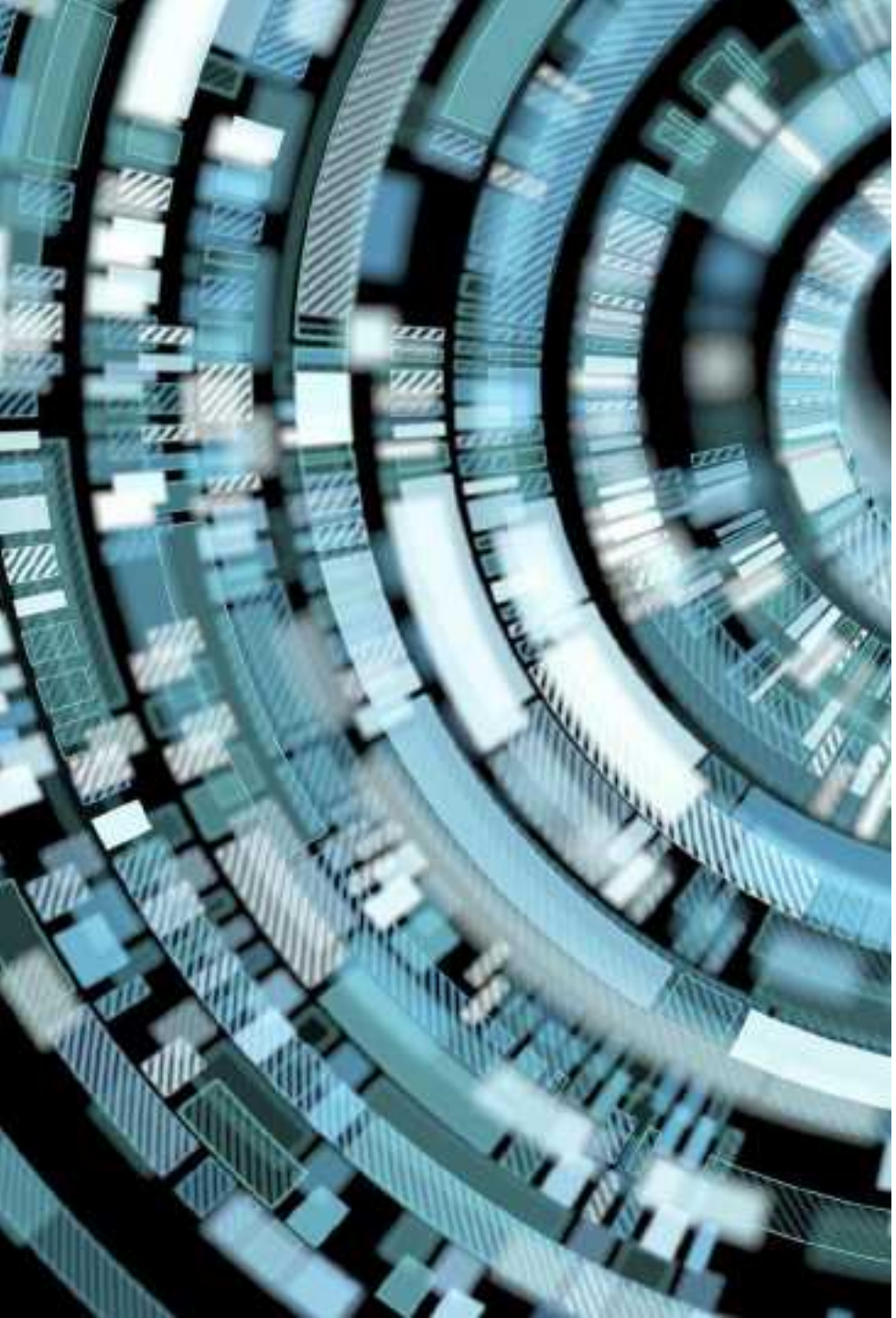
- Java doesn't support multiple inheritances.
- If a class extends Thread, it cannot extend other classes
- If a class implements Runnable, it can still extend other classes

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 8

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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();
            }
        }
    }
}
```

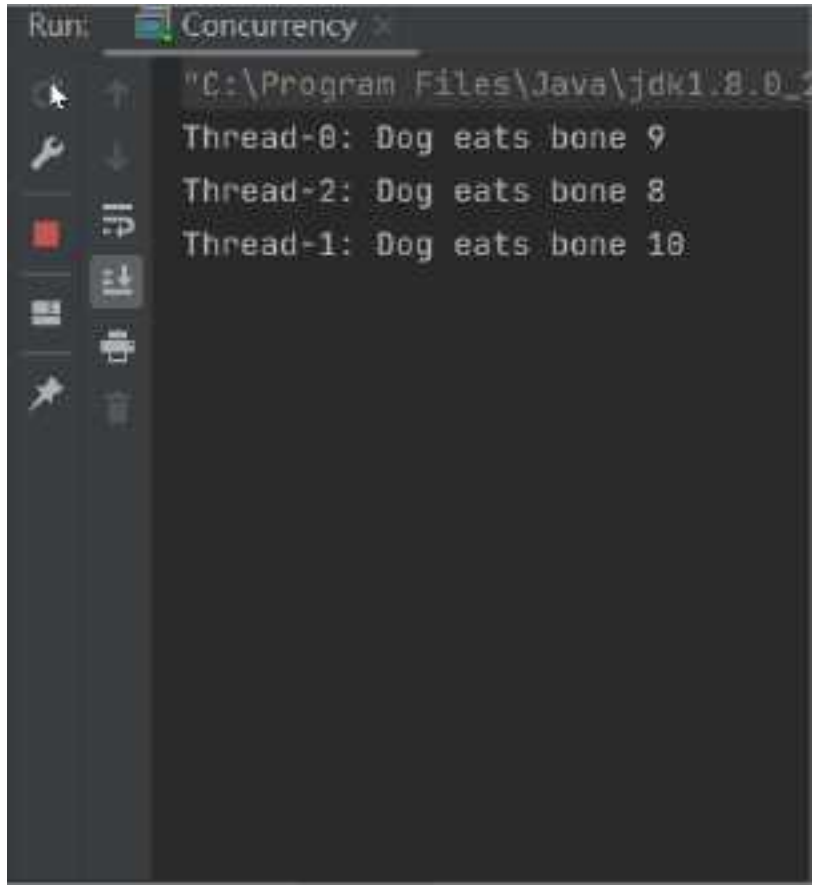
Inside main()

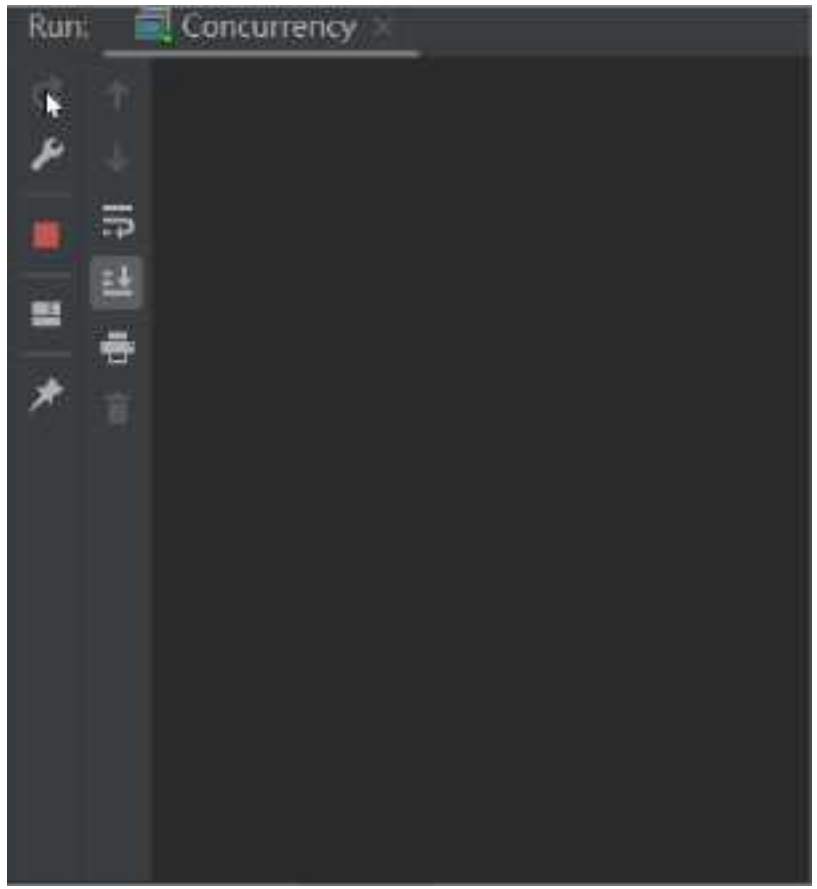
```
Runnable dog = new DogThread();
new Thread(dog).start();
new Thread(dog).start();
new Thread(dog).start();
```

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

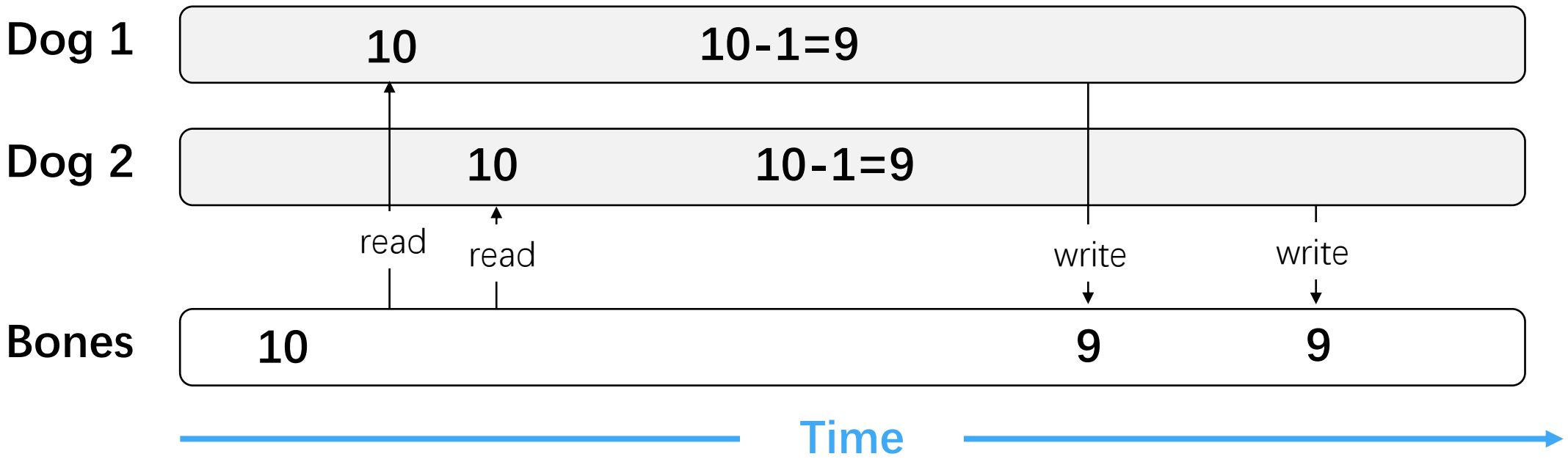
What we get

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

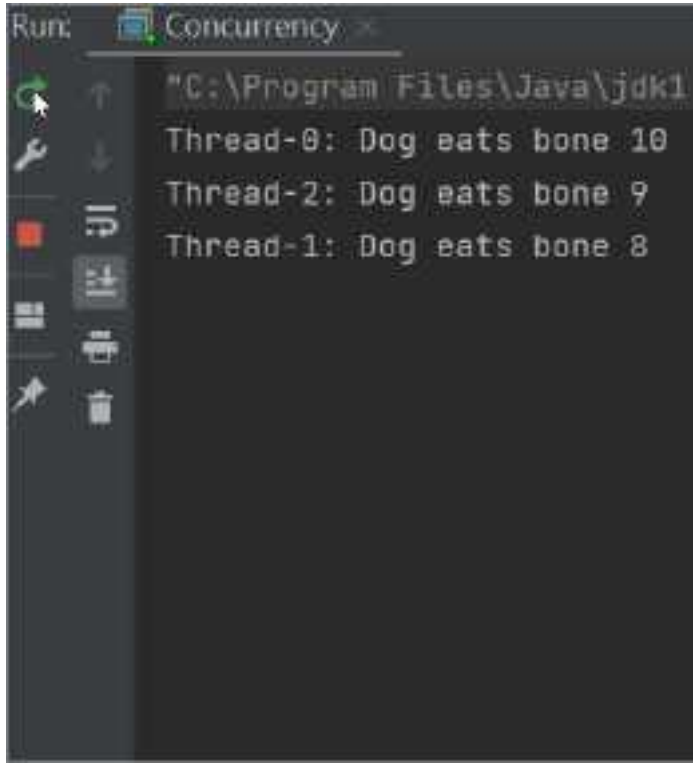
- A synchronized block is wrapped using the `synchronized` keyword
  - A code block inside a method (同步代码块)
  - A method (同步方法)

- 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();
            }
        }
    }
}
```

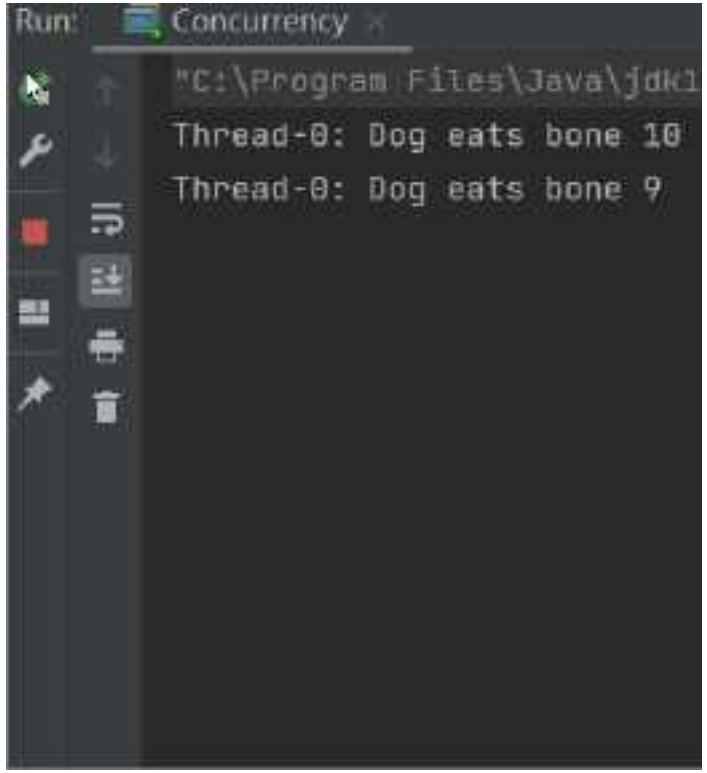
```java
Runnable dog = new DogThread();
new Thread(dog).start();
new Thread(dog).start();
new Thread(dog).start();
```



Can we synchronize the run() method?

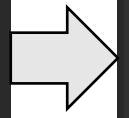
```java
public class DogThread implements Runnable{
    private int bones = 10;
    private boolean hasBone = true;

    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

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

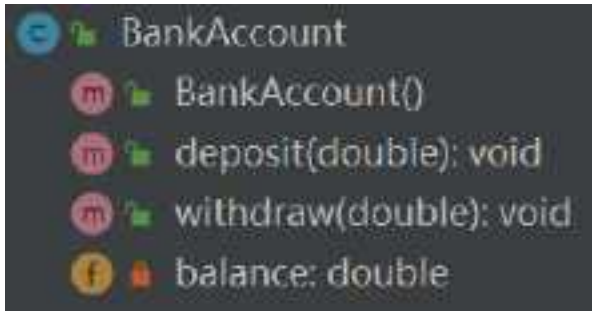


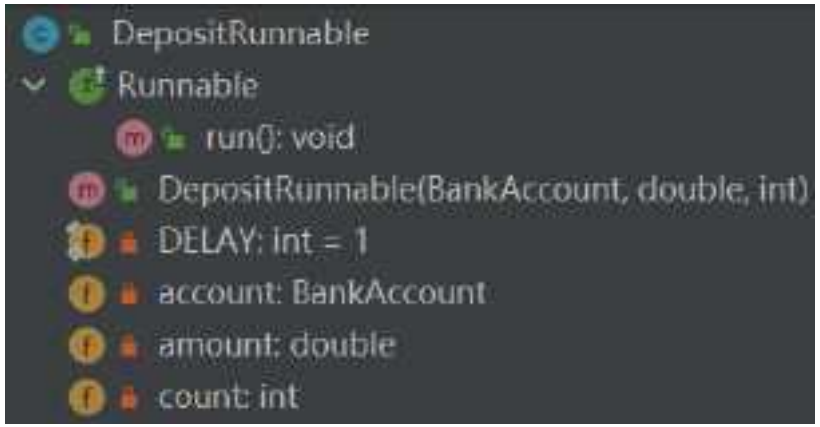
```
public void eat(){
    synchronized(this) {
        if (bones <= 0) {
            hasBone = false;
        } else {
            System.out.println(Thread.currentThread().getName()
                    + ": Dog eats bone " + (bones--));
        }
    }
}
```

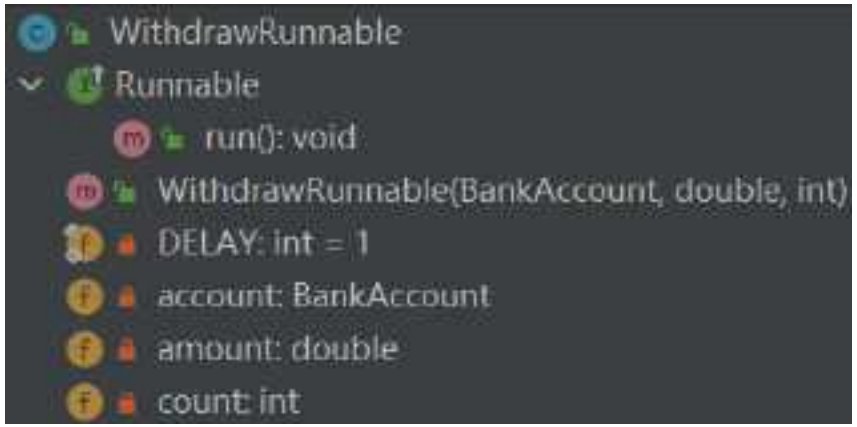
Using `Lock` in the `Concurrency` API

- 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 is more flexible and 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

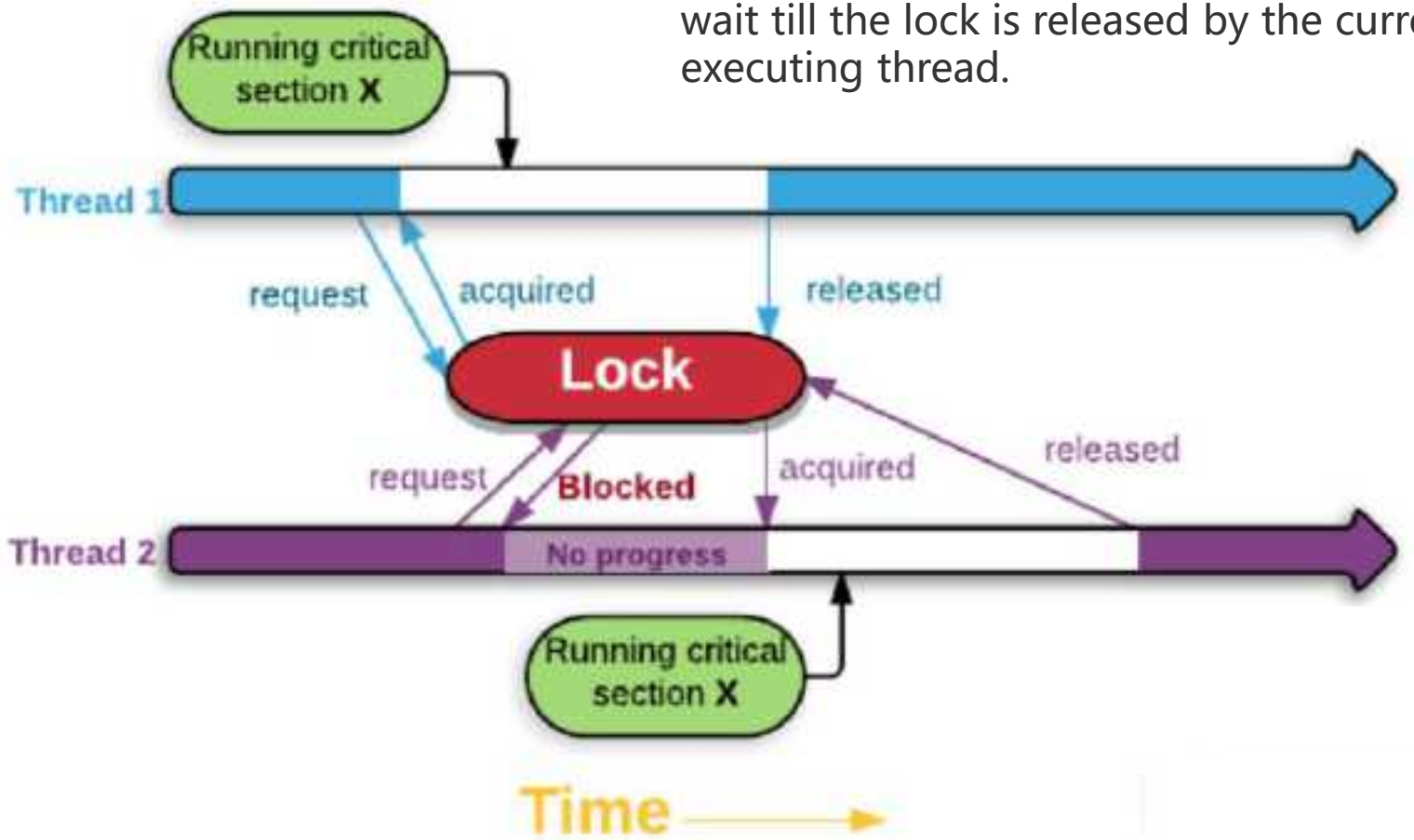
```
public class BankAccount {

   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.”

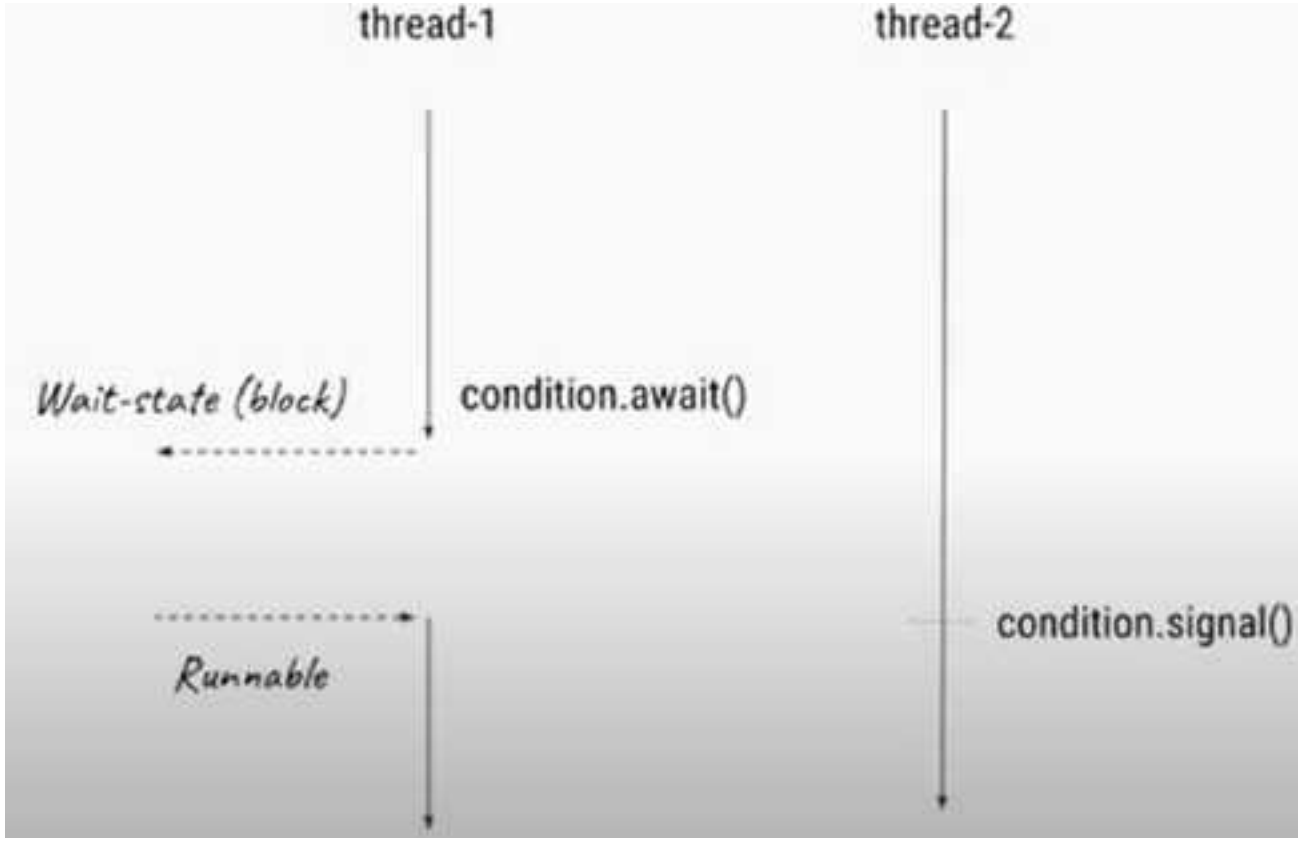
Me: “Hire me and I’ll explain it to you.”

Deadlock

- To disallow negative balance during withdraw, we can wait for other threads to deposit money
- Can we use sleep() to wait?
  - 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()`

When calling await, this thread is in a blocked state, and it will not be activated by the thread scheduler until it is unblocked.

- 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

- Calling `await()` on a condition object makes the current thread wait and allows another thread to acquire the lock object.

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

Using `Condition signalAll()`

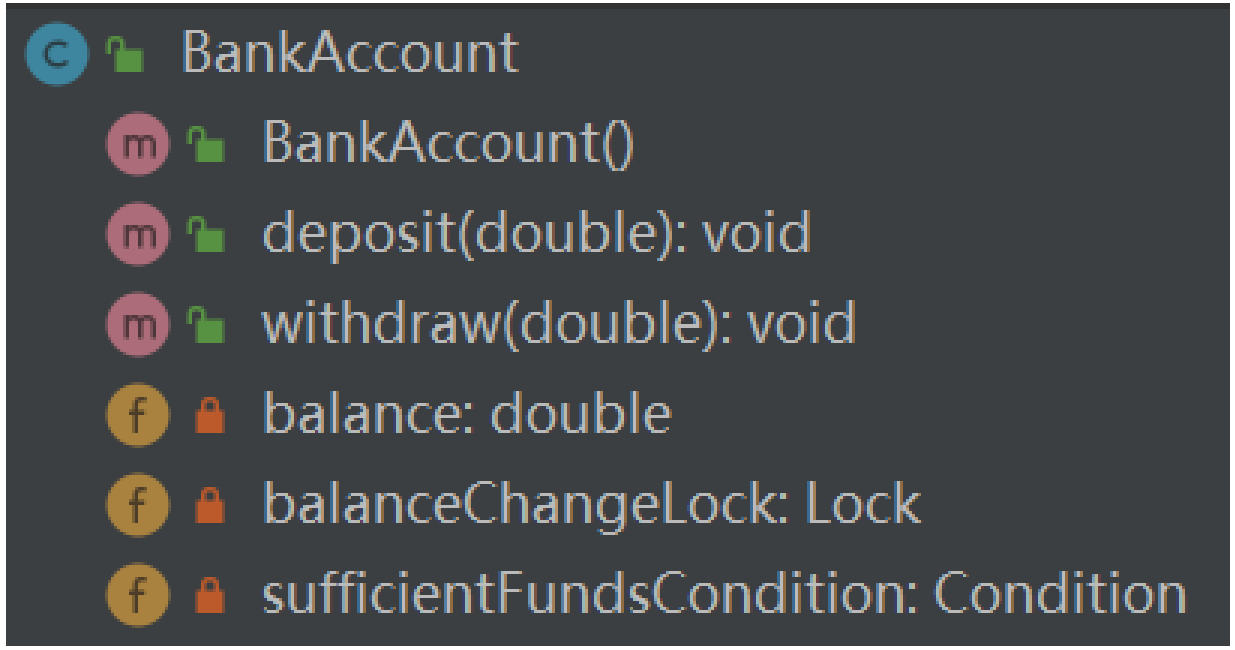
The call to signalAll() notifies the waiting threads that sufficient funds may be available, and that it is worth testing the loop condition again

- 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

```
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();
   }
```

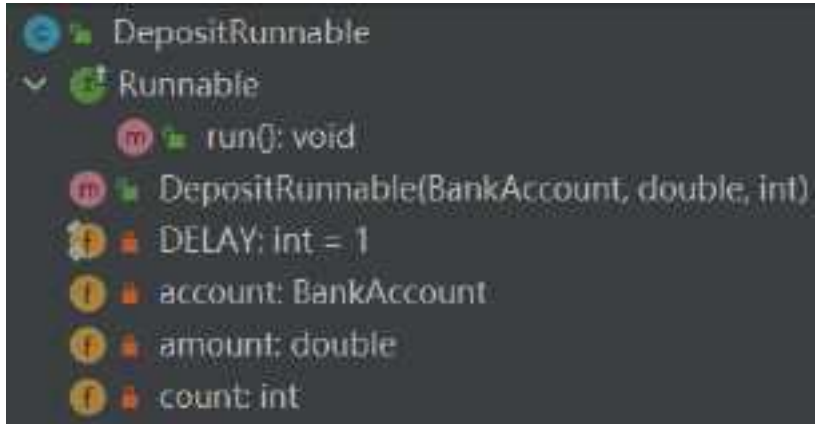


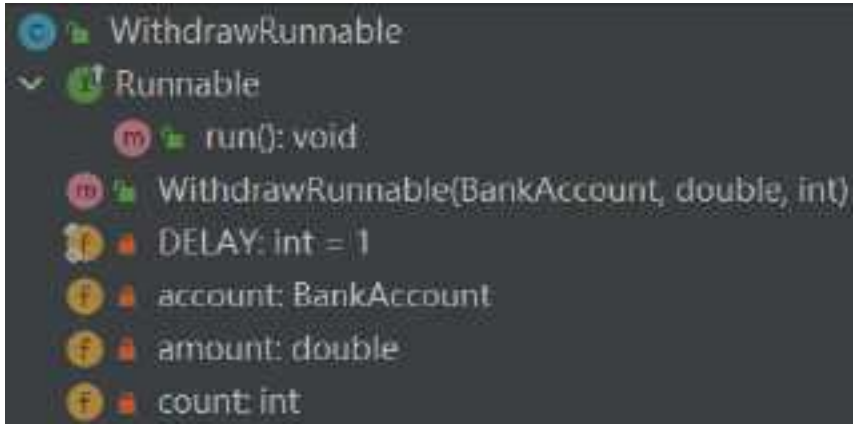
To Put it Altogether

```
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



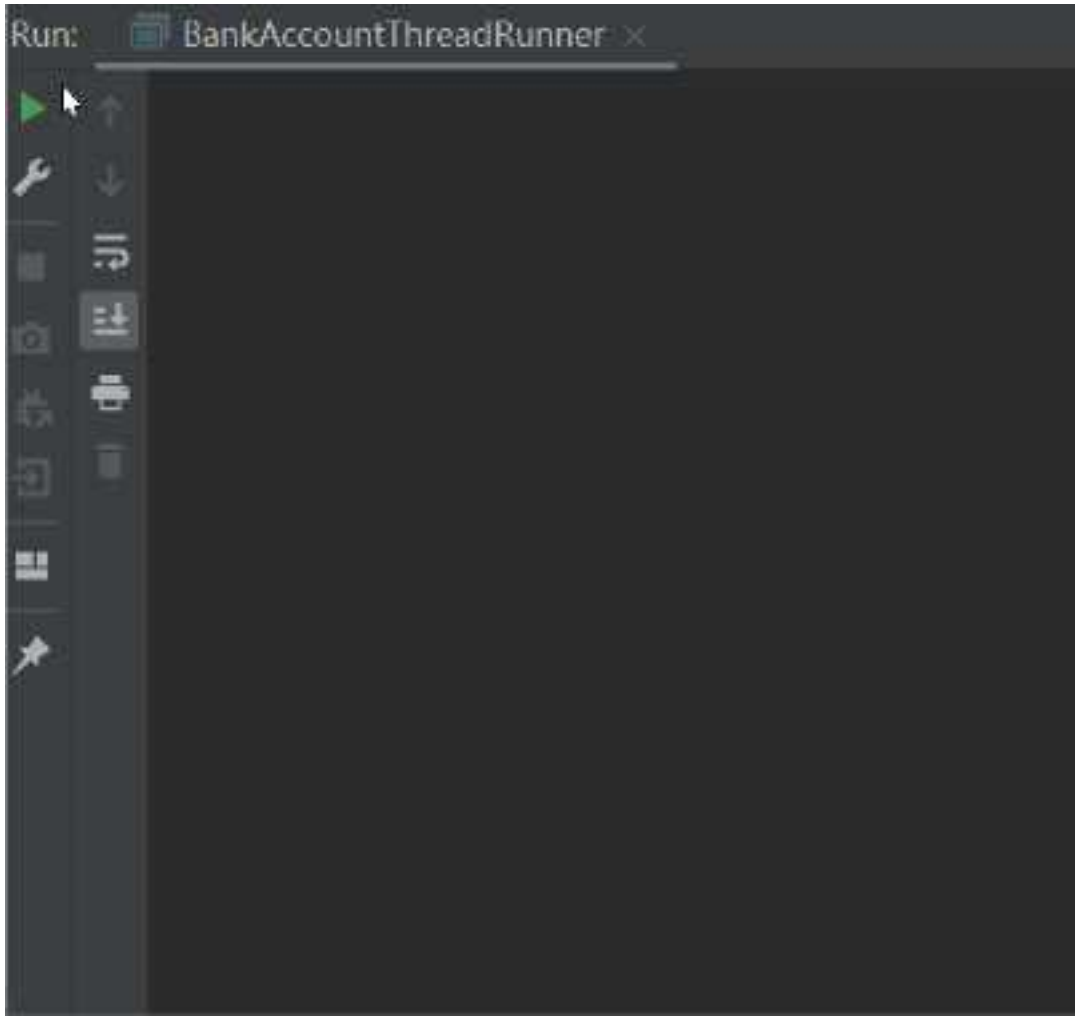



```
public void run() {
   try {
      for (int i = 1; i <= count; i++) {
         account.deposit( amount );
         Thread.sleep( DELAY );
      }
   } catch (InterruptedException exception) {}
}
```

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

To Put it Altogether

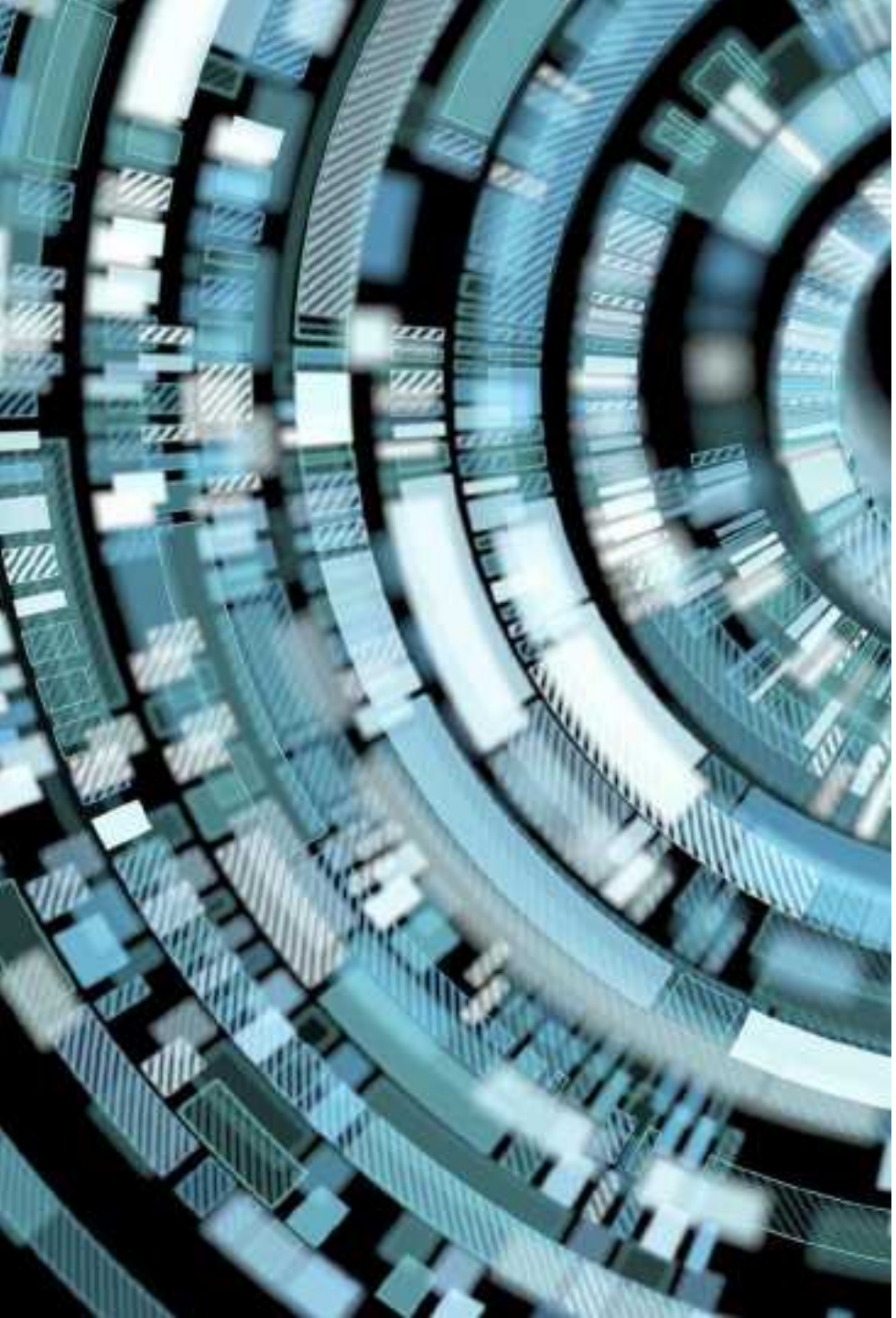
```java
public class BankAccountThreadRunner {
   public static void main (String[] args) {
      BankAccount account = new BankAccount();
      final double AMOUNT = 100;
      final int REPETITIONS = 100;
      final int THREADS = 100;

      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();
      }
   }
}
```



Lock vs synchronized block

Using the synchronized block	Using Lock
A synchronized block is fully contained within a method.	We can have Lock API's lock() and unlock() operation in separate methods
A synchronized block doesn't support the fairness (i.e., a waiting thread could risk waiting forever).	We can achieve fairness within the Lock APIs by specifying the fairness property (i.e., makes sure that longest waiting thread is given access to the lock)
A thread gets blocked if it can't get an access to the synchronized block.	The Lock API provides tryLock() method. The thread acquires lock only if it's available and not held by any other thread.
A thread which is in “waiting” state to acquire the access to synchronized block, can't be interrupted.	The Lock API provides a method lockInterruptibly() which can be used to interrupt the thread when it's waiting for the lock.

https://www.baeldung.com/java-concurrent-locks



Lecture 8

- 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

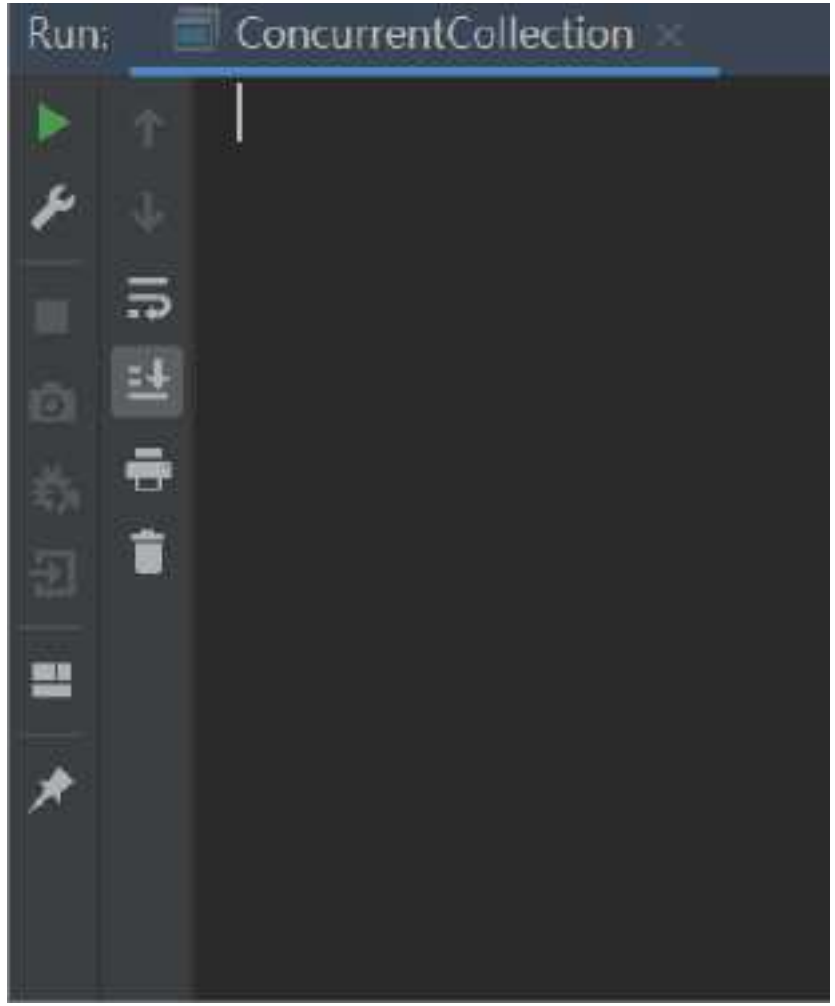
https://www.codejava.net/java-core/collections/understanding-collections-and-thread-safety-in-java

Example: Adding to ArrayList with Multithreading

```java
public class ArrayListThread implements Runnable{
    private List<Integer> numList;

    public ArrayListThread(List<Integer> numList){
        this.numList = numList;
    }
    @Override
    public void run() {
        for (int i = 0; i < 10; i++) {
            numList.add(i);
            System.out.println(Thread.currentThread().
                    getName() + ": added " + i);
            try {
                Thread.sleep( millis: 5);
            } catch (InterruptedException e) {
                e.printStackTrace();
            }
        }
    }
}
```

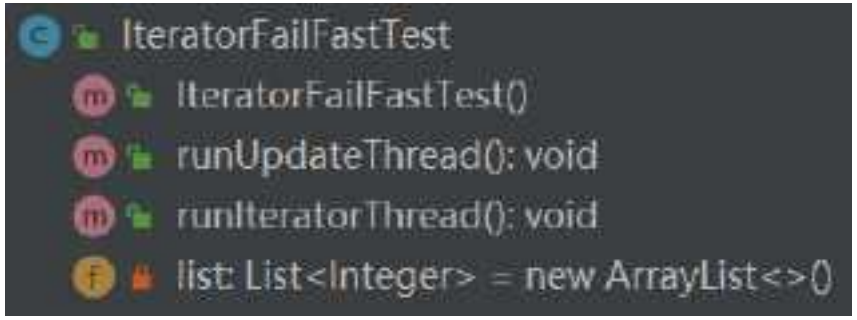
```java
public static void main(String[] args) throws Interrupted
    List<Integer> numList = new ArrayList<>();

    Thread t1 = new Thread(new ArrayListThread(numList));
    Thread t2 = new Thread(new ArrayListThread(numList));
    Thread t3 = new Thread(new ArrayListThread(numList));
    t1.start();
    t2.start();
    t3.start();

    t1.join();
    t2.join();
    t3.join();

    System.out.println(numList.size());


}
```

Example: Adding to ArrayList with Multithreading




```
public static void main(String[] args) throws Interrupted
    List<Integer> numList = new ArrayList<>();

    Thread t1 = new Thread(new ArrayListThread(numList));
    Thread t2 = new Thread(new ArrayListThread(numList));
    Thread t3 = new Thread(new ArrayListThread(numList));
    t1.start();
    t2.start();
    t3.start();

    t1.join();
    t2.join();
    t3.join();

    System.out.println(numList.size());


}
```

Example: fail-fast iterators




```java
public void runUpdateThread() {
    Thread thread1 = new Thread(new Runnable() {
        public void run() {
            for (int i = 101; i < 200; i++) {
                list.add(i);
            }
        }
    });
    thread1.start();
}
```

```java
public void runIteratorThread() {
    Thread thread2 = new Thread(new Runnable() {
        public void run() {
            ListIterator<Integer> iterator = list.listIterator();
            while (iterator.hasNext()) {
                System.out.println(iterator.next());
            }
        }
    });
    thread2.start();
}
```

Example: fail-fast iterators

```
IteratorFailFastTest tester = new IteratorFailFastTest();

tester.runIteratorThread();
tester.runUpdateThread();
```

```
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

Synchronized Wrappers

- Java Collections Framework provides factory methods for creating thread-safe collections.

```
List<String> safeList = Collections.synchronizedList(new ArrayList<>());

Map<Integer, String> unsafeMap = new HashMap<>();
Map<Integer, String> safeMap = Collections.synchronizedMap(unsafeMap);
```

- Problems?
  - Still need to explicitly put iterators in a synchronized block
  - Performance overhead: other threads need to wait for a thread to release the lock

Concurrent Collections in Java

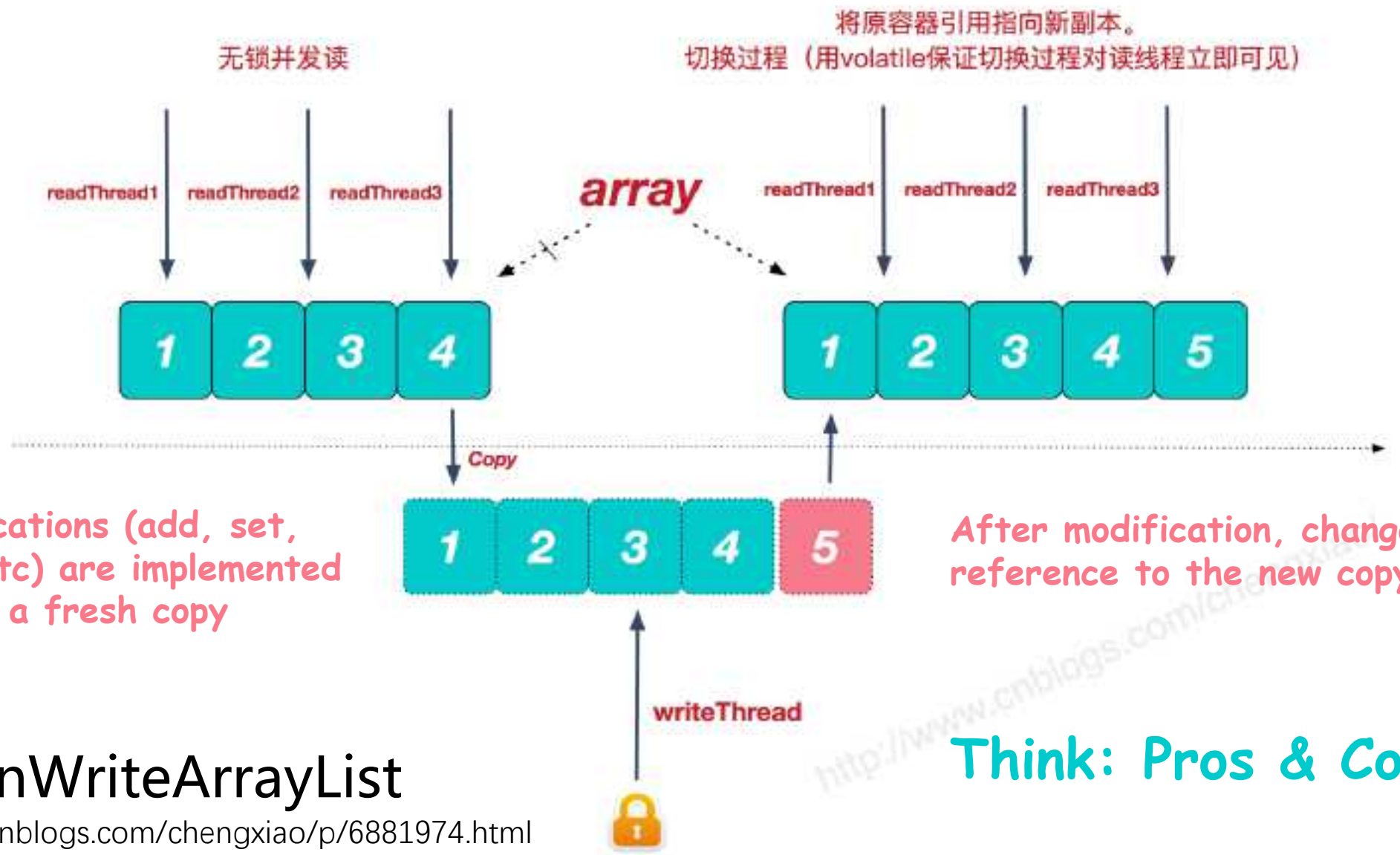
- Introduced in Java 5 in `java.util.concurrent` package
- 3 categories w.r.t. thread-safety mechanism
  - Copy-on-Write collections
  - Compare-and-Swap collections (CAS)
  - Collections using Lock

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

- 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)
  - `AddIfAbsent(), AddAllAbsent()`
  - `iterator(), listIterator()`



All modifications (add, set, remove, etc) are implemented by making a fresh copy

After modification, change the reference to the new copy

Think: Pros & Cons?

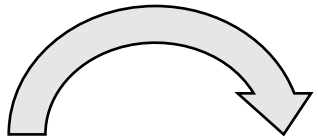
CopyOnWriteArrayList

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

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
  - ConcurrentHashMap
  - Most implementations of BlockingQueue

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.

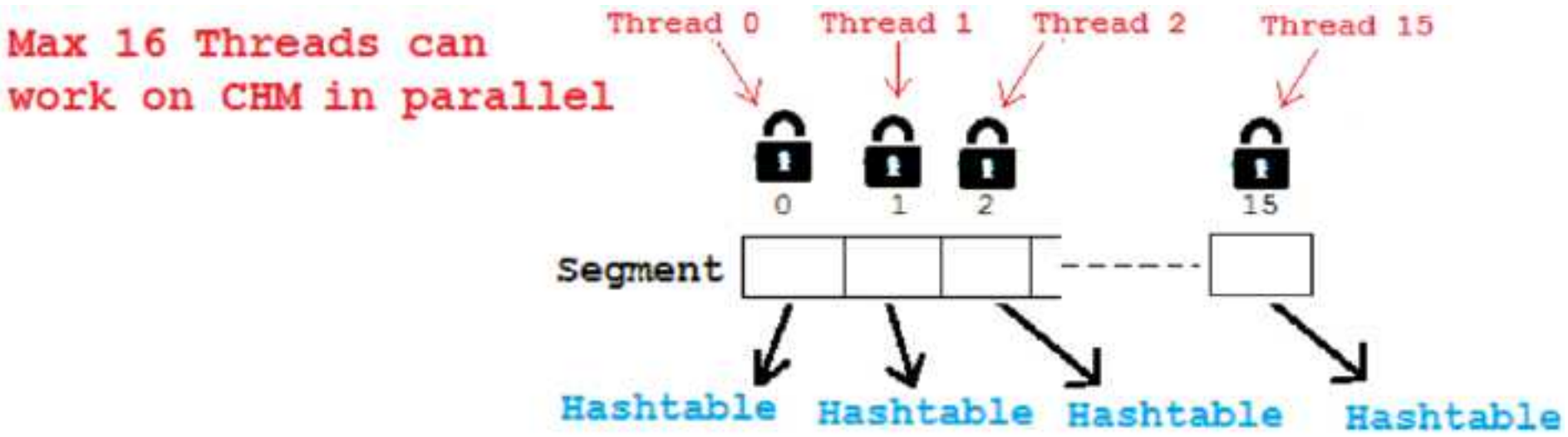
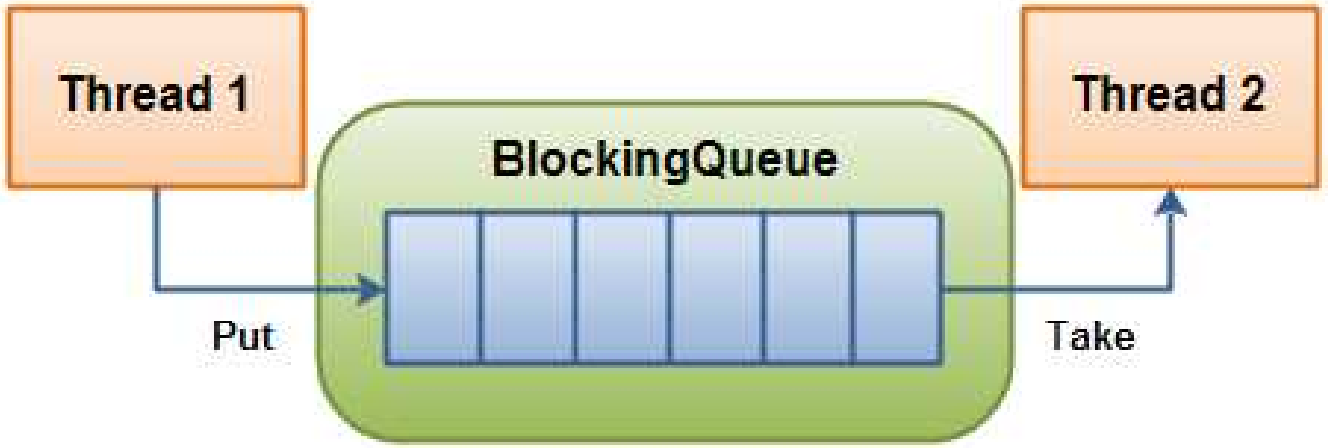


Image source: https://javabypatel.blogspot.com/2016/09/concurrenthashmap-interview-questions.html

BlockingQueue

- Multiple threads can be inserting and taking elements from a BlockingQueue concurrently, without concurrency issues arising
- Typically used to have one thread produce objects (put), which another thread consumes (take)



http://tutorials.jenkov.com/java-util-concurrent/blockingqueue.html

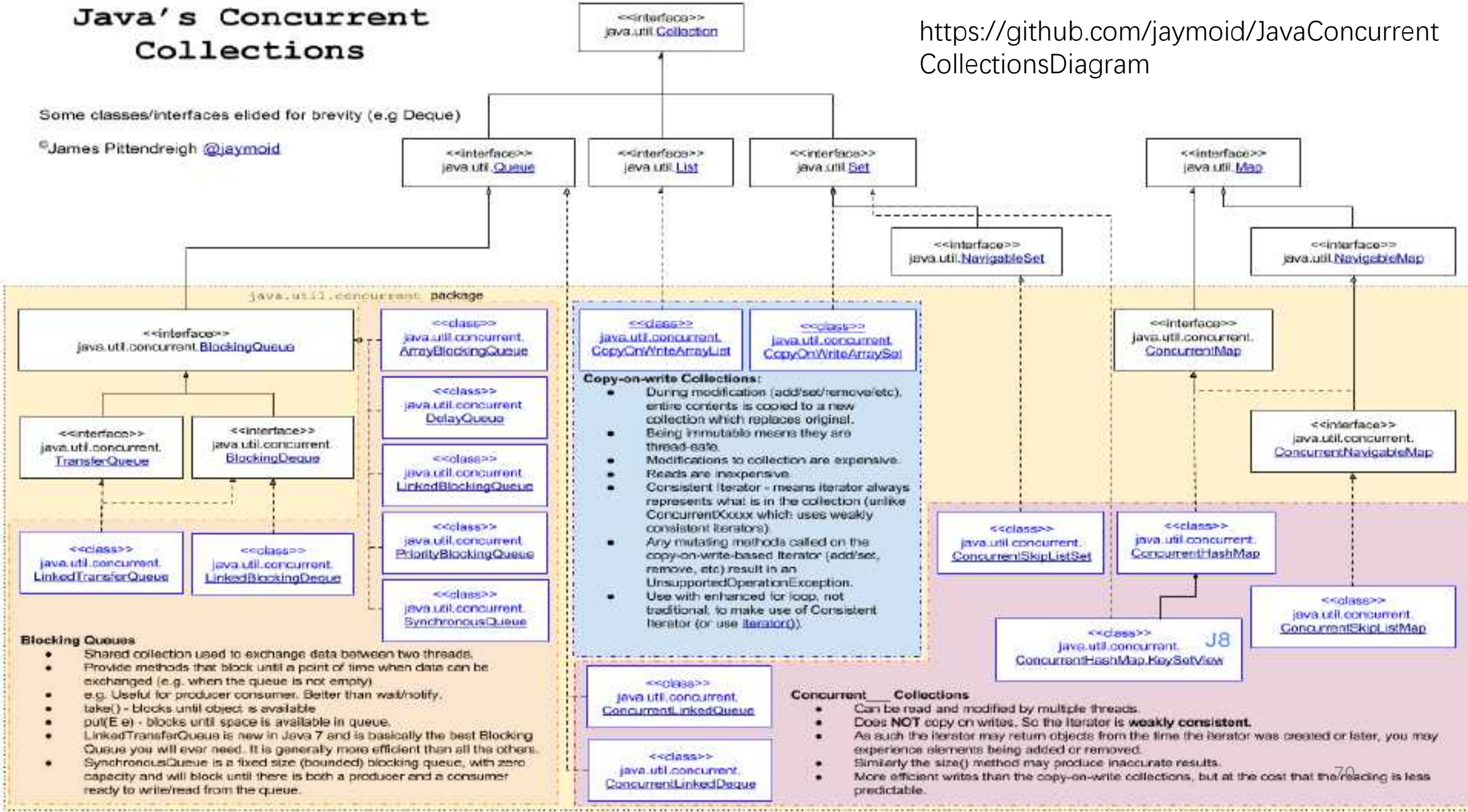
Summary of BlockingQueue methods

	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*

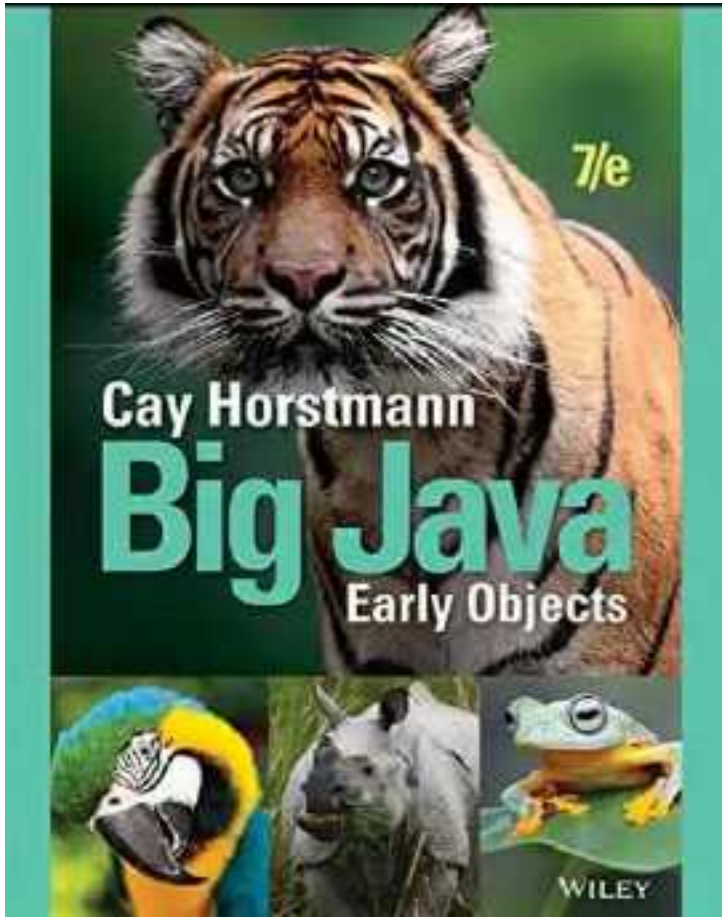
1. **Throws Exception**:
   If the attempted operation is not possible immediately, an exception is thrown.
2. **Special Value**:
   If the attempted operation is not possible immediately, a special value is returned (often true / false).
3. **Blocks**:
   If the attempted operation is not possible immediately, 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).

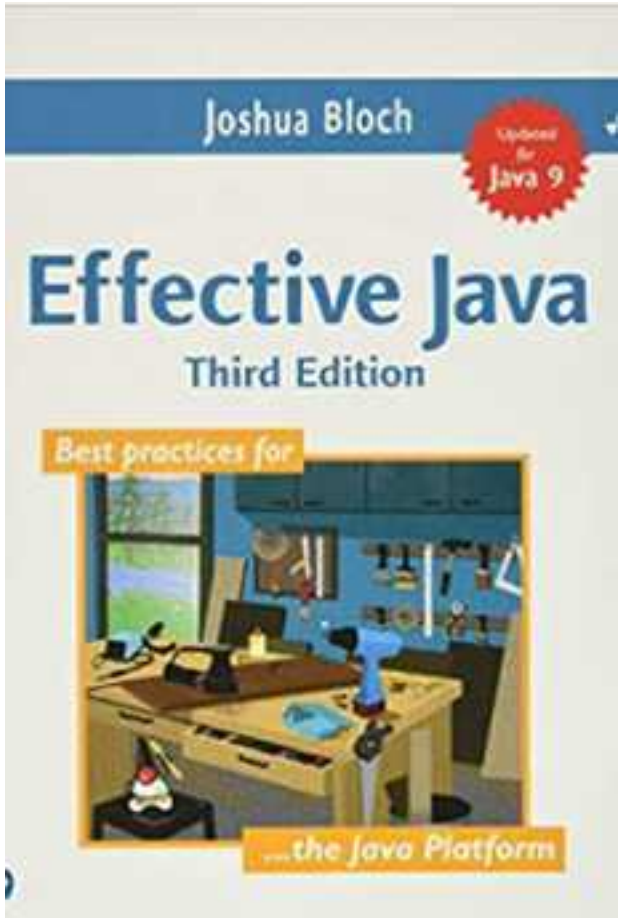
Java's Concurrent Collections

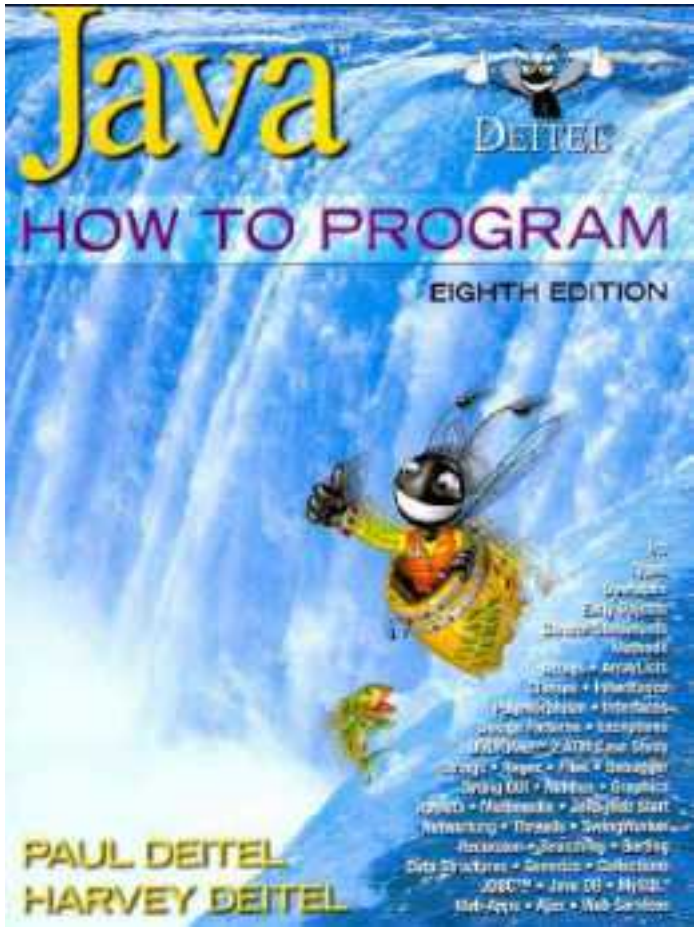
https://github.com/jaymoid/JavaConcurrentCollectionsDiagram



Further Reading







Next Lecture

- Network Programming