Parallel Programming Practice

Fork-Join Framework

Susanne Cech Previtali
Thomas Gross

Last update: 2009-11-05, 09:39

Today

Nested classes in Java

Parallel decomposition

Fork-Join framework

Nested classes in Java

Overview

Nested class

- A class defined within another class

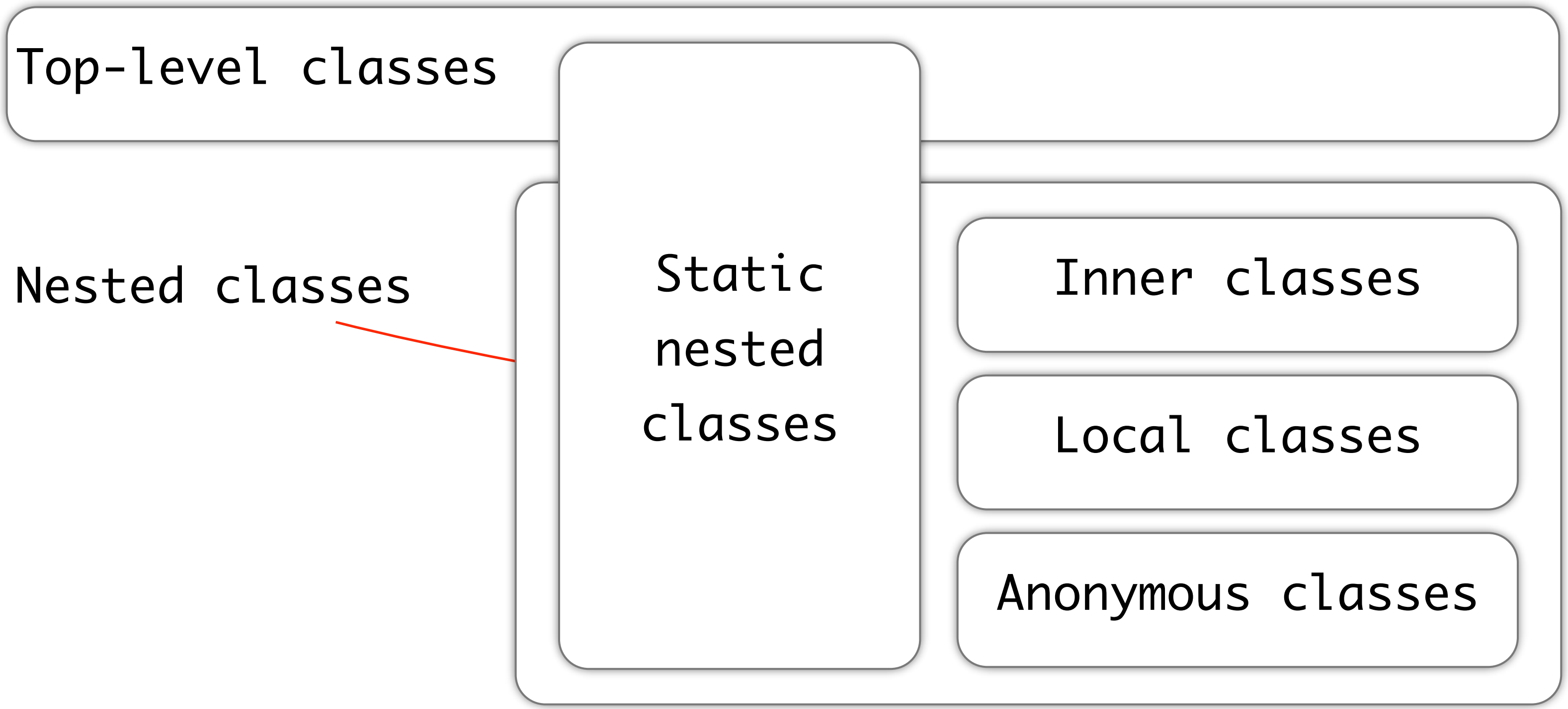
Usage

- Logical grouping of classes
  - If a class is useful to only one other class
  - “Helper” classes
- Increased encapsulation
  - Classes A, B: B must access private members of A
- More readable, maintainable code
  - Code placed closer to where it is used

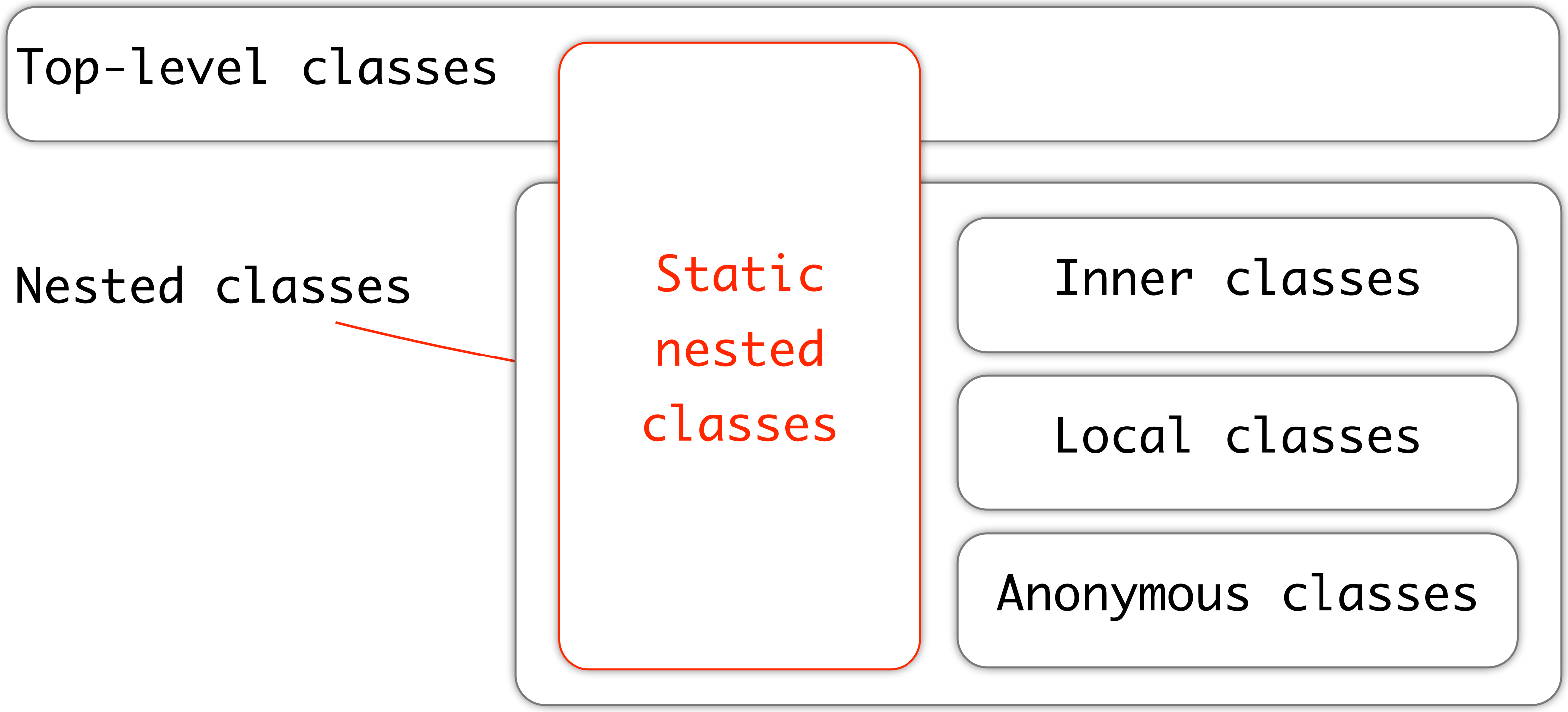
Categorization

Venn diagram

- Set-oriented view of classes in Java



Categorization



Static nested classes

Member of the outer class

Packaging convenience

- Behavior like a top-level class

```
public class Outer {
  private String name;

  static class StaticNested {
    private int count;
    public void set(Outer o) {
       count = o.name.length();
    }
  }
}
```

Static nested classes

Member of the outer class

Packaging convenience

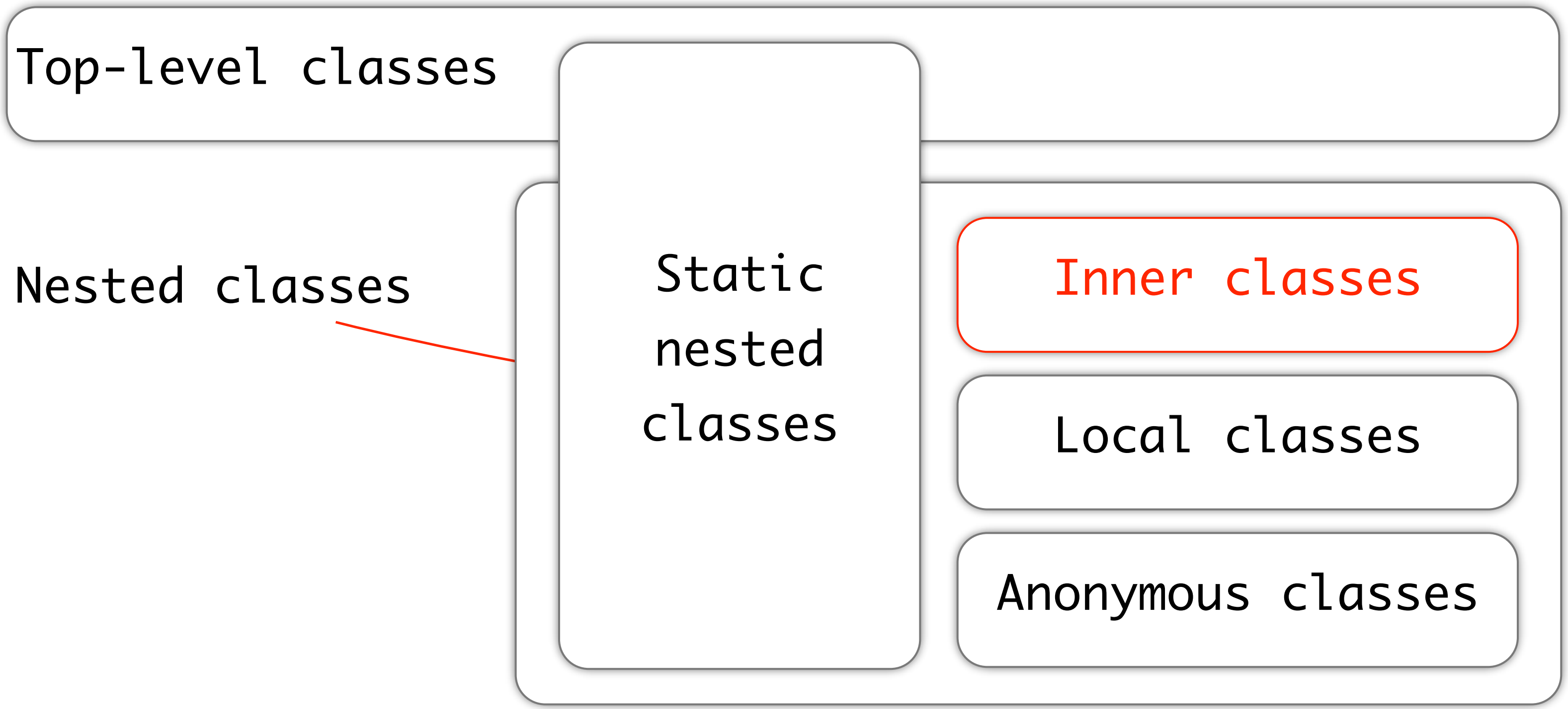
- Behavior like a top-level class

```
Outer o = new Outer();
Outer.StaticNested s =
    new Outer.StaticNested();
s.set(o);
```

```
public class Outer {
  private String name;

  static class StaticNested {
    private int count;
    public void set(Outer o) {
       count = o.name.length();
    }
  }
}
```

Categorization



Inner classes

Member of the outer class

- Cannot define static members
- Object exists *within* instance of outer class ⇒ like instance members

```
Outer o = new Outer();
Outer.Inner i =
    o.new Inner();
i.set();
```

```
public class Outer {
  private String name;

  class Inner {
    private int count;
    public void set() {
      count = name.length();
    }
  }
}
```

Inner classes

Member of the outer class

- Cannot define static members
- Object exists *within* instance of outer class ⇒ like instance members

```
Outer o = new Outer();
Outer.Inner i =
    o.new Inner();
i.set();
```

access to members of the outer class ⇒

```
public class Outer {
  private String name;

  class Inner {
    private int count;
    public void set() {
       count = name.length();
    }
  }
}
```

```
public class DataStructure {
    private int[] array = {1, 2, 3, 4, 5, 6, 7, 8, 9, 10};
    public void printEven() {
        MyIterator it = this.new MyIterator();
        while (it.hasNext()) { System.out.print(it.getNext() + " "); }
    }









}
```

```java
public class DataStructure {
    private int[] array = {1, 2, 3, 4, 5, 6, 7, 8, 9, 10};
    public void printEven() {
        MyIterator it = this.new MyIterator();
        while (it.hasNext()) { System.out.print(it.getNext() + " "); }
    }
    private class MyIterator {
        private int next = 0;
        public boolean hasNext() {
            return (next <= array.length - 1);
        }
        public int getNext() {
            int retValue = array[next];
            next += 2;
            return retValue;
        }

    }
}
```

```java
public class DataStructure {
    private int[] array = {1, 2, 3, 4, 5, 6, 7, 8, 9, 10};
    public void printEven() {
        MyIterator it = this.new MyIterator();
        while (it.hasNext()) { System.out.print(it.getNext() + " "); }
    }
    private class MyIterator {
        private int next = 0;
        public boolean hasNext() {
            return (next <= array.length - 1);
        }
        public int getNext() {
            int retValue = array[next];
            next += 2;
            return retValue;
        }

    }
}
```

private, public, protected, default

```
public class DataStructure {
    private int[] array = {1, 2, 3, 4, 5, 6, 7, 8, 9, 10};
    public void printEven() {
        MyIterator it = this.new MyIterator();
        while (it.hasNext()) { System.out.print(it.getNext() + " "); }
    }
    private class MyIterator {
        private int next = 0;
        public boolean hasNext() {
            return (next <= array.length - 1);
        }
        public int getNext() {
            int retValue = array[next];
            next += 2;
            return retValue;
        }
        private static final int MAX = 10;
    }
}
```

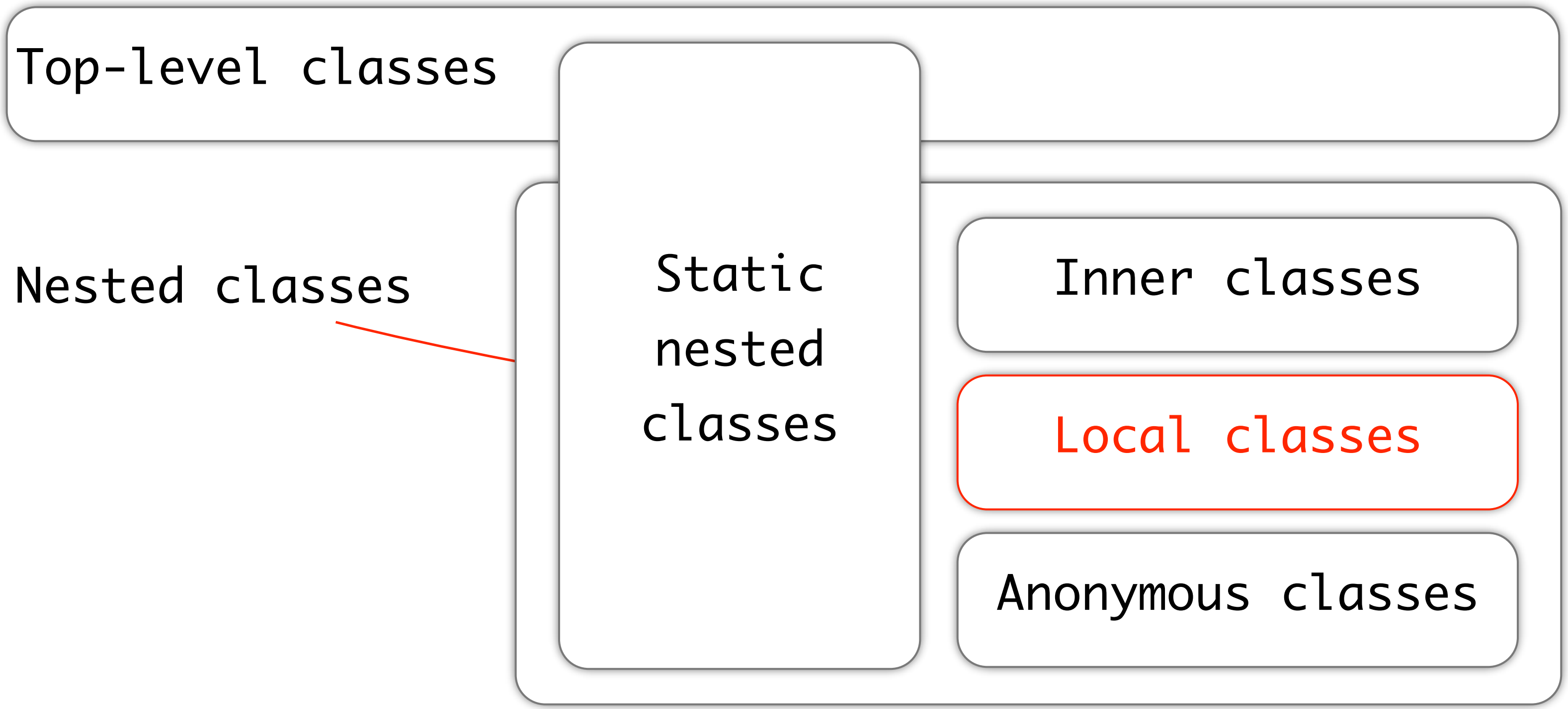
`private, public, protected, default`

cannot declare static members ⇒

associated with instance of outer class

compile-time constant fields: YES

Categorization



Local classes

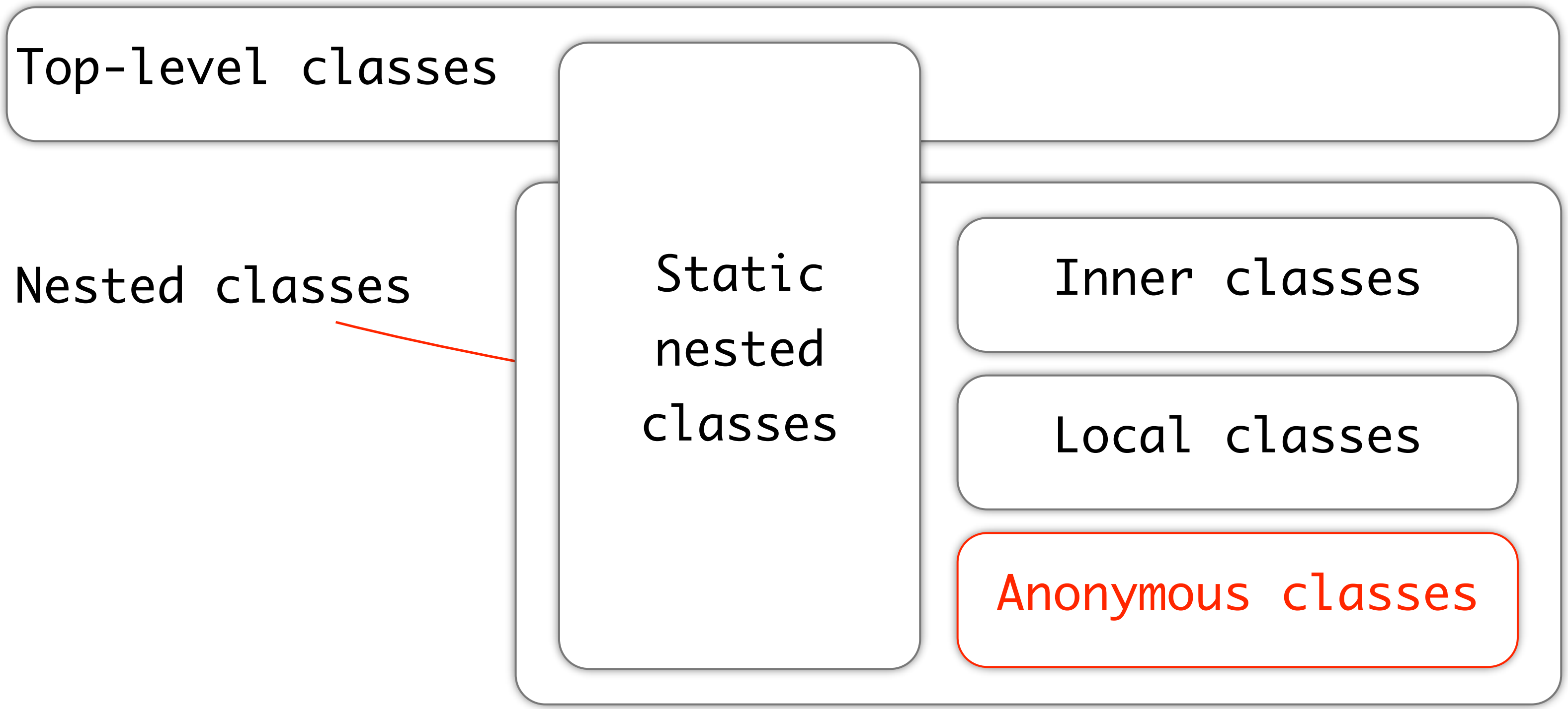
Named class

- Implicitly `final`

Scope local to a block

```
public class MethodLocal1 {
    public void execute() {
        class MyRunnable implements Runnable {
            public void run() {
                System.out.println("Working a lot....");
            }
        };
        new Thread(new MyRunnable()).start();
    }
}
```

Categorization



Anonymous classes

Unnamed

Local to a method or a field

```
public class FieldLocal {
    private Runnable r = new Runnable() {
        public void run() {
            System.out.println("Working a lot....");
        }
    };
    public void execute() {
        new Thread(this.r).start();
    }
}
```

Anonymous classes

Unnamed

Local to a method or a field

```
public class MethodLocal2 {
    public void execute() {
        Runnable r = new Runnable() {
            public void run() {
                System.out.println("Working a lot....");
            }
        };
        new Thread(r).start();
    }
}
```

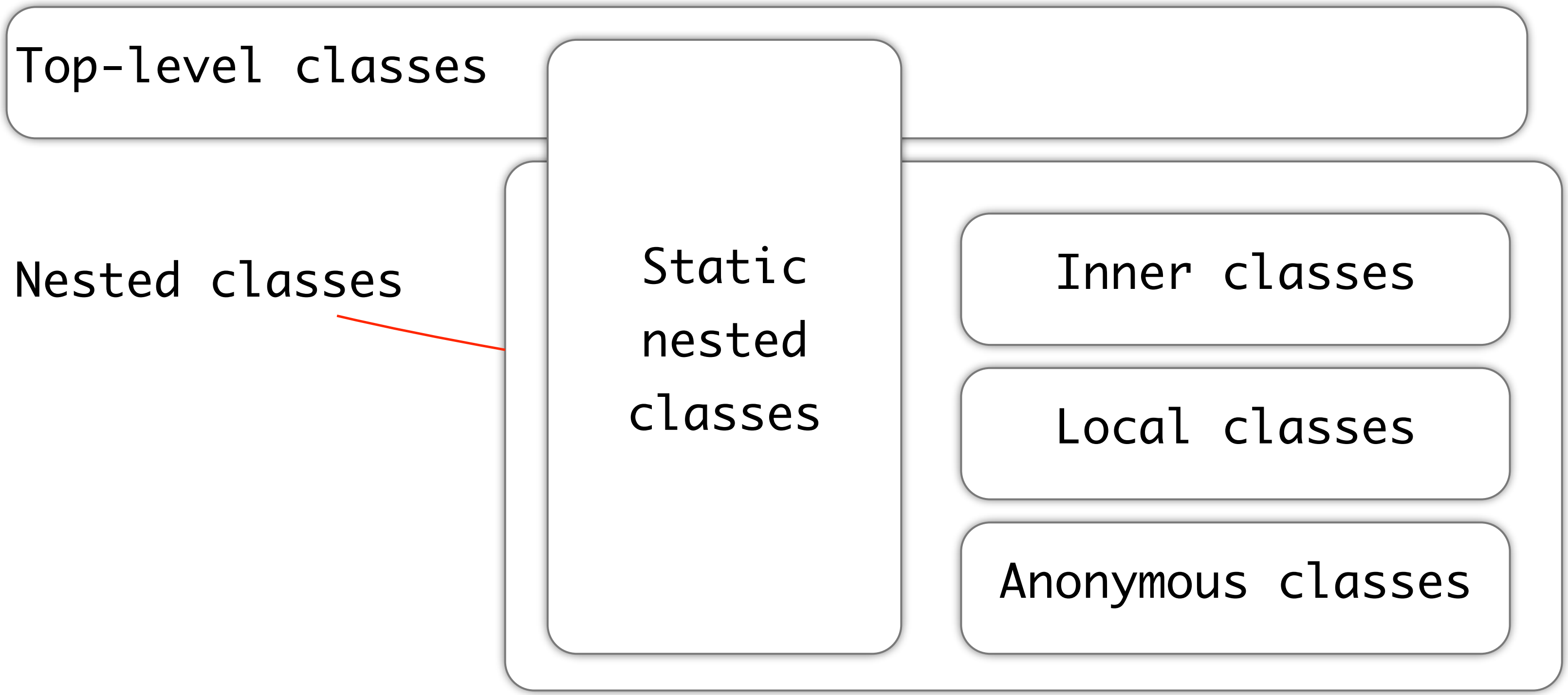
Anonymous classes

Unnamed

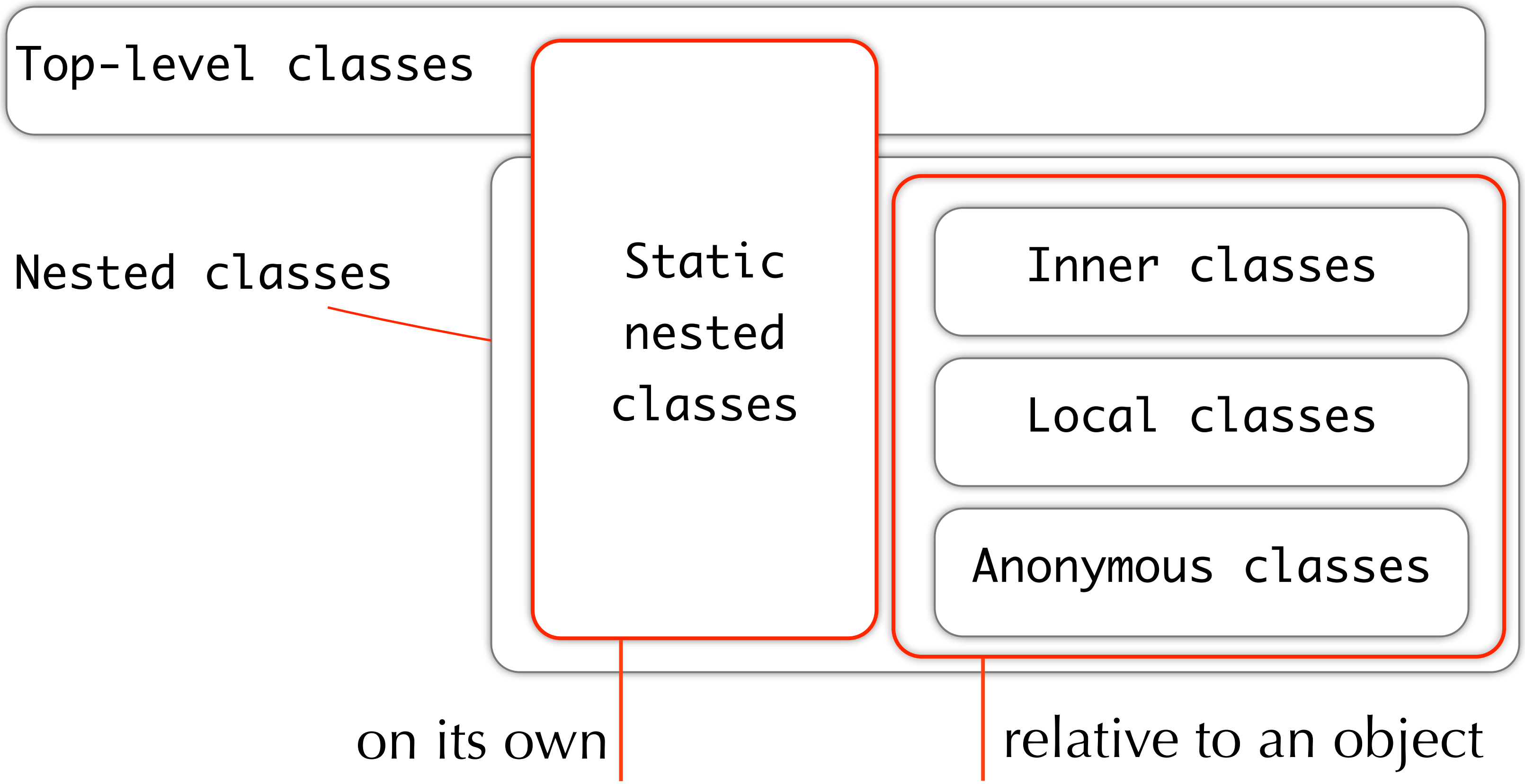
Local to a method or a field

```
public class MethodLocal3 {
    public void execute() {
        new Thread(new Runnable() {
            public void run() {
                System.out.println("Working a lot....");
            }
        }).start();
    }
}
```

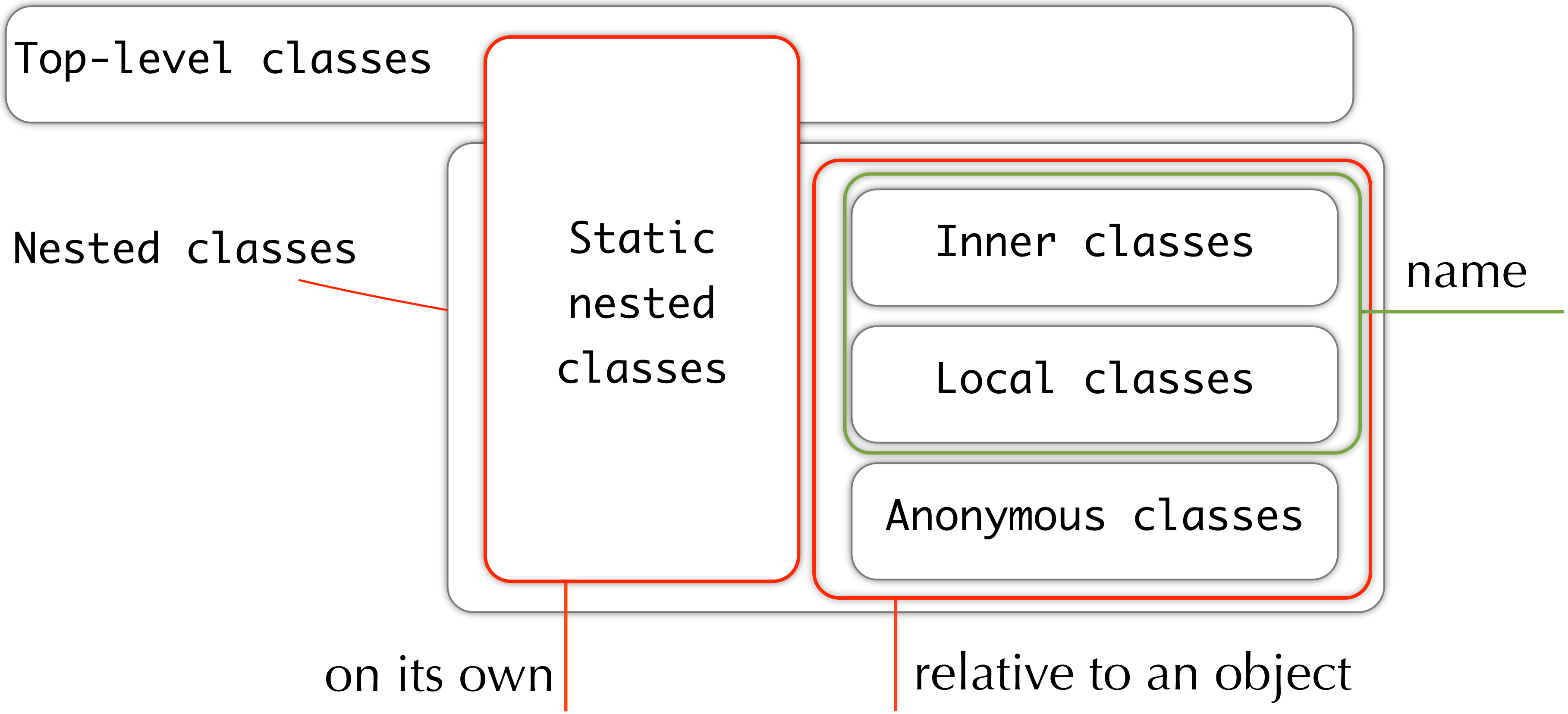
Categorization



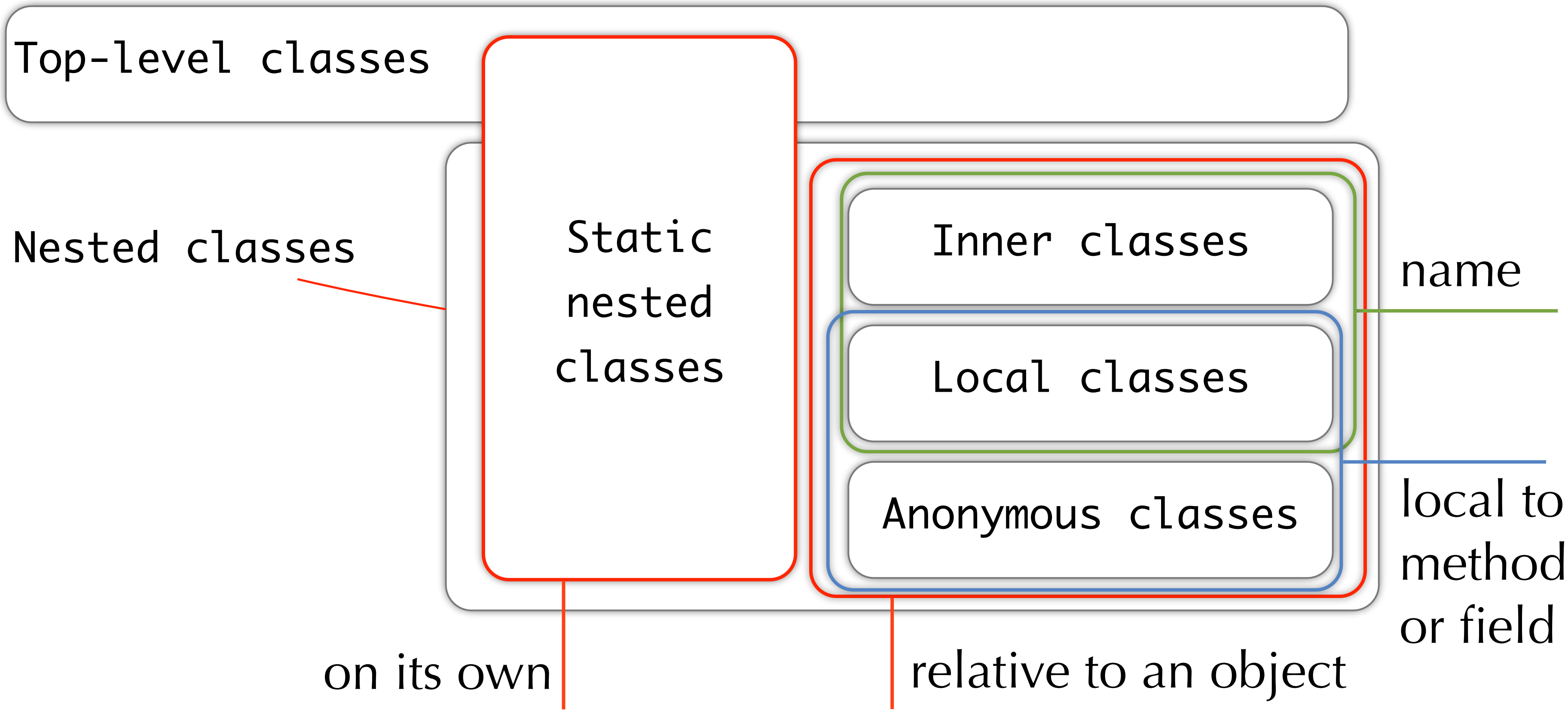
Categorization



Categorization



Categorization



Compiling nested classes

```
// Static nested classes and inner classes
$ javac OuterClass.java
OuterClass$StaticNestedClass.class OuterClass.class

// Local classes
$ javac MethodLocal1.java
MethodLocal1$1MyRunnable.class  MethodLocal1.class

// Anonymous classes
$ javac MethodLocal3.java
MethodLocal3$1.class  MethodLocal3.class
```

Disassembling

javap -c MethodLocal$1

```
Compiled from "MethodLocal.java"
class MethodLocal$1 extends java.lang.Object implements java.lang.Runnable{
final MethodLocal this$0;

MethodLocal$1(MethodLocal);
  Code:
   0:    aload_0
   1:    aload_1
   2:    putfield #1; //Field this$0:LMethodLocal;
   5:    aload_0
   6:    invokespecial    #2; //Method java/lang/Object."<init>":()V
   9:    return

public void run();
  Code:
   0:    getstatic    #3; //Field java/lang/System.out:Ljava/io/PrintStream;
   3:    ldc #4; //String Working ....
   // ...
}
```

Local variables of enclosing method

Local classes have access to local variables of method

- Local variables must be declared final

```
public class MethodLocal4 {
    public void execute() {
        final int i = 3;
        final Integer x = new Integer(42);
        Runnable r = new Runnable() {
            public void run() {
                System.out.println("Working ...." + i + " " + x);
            }
        };
        new Thread(r).start();
    }
}
```

Disassembling for local variables

```
Compiled from "MethodLocal4.java"
class MethodLocal4$1 extends java.lang.Object implements java.lang.Runnable{
final java.lang.Integer val$x;
final MethodLocal4 this$0;
MethodLocal4$1(MethodLocal4, java.lang.Integer);
  Code:
   0:   aload_0
   1:   aload_1
   2:   putfield    #1; //Field this$0:LMethodLocal4;
   5:   aload_0
   6:   aload_2
   7:   putfield    #2; //Field val$x:Ljava/lang/Integer;
   10:  aload_0
   11:  invokespecial   #3; //Method java/lang/Object."<init>":()V
   14:  return

public void run();
   Code: // removed...
```

Disassembly for local variables

```
// continued

public void run();
  Code:
   0:   getstatic   #4; //Field java/lang/System.out:Ljava/io/PrintStream;
   3:   new #5; //class java/lang/StringBuilder
   6:   dup
   7:   invokespecial   #6; //Method java/lang/StringBuilder."<init>":()V
   10:  ldc #7; //String Working ...3
   12:  invokevirtual   #8; //Method java/lang/StringBuilder.append:(.....
   15:  aload_0
   16:  getfield    #2; //Field val$x:Ljava/lang/Integer;
   19:  invokevirtual   #9; //Method java/lang/StringBuilder.append:(....
   22:  invokevirtual   #10; //Method java/lang/StringBuilder.toString:()....
   25:  invokevirtual   #11; //Method java/io/PrintStream.println:(....
   28:  return

}
```

Parallel decomposition

Problem decomposition

Goal: Map a problem to multiple threads

Two principle approaches

- Task partitioning
  - Focus on computation
- Data partitioning
  - Focus on data

Ways to exploit parallelism

Task decomposition

- Each thread works on a subset of the tasks

Data decomposition

- Each thread works on a subset of the data
- Single program, multiple data

Task decomposition

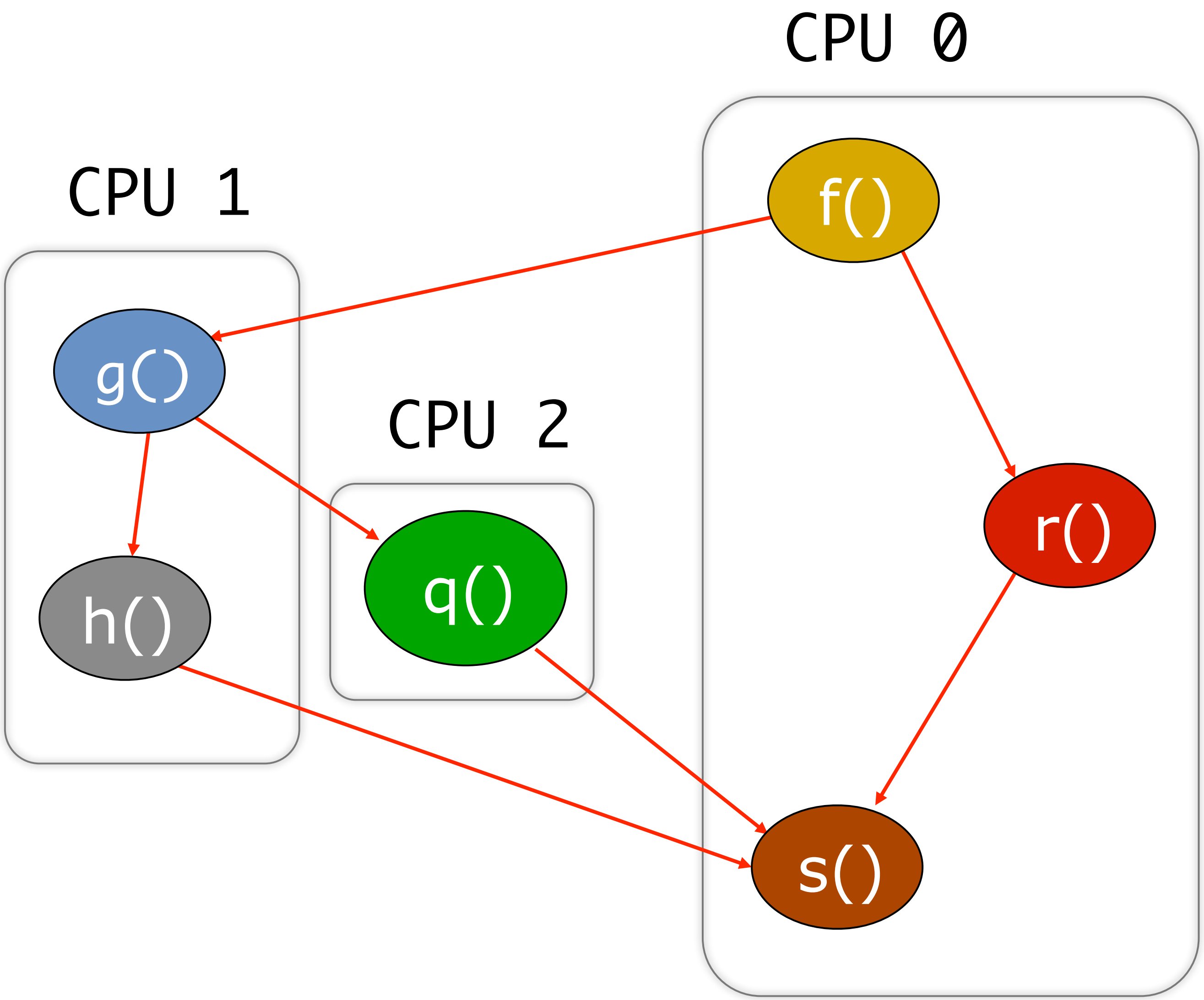
Task parallelism

1. Divide tasks among processors
2. Decide which data elements are going to be accessed (read and/or written) by which processors

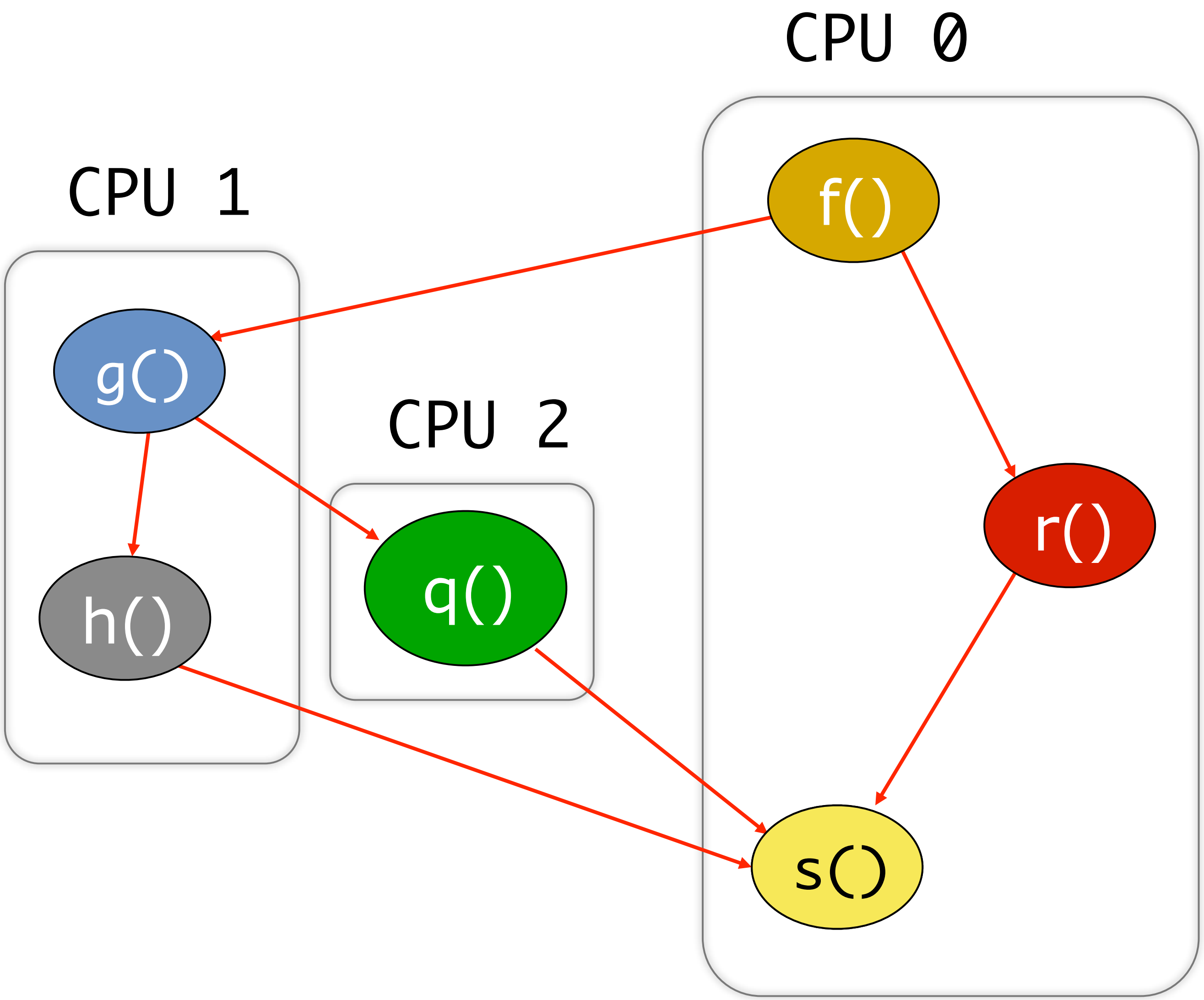
Example

- Event handler for GUI

Example: Functional decomposition



Example: Functional decomposition



Domain decomposition

Data parallelism

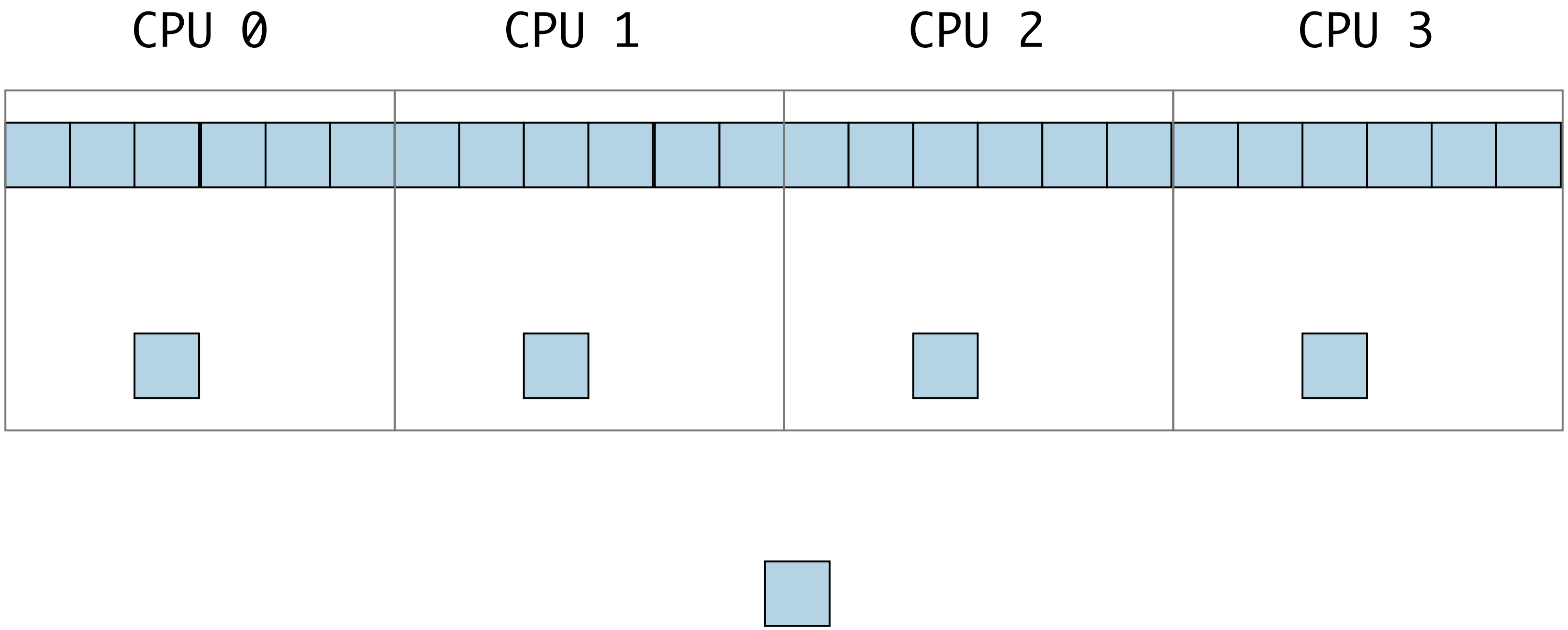
1. Divide data elements among processors
2. Assign tasks to each processor

Example: Data decomposition

Search for maximum in array

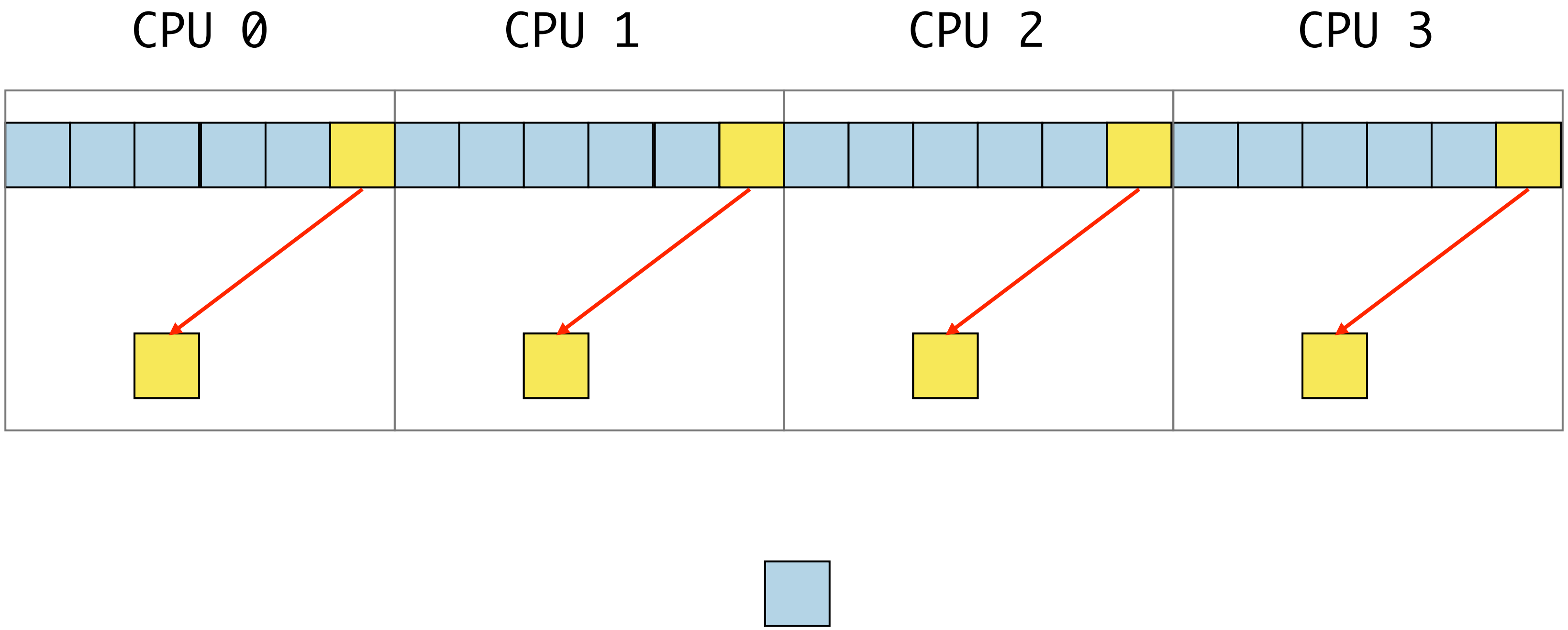
Example: Data decomposition

Search for maximum in array



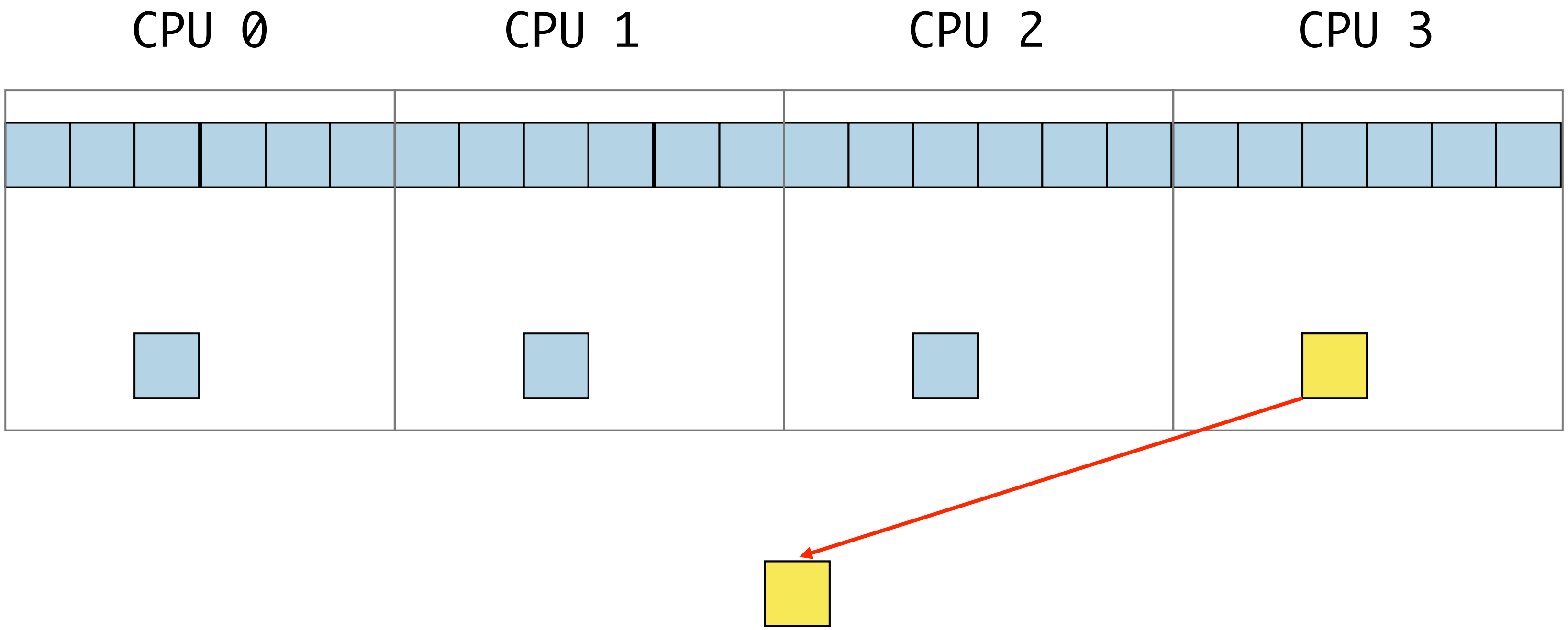
Example: Data decomposition

Search for maximum in array



Example: Data decomposition

Search for maximum in array



Task versus data partitioning

Java 1.0-1.4: Thread objects

Java 5: Course-grained parallelism

Java 7: Fine-grained parallelism

Java 1.0-1.4: Thread objects

Hardware

- No (or limited) parallel hardware

Constructs

- Thread, synchronized, volatile
- Broken memory model

Programming

- Asynchronous tasks
- Error-prone

Java 5: Concurrent components

Hardware

- Multi-cores

Components

- Executor framework
- Course-grained concurrency
- Task decomposition
  - Asynchronous tasks
  - #task ≅ #cores

Discussion

- Does not scale to many-cores

JSR-166: Fine-grained parallelism

Hardware

- Multi- and manycores

Components

- Fork-join framework
- Divide and conquer algorithms
- Task and data decomposition

Fork-join framework

Introduction

Remember divide-and-conquer algorithm design?

Examples

- Sorting and searching
- Data structures
- Matrix algorithms
- Image processing

Parallelize easily if recursive tasks are independent, either

- Operate on different data sets
- Solve different subproblems
- No communication needed

Fork-join decompositions

Parallel version of divide-and-conquer

Generic divide-and conquer algorithm

```
// Pseudo code
Result solve(Problem problem) {
    if (problem.size < SEQ_THRESHOLD) {
        return solveSequentially(problem);
    } else {
        Result left, right;
        INVOKE_IN_PARALLEL {
            left = solve(extractLeftHalf(problem));
            right = solve(extractRightHalf(problem));
        }
        return combine(left, right);
    }
}
```

Generic divide-and conquer algorithm

```
// Pseudo code
Result solve(Problem problem) {
    if (problem.size < SEQ_THRESHOLD) {
        return solveSequentially(problem);
    } else {
        Result left, right;
        INVOKE_IN_PARALLEL {
            left = solve(extractLeftHalf(problem));
            right = solve(extractRightHalf(problem));
        }
        return combine(left, right);
    }
}
```

sequential solution would be faster

divide in subproblems solve recursively

Generic divide-and conquer algorithm

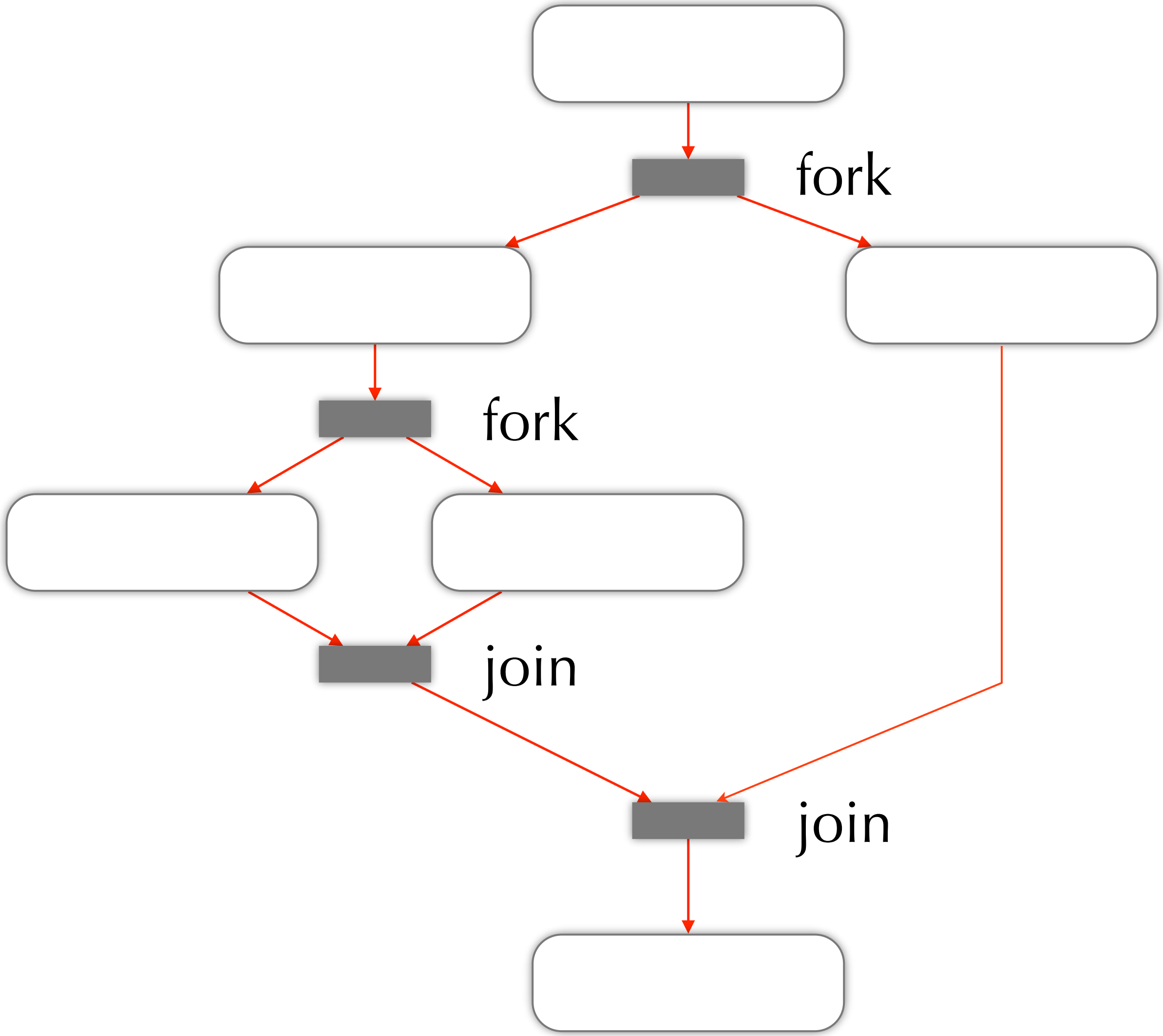
```
// Pseudo code
Result solve(Problem problem) {
    if (problem.size < SEQ_THRESHOLD) {
        return solveSequentially(problem);
    } else {
        Result left, right;
        INVOKE_IN_PARALLEL {
            left = solve(extractLeftHalf(problem));
            right = solve(extractRightHalf(problem));
        }
        return combine(left, right);
    }
}
```

cost function:
coordinate parallel tasks

sequential solution
would be faster

divide in subproblems
solve recursively

Task activity diagram



fork: start subtasks
join: wait for completion

Task granularity and structure

Maximizing parallelism

Minimizing overhead

Minimizing contention

Maximizing locality

Note

- Every solution is a compromise!

Task granularity and structure

Maximizing parallelism

- The smaller the tasks, the more opportunity for parallelism
- Using more fine-grained tasks
  - Keeps more CPUs busy
  - Improves load balancing, locality, scalability
  - Decreases time that CPUs must wait for one another

Minimizing overhead

Minimizing contention

Maximizing locality

Task granularity and structure

Maximizing parallelism

Minimizing overhead

- Task and thread creation versus sequential objects
- Memory consumption, garbage collection

Minimizing contention

Maximizing locality

Task granularity and structure

Maximizing parallelism

Minimizing overhead

Minimizing contention

- Not much speed-up if
  - Frequent communication
  - Block waiting for other threads/resources
- Minimize shared resources, global variables, locks

Maximizing locality

Task granularity and structure

Maximizing parallelism

Minimizing overhead

Minimizing contention

Maximizing locality

- Memory access patterns ⇒ caches

Note again:

- Every solution is a compromise

Select max element from array

```
public class SelectMaxProblem {
    private final int[] numbers;
    private final int start;
    private final int end;
    public final int size;
    public SelectMaxProblem(int[] numbers, int start, int end) {
        this.numbers = numbers;
        this.start = start;
        this.end = end;
        this.size = end - start;
    }

    // to be continued...
}
```

Select max element from array

```
public class SelectMaxProblem {
    private final int[] numbers;
    private final int start;
    private final int end;
    public final int size;
    public SelectMaxProblem(int[] numbers, int start, int end) {
        this.numbers = numbers;
        this.start = start;
        this.end = end;
        this.size = end - start;
    }

    // to be continued...
}
```

parameters of the problem

established in constructor

Select max element from array

```java
public class SelectMaxProblem {
    private final int[] numbers;
    private final int start;
    private final int end;
    public final int size;
    public SelectMaxProblem(int[] numbers, int start, int end) {
        this.numbers = numbers;
        this.start = start;
        this.end = end;
        this.size = end - start;
    }

    // to be continued...
}
```

parameters of the problem

established in constructor

constructor

copy array references

disjoint data subsets, read-only

Select max element from array

```
public class SelectMaxProblem {
    // continued

    public int solveSequentially() {
        int max = Integer.MIN_VALUE;
        for (int i=start; i<end; i++) {
            int n = numbers[i];
            if (n > max) max = n;
        }
        return max;
    }
    public SelectMaxProblem divide(int subStart, int subEnd) {
        return new SelectMaxProblem(numbers,
                                    start + subStart,
                                    start + subEnd);
    }
}
```

Select max element from array

```
public class SelectMaxProblem {
    // continued

    public int solveSequentially() {
        int max = Integer.MIN_VALUE;
        for (int i=start; i<end; i++) {
            int n = numbers[i];
            if (n > max) max = n;
        }
        return max;
    }
    public SelectMaxProblem divide(int subStart, int subEnd) {
        return new SelectMaxProblem(numbers,
                                    start + subStart,
                                    start + subEnd);
    }
}
```

sequential computation

Select max element from array

```
public class SelectMaxProblem {
    // continued

    public int solveSequentially() {
        int max = Integer.MIN_VALUE;
        for (int i=start; i<end; i++) {
            int n = numbers[i];
            if (n > max) max = n;
        }
        return max;
    }
    public SelectMaxProblem divide(int subStart, int subEnd) {
        return new SelectMaxProblem(numbers,
                                    start + subStart,
                                    start + subEnd);
    }
}
```

sequential computation

split into subproblems

Example FJ framework

```
public class MaxWithFJ extends RecursiveAction {
  private final int threshold;
  private final SelectMaxProblem p; // problem
  public int result;
  public MaxWithFJ(SelectMaxProblem problem, int threshold) { .. }
  protected void compute() { // overriddden
    if (p.size < threshold)
      result = p.solveSequentially();
    else {
      int mid = p.size / 2;
      MaxWithFJ left = new MaxWithFJ(p.divide(0, mid), threshold);
      MaxWithFJ right = new MaxWithFJ(p.divide(mid, p.size), threshold);
      invokeAll(left, right);
      result = Math.max(left.result, right.result);
    }
  }
}
```

Solving the problem

```
public static void main(String[] args) {
    int size = 500000;
    int[] array = new int[size];
    for (int i = 0; i < size; i++) {
        array[i] = i;
    }
    SelectMaxProblem problem = new SelectMaxProblem(array, 0, size);
    int threshold = 100;
    int nThreads = 4;
    MaxWithFJ mfj = new MaxWithFJ(problem, threshold);
    ForkJoinPool fjPool = new ForkJoinPool(nThreads);
    fjPool.invoke(mfj);
    int result = mfj.result;
}
```

Solving the problem

```
public static void main(String[] args) {
    int size = 500000;
    int[] array = new int[size];
    for (int i = 0; i < size; i++) {
        array[i] = i;
    }
    SelectMaxProblem problem = new SelectMaxProblem(array, 0, size);
    int threshold = 100;
    int nThreads = 4;
    MaxWithFJ mfj = new MaxWithFJ(problem, threshold);
    ForkJoinPool fjPool = new ForkJoinPool(nThreads);
    fjPool.invoke(mfj);
    int result = mfj.result;
}
```

implements Executor, ExecutionService
optimized for fork-join tasks

Solving the problem

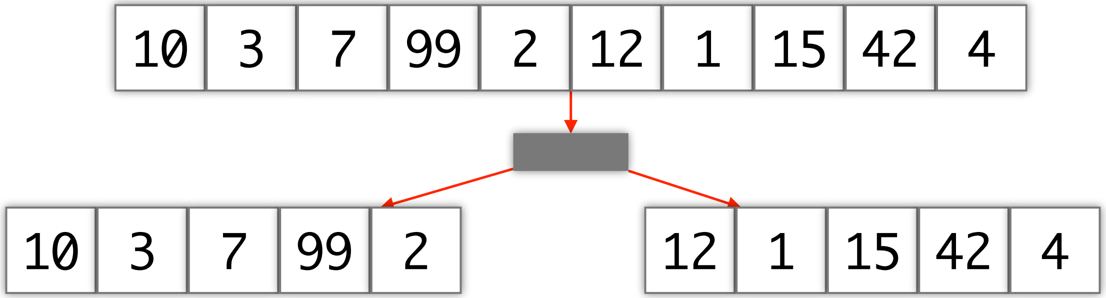
```
public static void main(String[] args) {
    int size = 500000;
    int[] array = new int[size];
    for (int i = 0; i < size; i++) {
        array[i] = i;
    }
    SelectMaxProblem problem = new SelectMaxProblem(array, 0, size);
    int threshold = 100;  // avoid ridiculously low and high
    int nThreads = 4;     // use Runtime.availableProcessors();
    MaxWithFJ mfj = new MaxWithFJ(problem, threshold);
    ForkJoinPool fjPool = new ForkJoinPool(nThreads); // ForkJoinPool()
    fjPool.invoke(mfj);
    int result = mfj.result;
}
```

implements Executor, ExecutionService
optimized for fork-join tasks

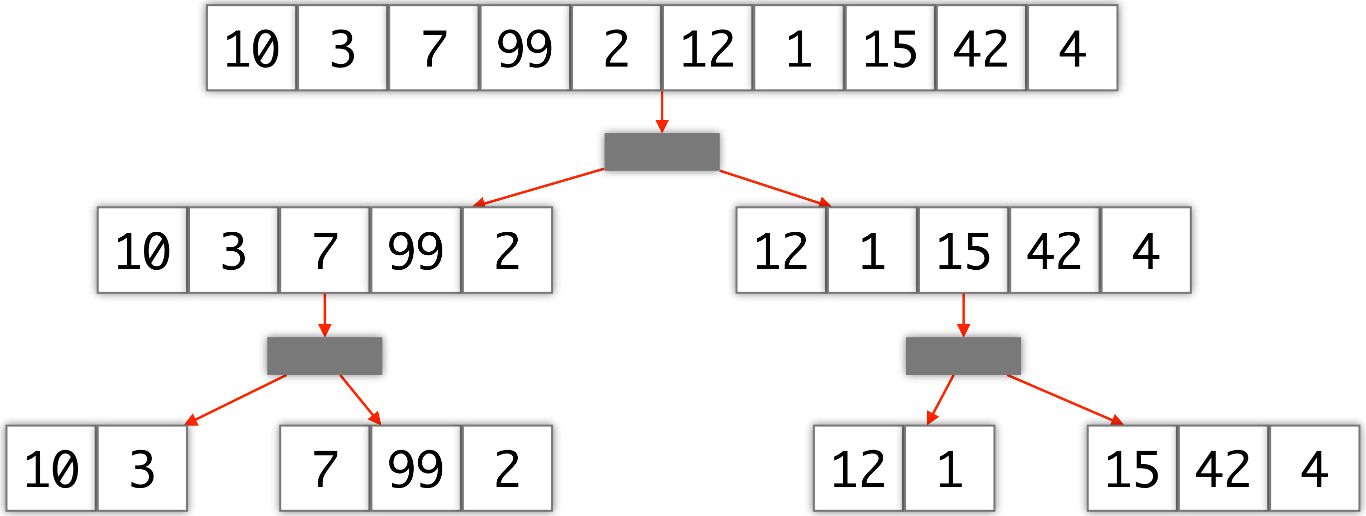
Execution sequence (threshold=2)

10	3	7	99	2	12	1	15	42	4

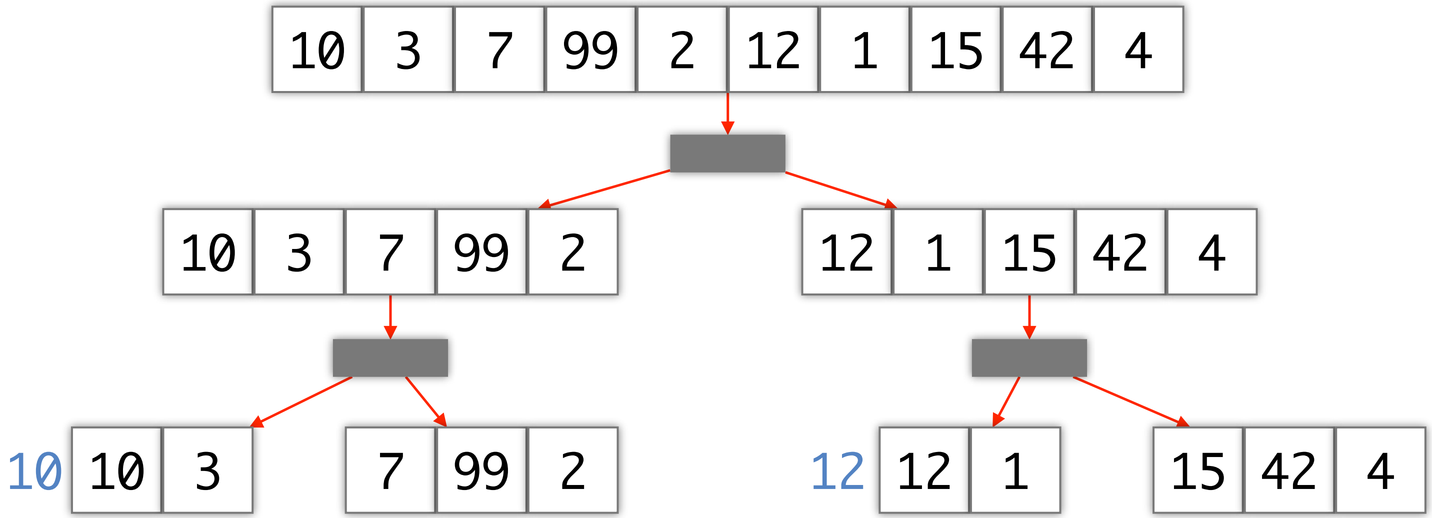
Execution sequence (threshold=2)



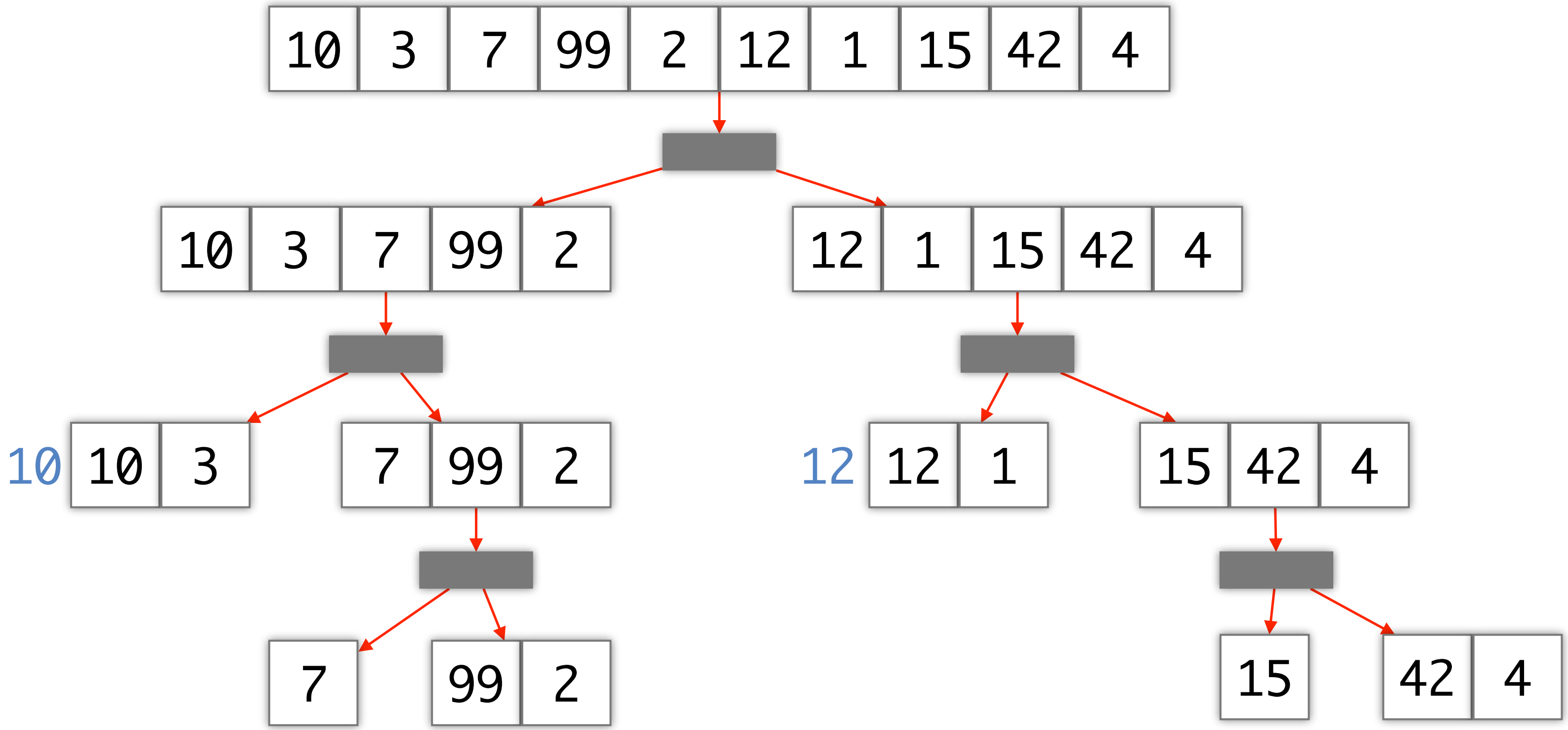
Execution sequence (threshold=2)



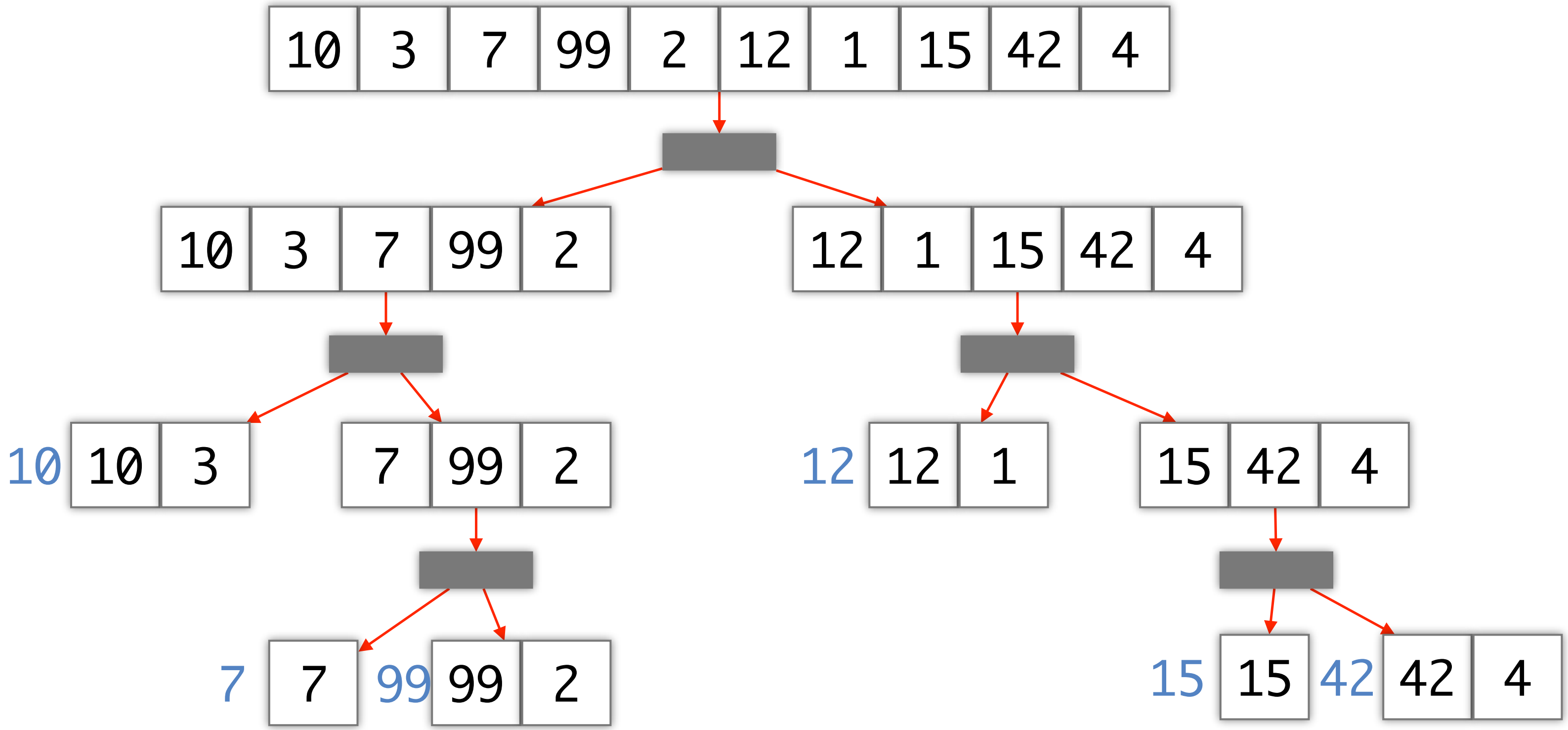
Execution sequence (threshold=2)



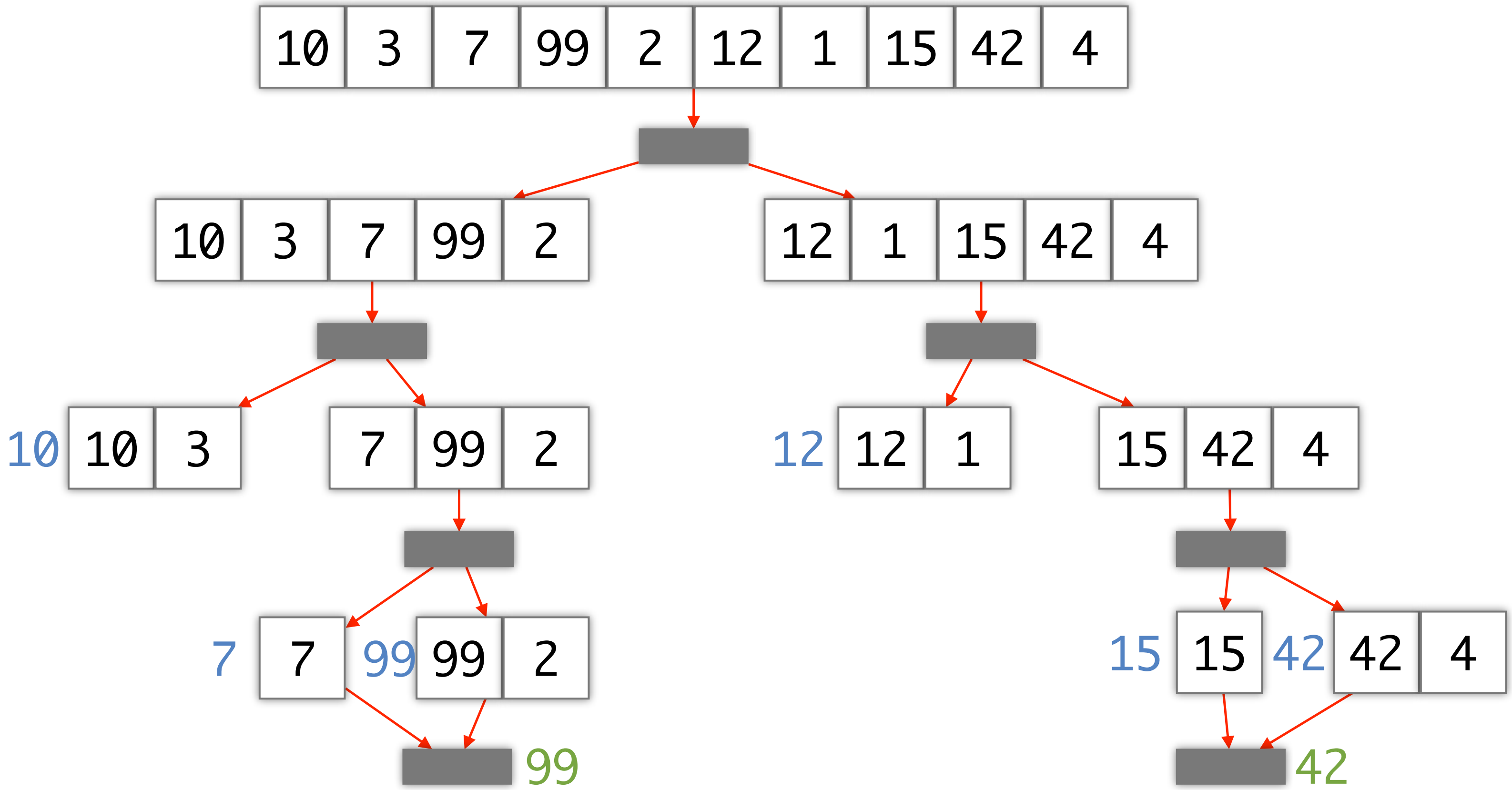
Execution sequence (threshold=2)



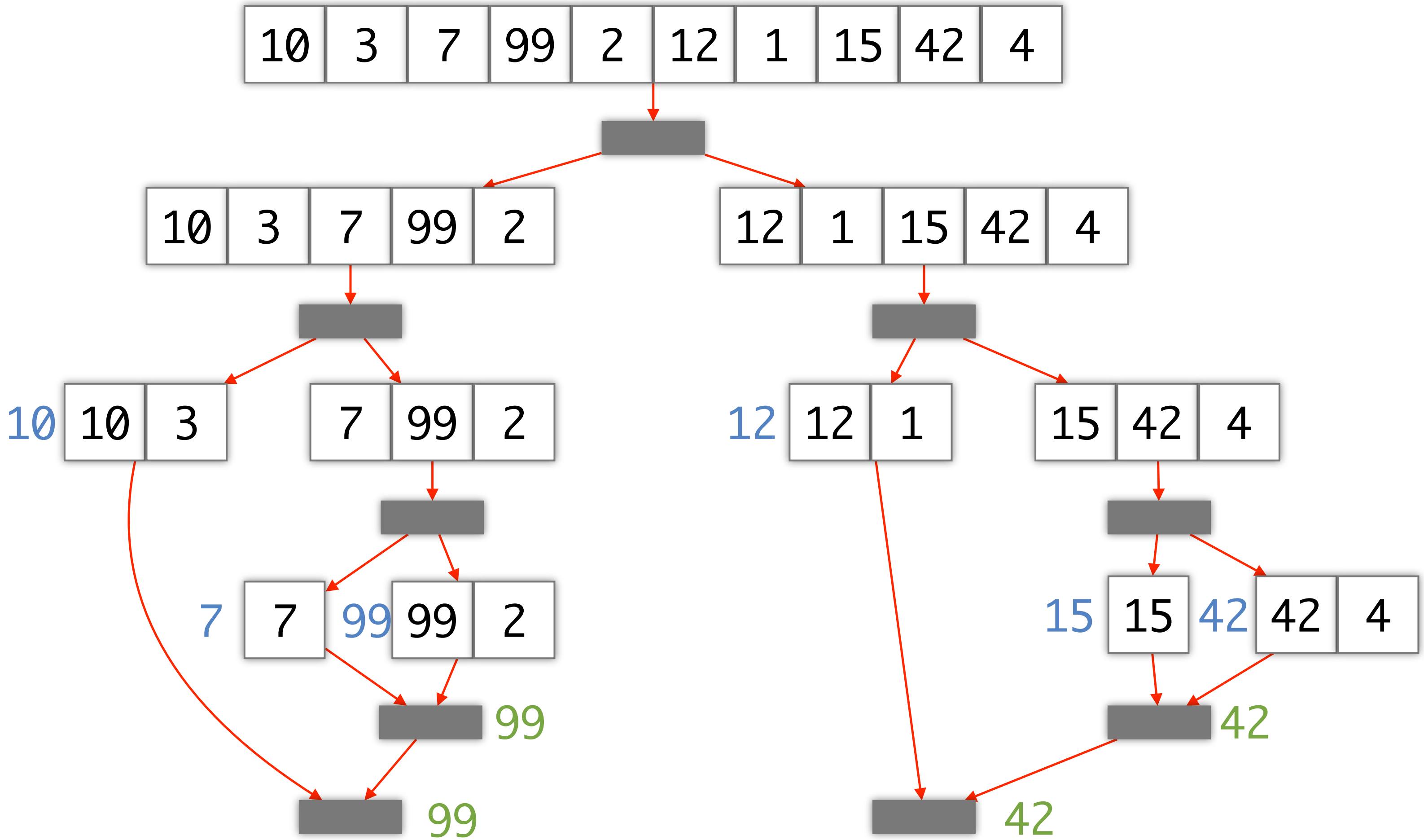
Execution sequence (threshold=2)



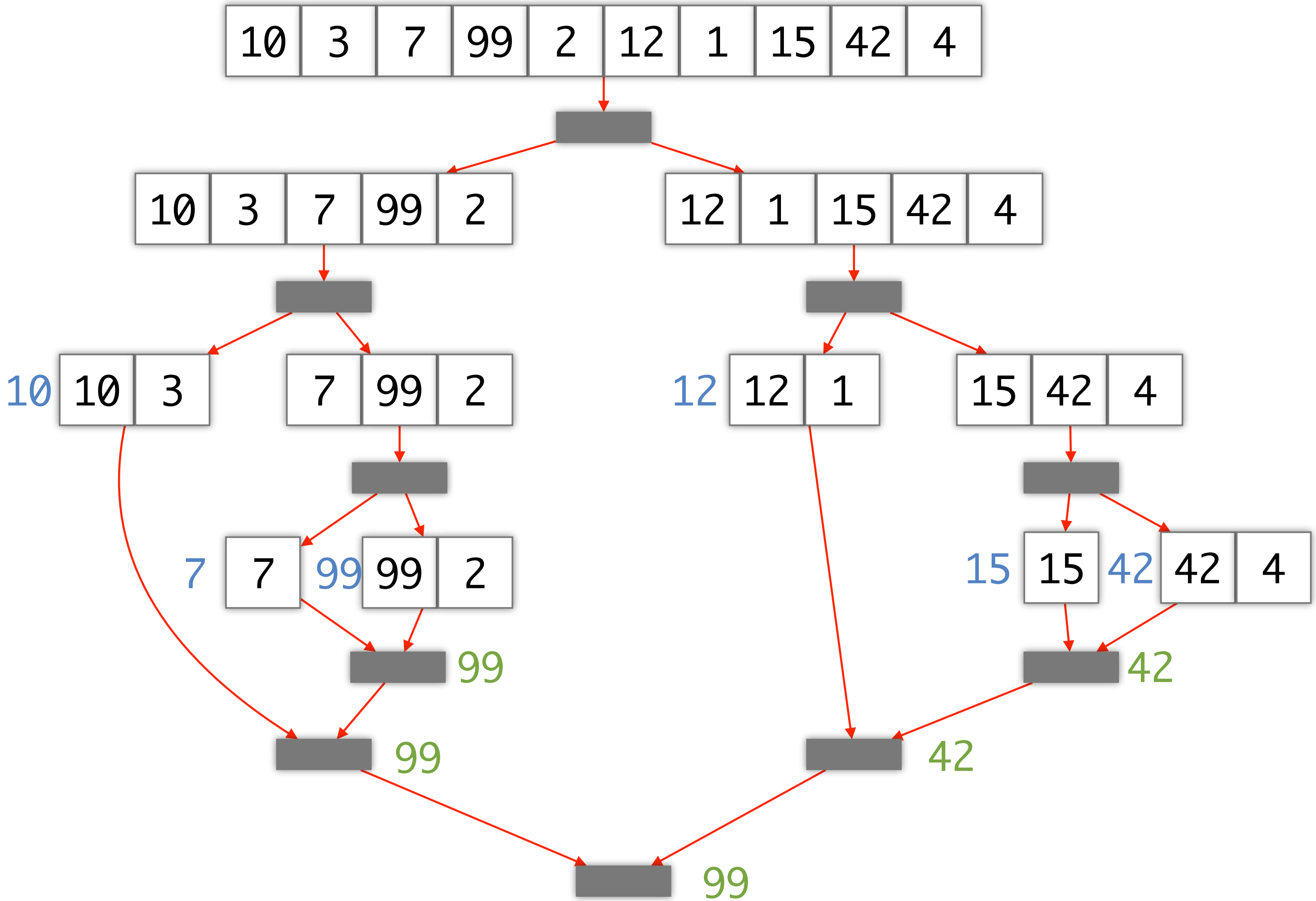
Execution sequence (threshold=2)



Execution sequence (threshold=2)



Execution sequence (threshold=2)



Implementation considerations of FJ

Thread objects

- Fork operation: `Thread.start()`
- Join operation: `Thread.join()`
- Expensive thread creation, number of threads

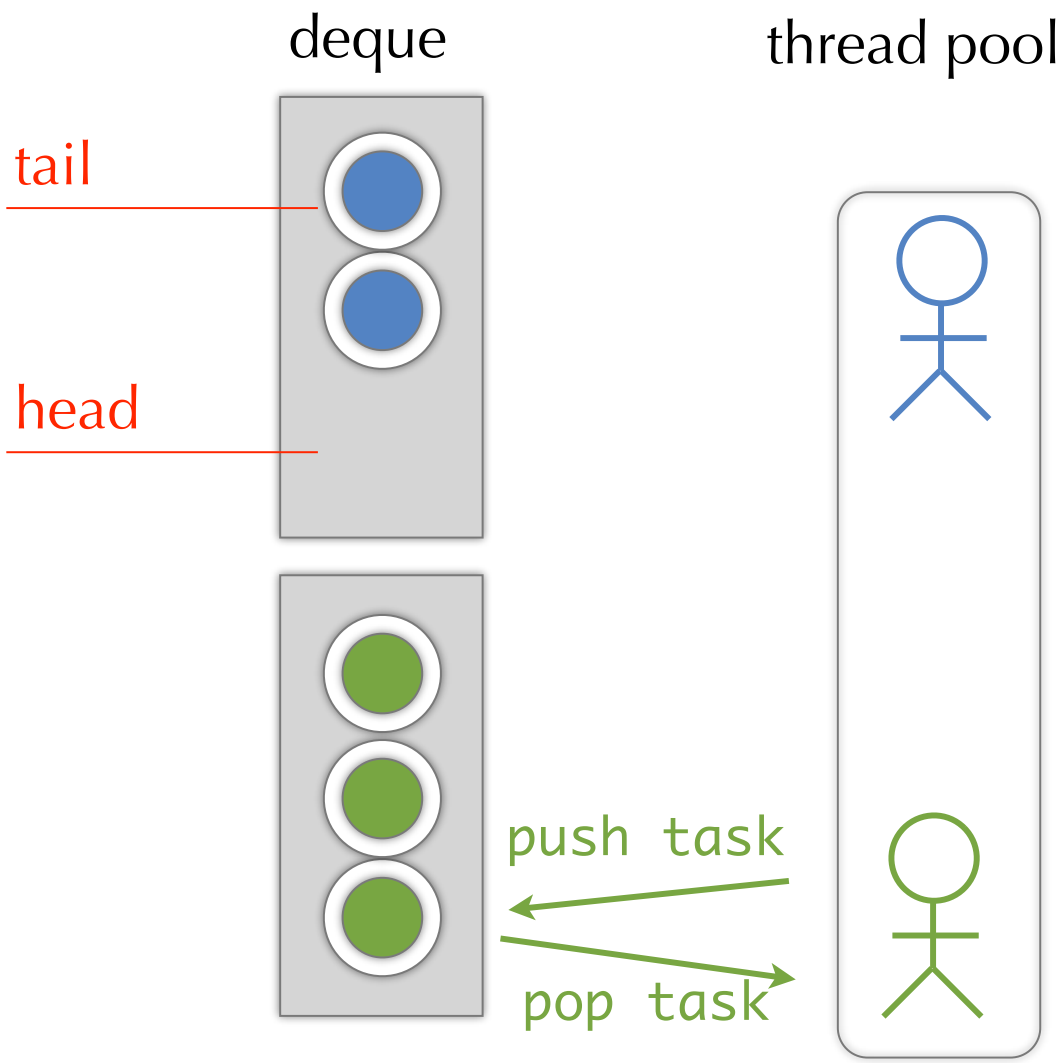
Executor thread pools

- Tasks wait for other tasks to complete ⇒ high contention
- Designed for independent, maybe blocking, coarse-grained tasks

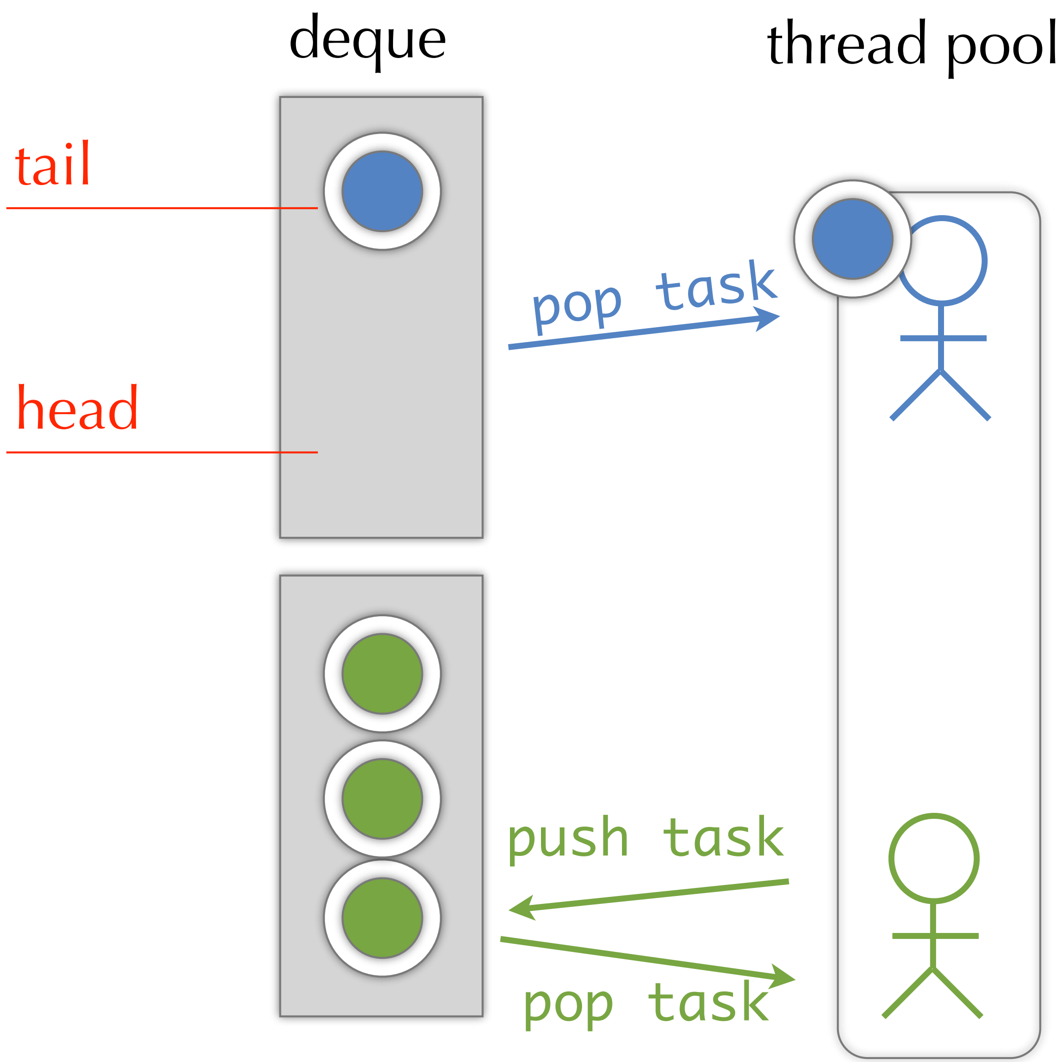
Ideal solution minimizes

- Context switch overhead between worker threads
- Contention for task queue ⇒ avoids a common task queue

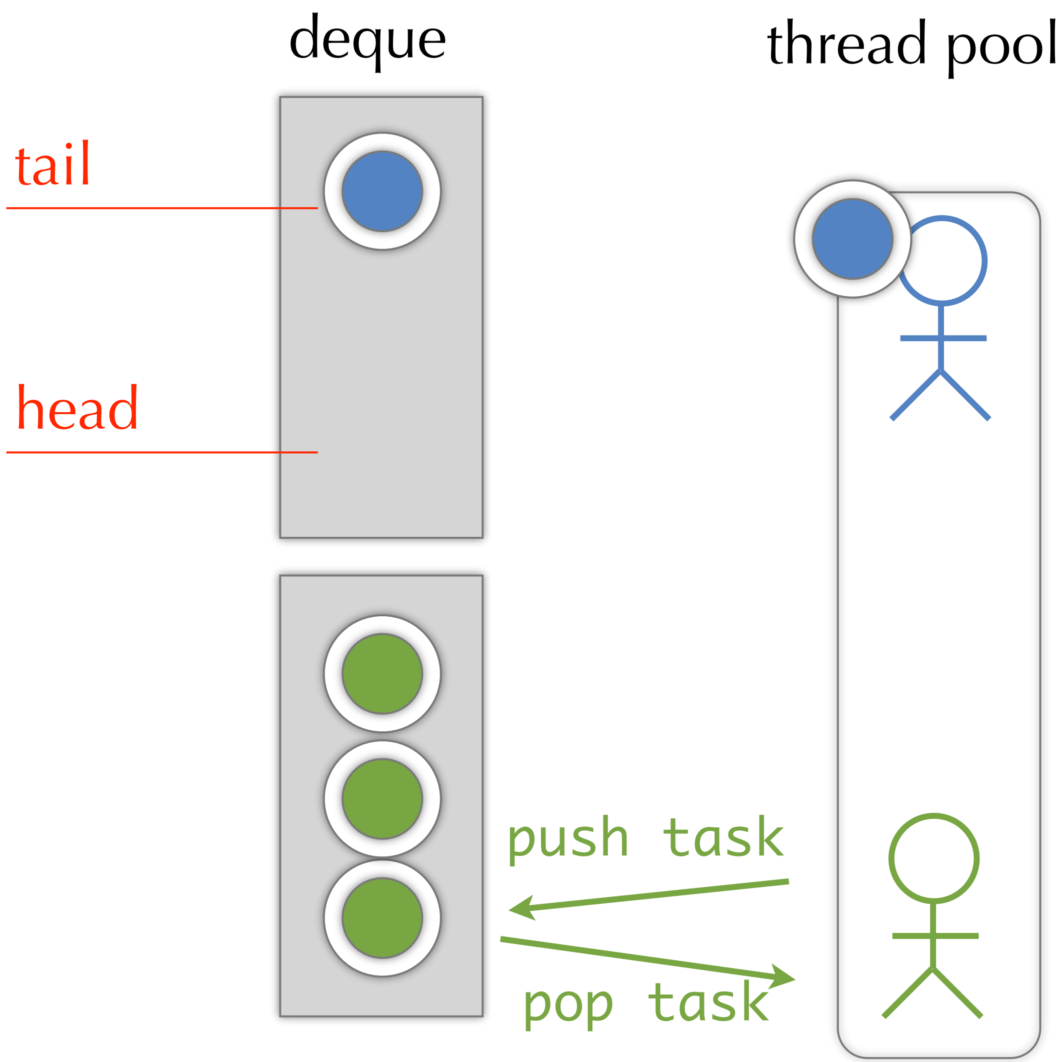
Thread scheduling



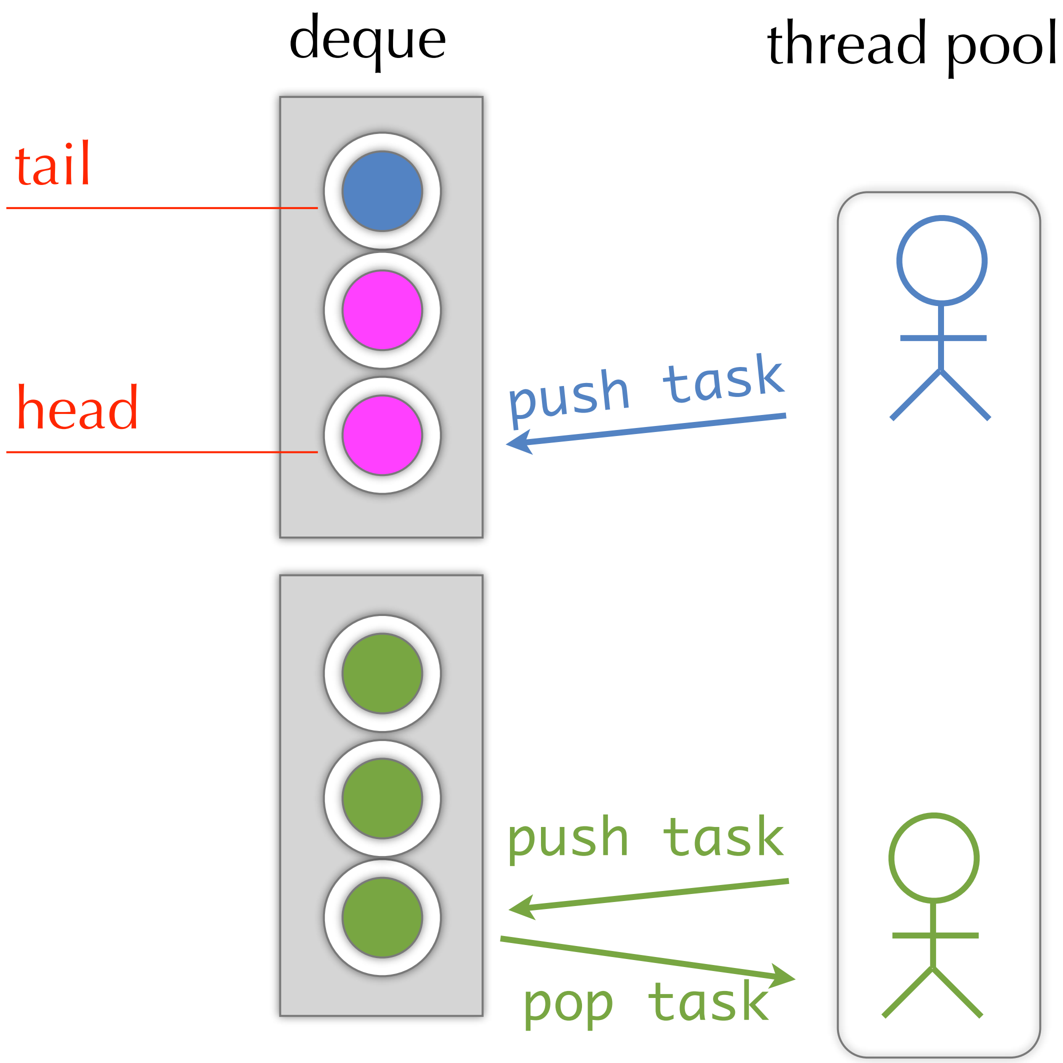
Thread scheduling



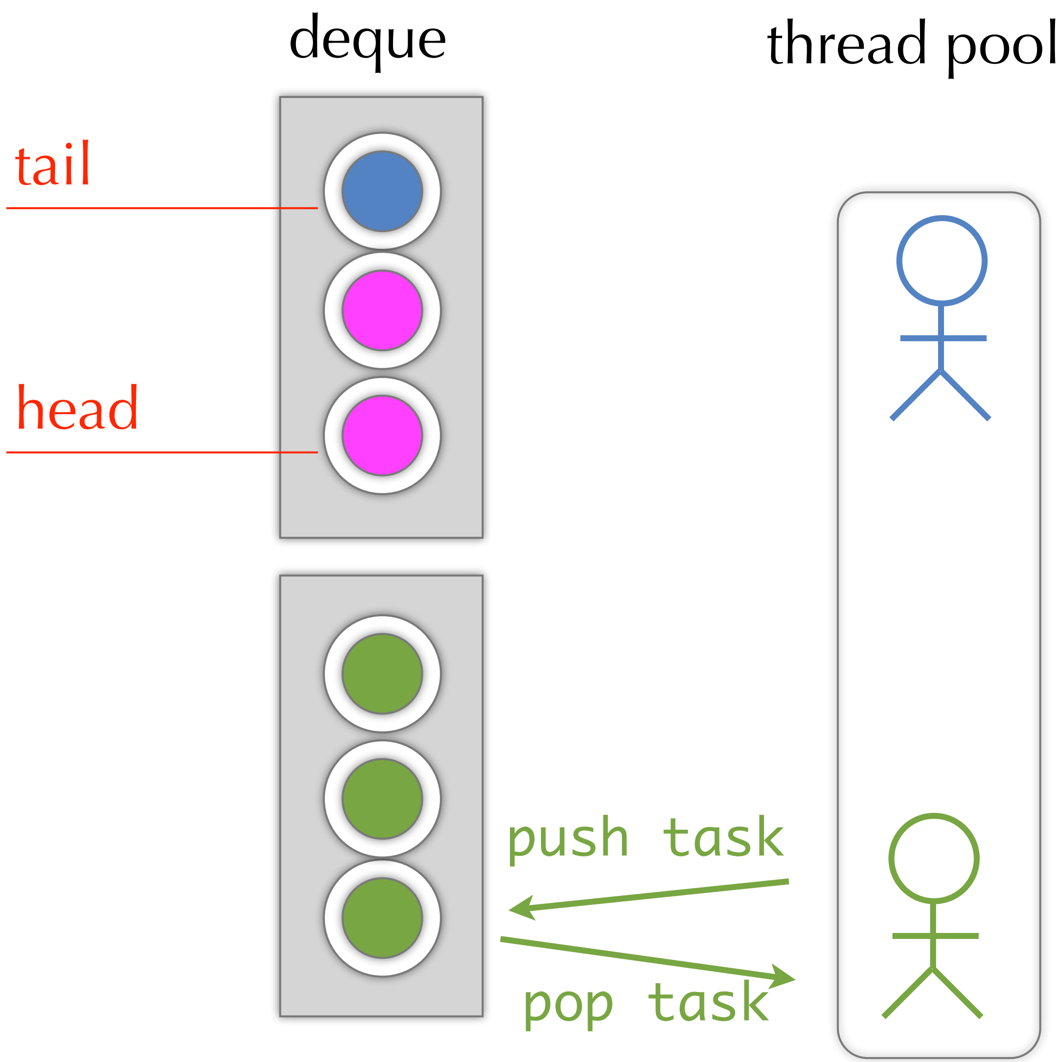
Thread scheduling



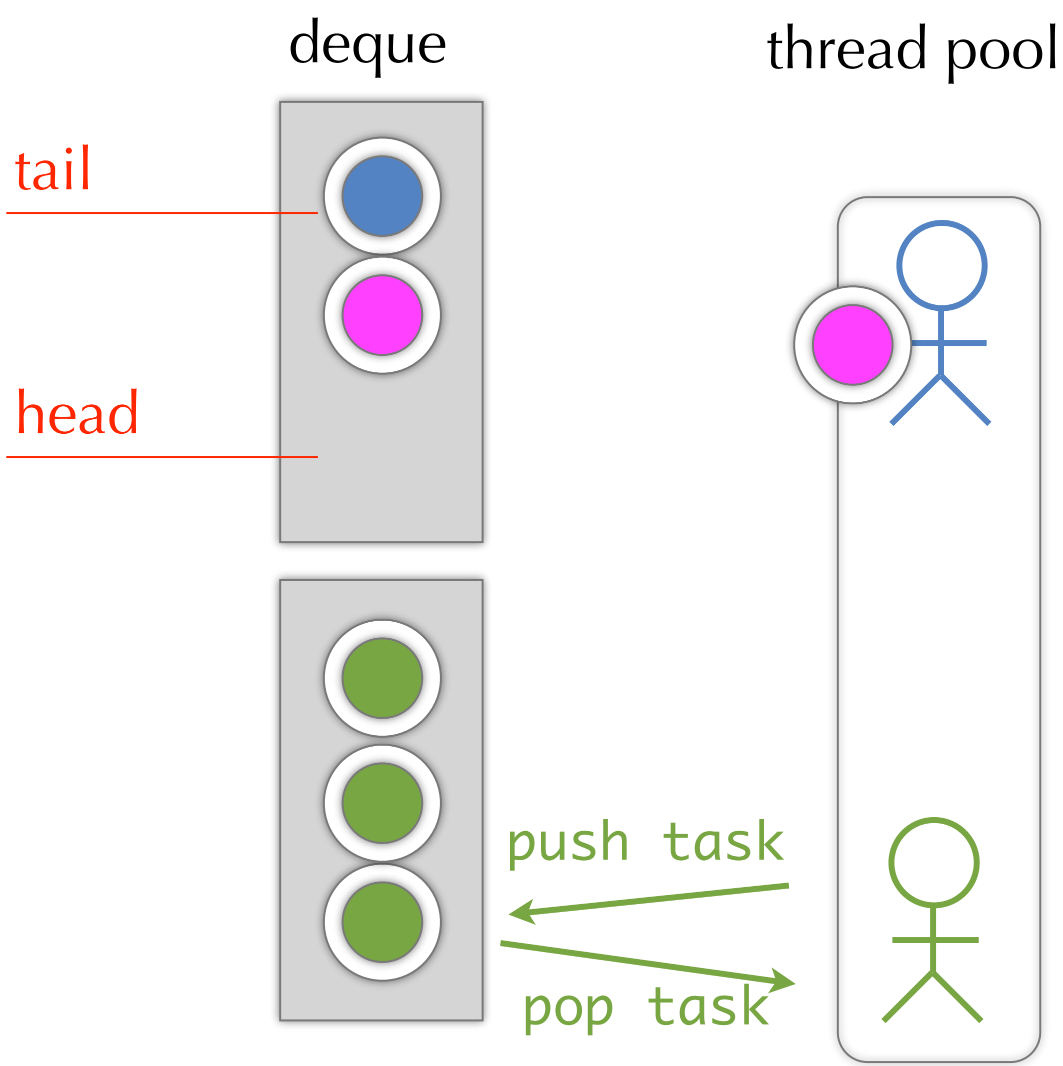
Thread scheduling



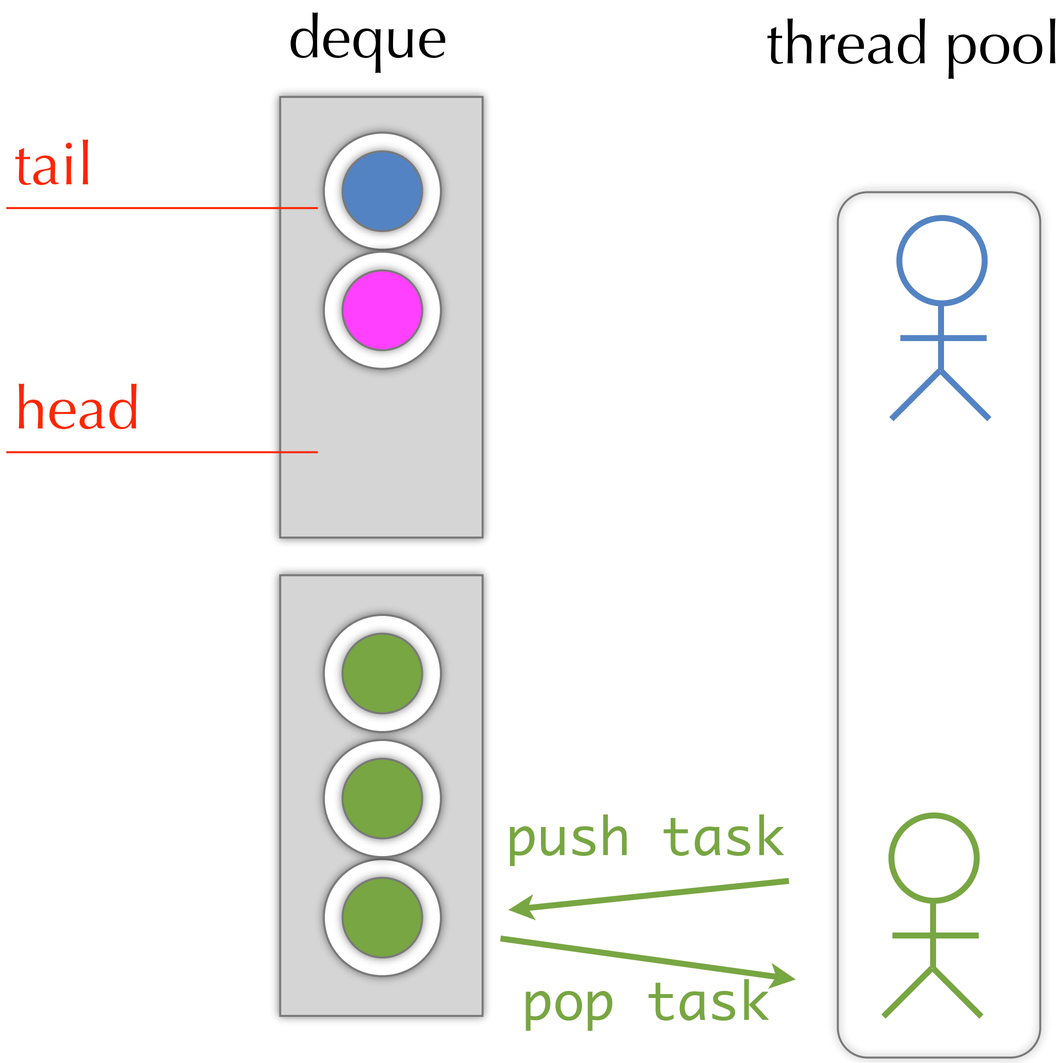
Thread scheduling



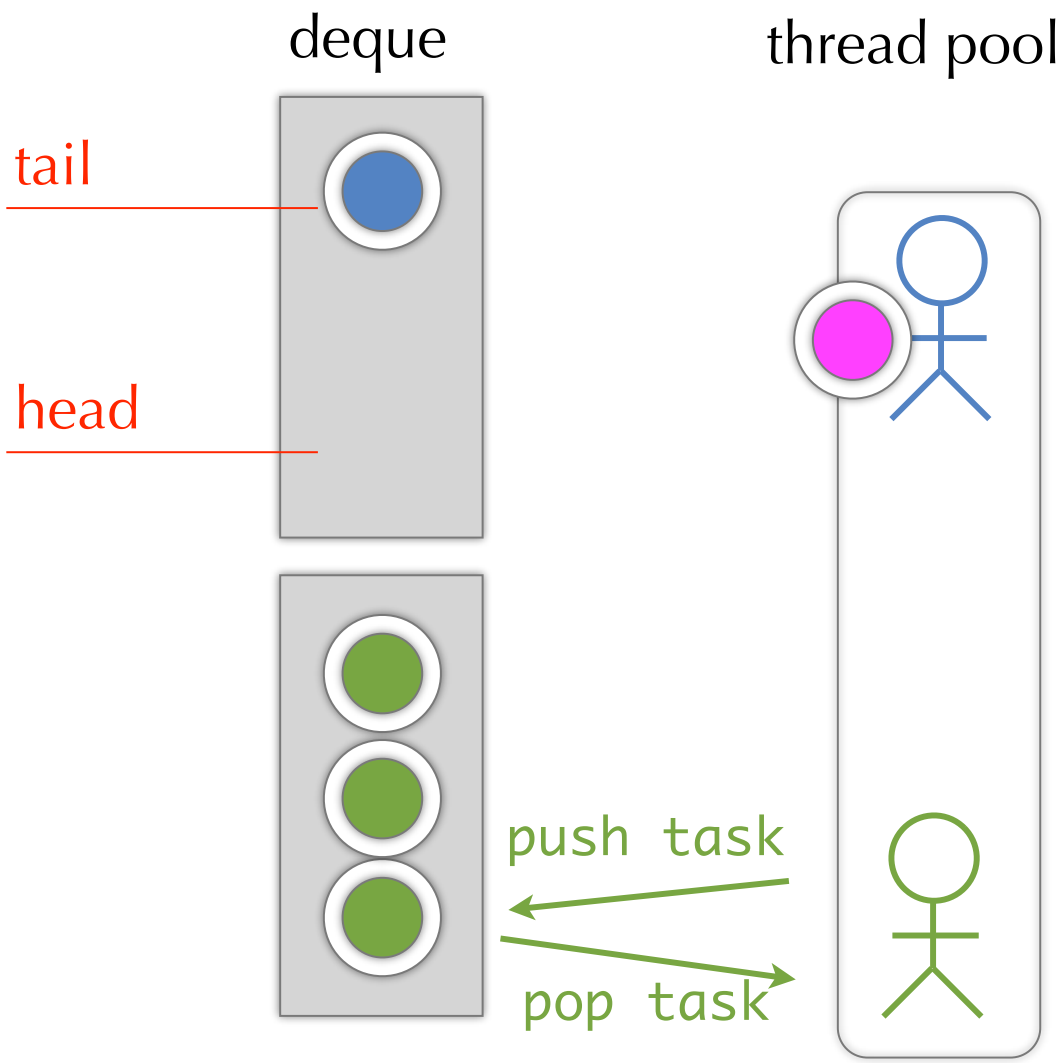
Thread scheduling



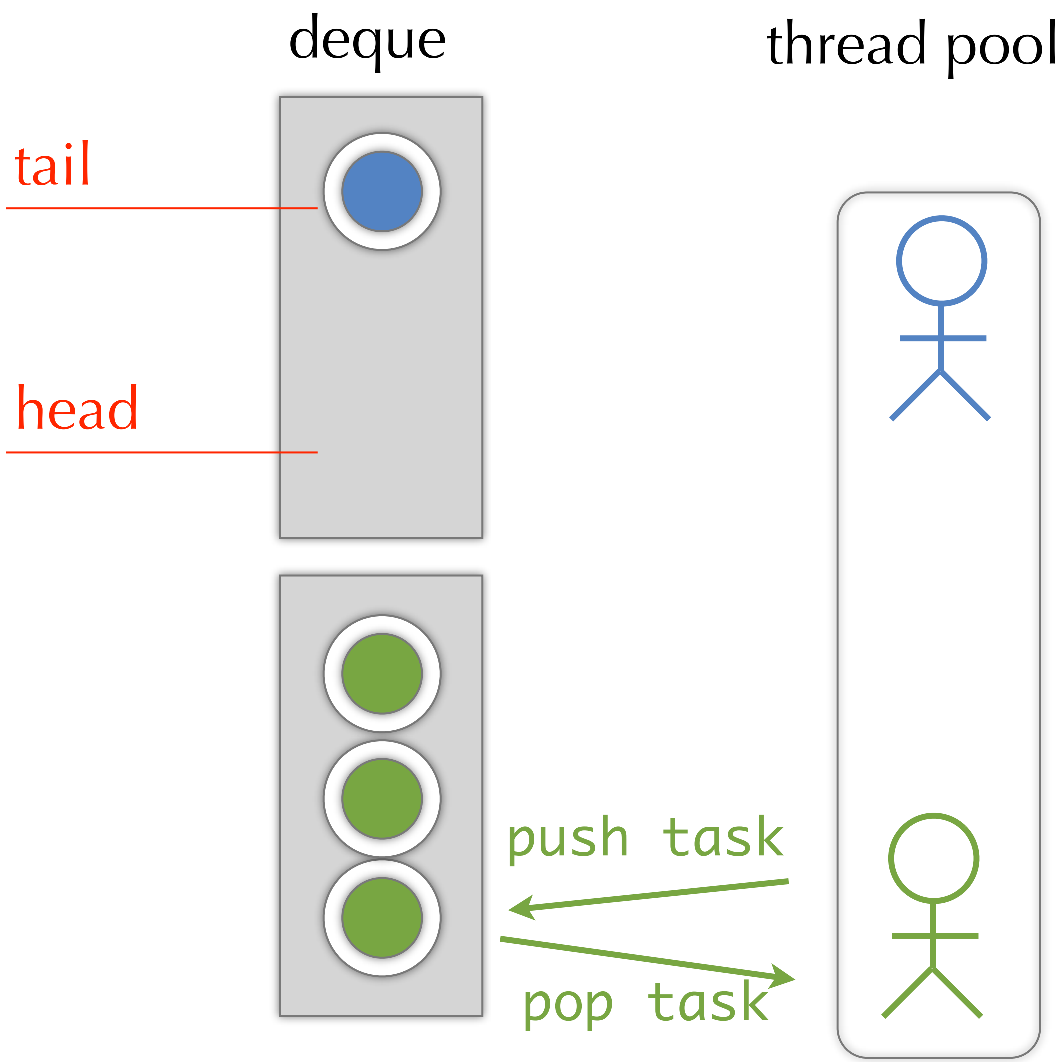
Thread scheduling



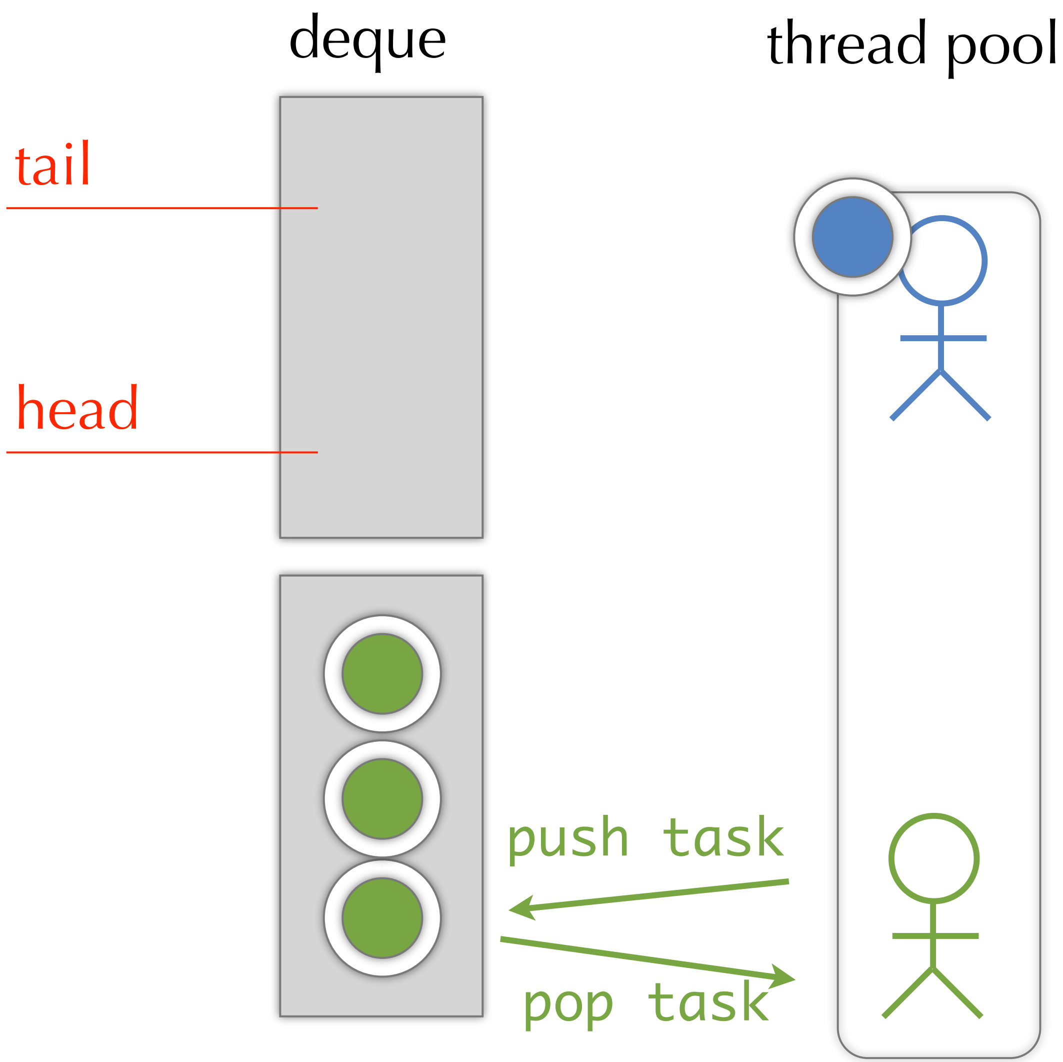
Thread scheduling



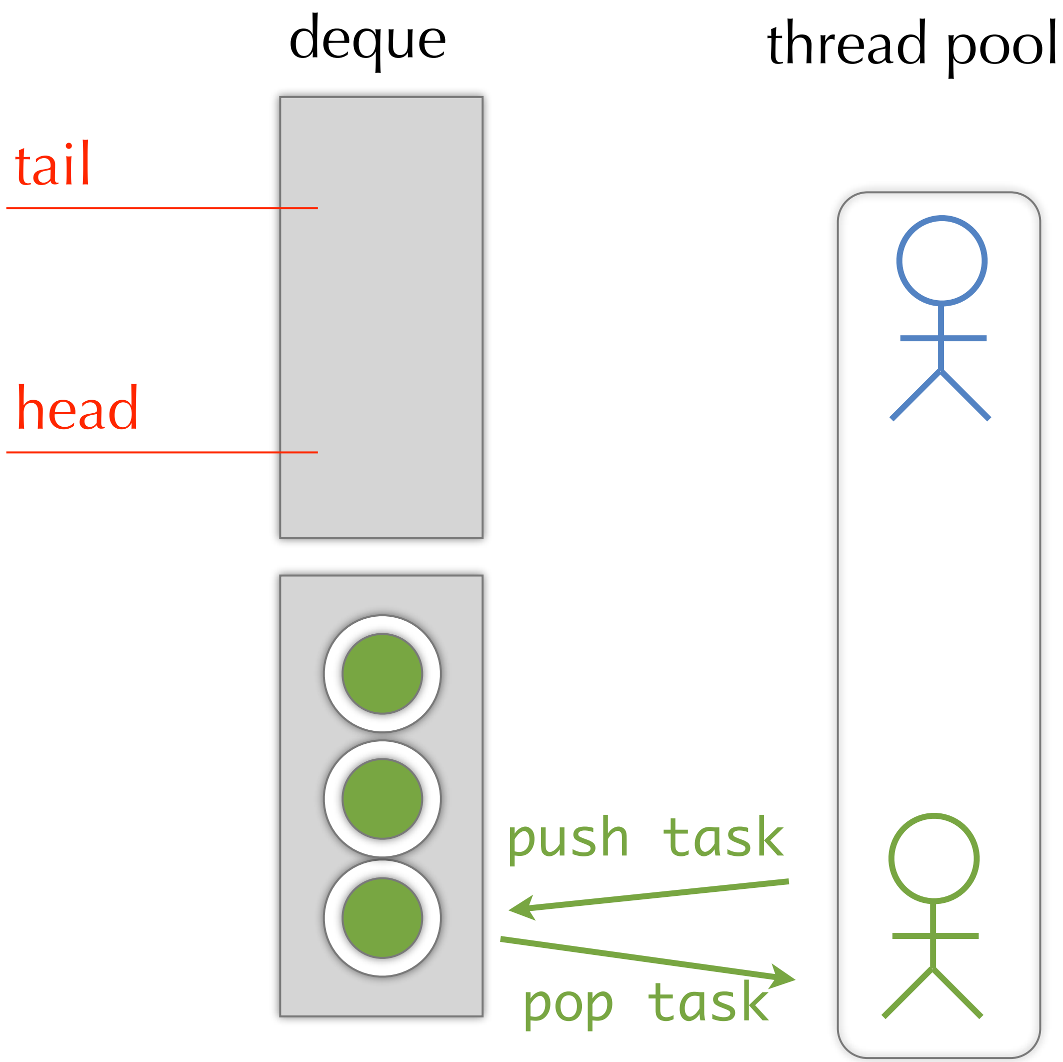
Thread scheduling



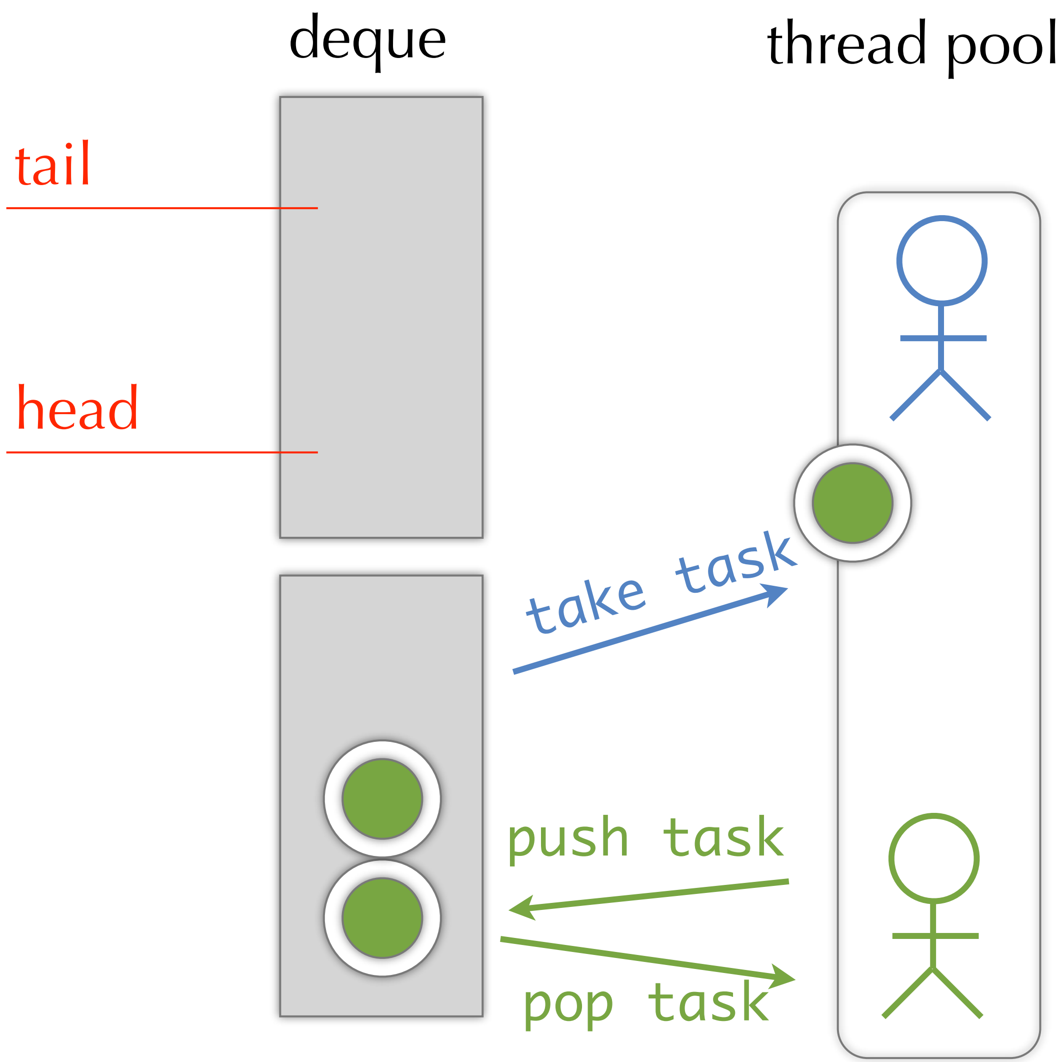
Thread scheduling



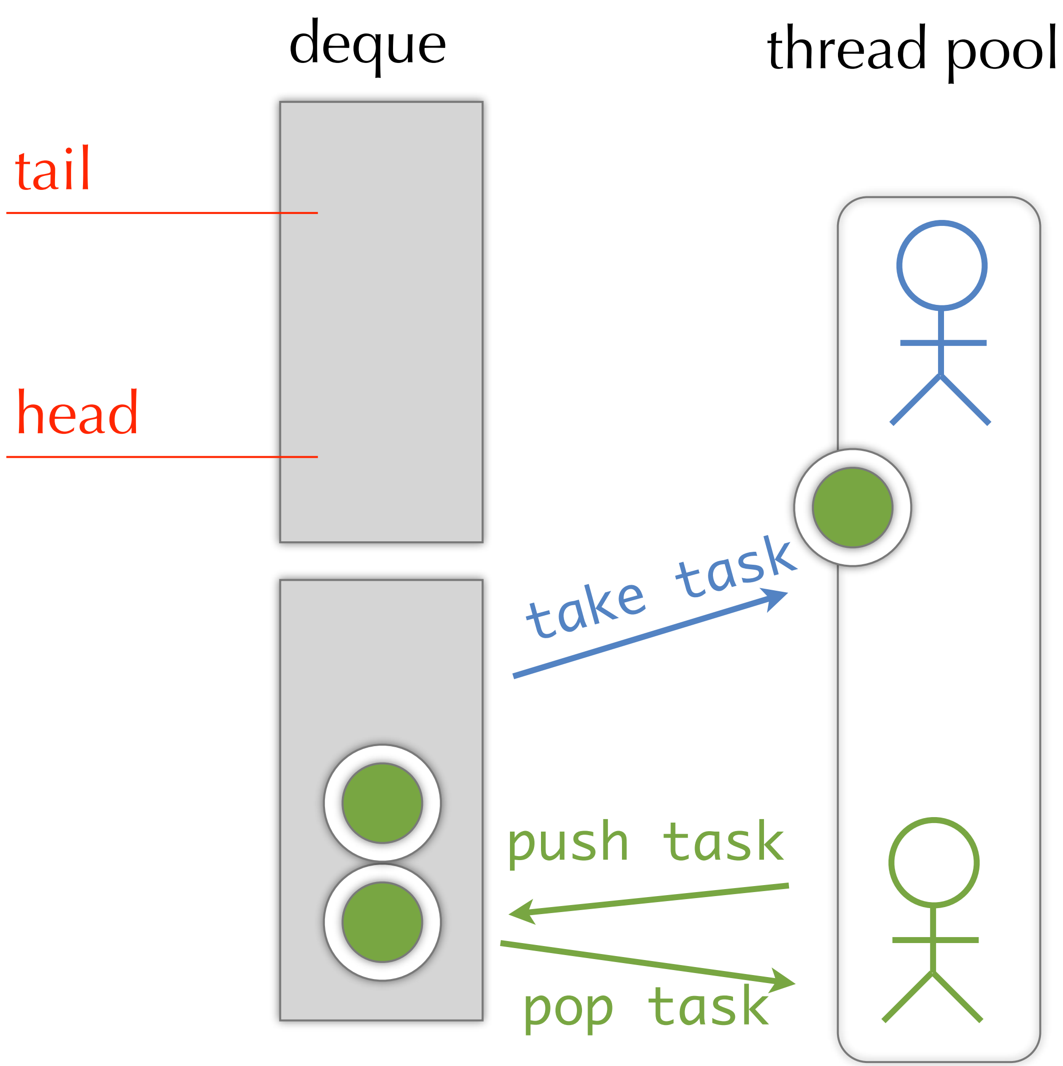
Thread scheduling



Thread scheduling



Thread scheduling



Double ended queues ("deck")

- LIFO for owner
- FIFO for other

Work stealing

- When no local tasks to run
- Steal task from other thread

On join operation

- Process other tasks

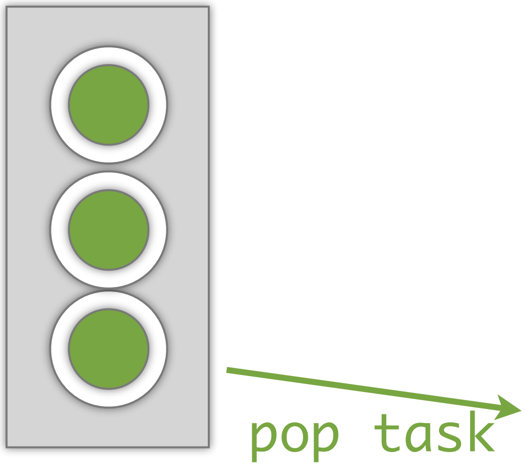
Advantages of work-stealing

Reduces contention

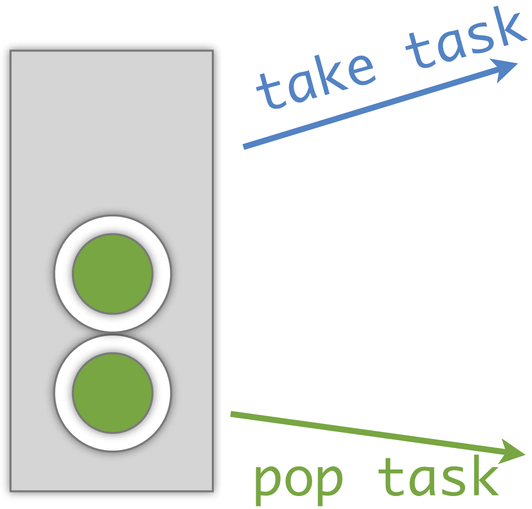
- Steal from opposite side of the deque as owner

Fits divide-and-conquer

- Generate large tasks early
- Older stolen task ⇒ large work unit ⇒ work decomposition
- #pop > #take



Advantages of work-stealing



Reduces contention

- Steal from opposite side of the deque as owner

Fits divide-and-conquer

- Generate large tasks early
- Older stolen task ⇒ large work unit ⇒ work decomposition
- #pop > #take

ForkJoinTask<V>

Lightweight form of Future<V> because of restrictions

Intended use as computational tasks

- Calculating pure functions (no side effects)
- Operating on purely isolated objects

Restrictions

- Avoid synchronized methods and blocks
- Minimize other blocking (except join)
  - No blocking IO
  - Access independent variables

Begins execution when submitted to a ForkJoinPool

- Once started, it will start other subtasks

`ForkJoinTask<V>`: Coordination mechanisms

`fork()`

- Arrange for asynchronous execution

Variants

- `invoke()`
  - Semantically: `fork(); join();`
  - Attempts to begin execution in current thread
- `invokeAll()`
  - Most common form: Fork a set of tasks and join them all

`join()`

- Do not proceed until the task's result has been computed

Variants

- `Future.get()`
  - Interruptible/timed waits
- `helpJoin()`
  - Actively execute other threads while waiting for completion

ForkJoinTask<V>: Queries

Execution status of tasks

- `isDone()`
- `isCompletedNormally()`
- `isCancelled()`

ForkJoinTask<V>: Usage

Use one of the subclasses

- RecursiveAction<V> = resultless
- RecursiveTask<V> = result-bearing

Declare fields

- Comprise parameters
- Established in constructor

Override compute()

- Use control/coordination methods

ForkJoinPool<V>: Overview

Extends

- AbstractExecutorService

Implements

- Executor, ExecutorService

Difference to other ExecutorServices

- Employs work-stealing

ForkJoinPool<V>: Queries

Status checking to help in tuning and debugging

- `getStealCount()`
  - Estimated number of stolen tasks
- `getActiveThreadCount()`
  - Estimated number of thread currently stealing or executing
- `getQueuedSubmissionCount()`
  - Estimated number of tasks submitted but not yet executed
- `getRunningThreadCount()`
  - Estimated number of threads that are not blocked

Howto use JSR166

Goto

- *http://gee.cs.oswego.edu/dl/concurrency-interest/index.html*

Use

- JSR166 maintenance updates

Compile with jar file included in classpath

- `export CLASSPATH=$CLASSPATH:<path to jar file>/jsr166.jar`

Execute

- `java -Xbootclasspath/p:<path to jar file>/jsr166.jar Main`