Multithreading and Concurrency

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Overview

Single threading vs. multithreading

Threading foundation types

Thread pools

Concurrency issues

Coordinating method access

Manual thread synchronization

Concurrency related types & packages

Threading and Concurrency Coverage

New to threading

Provide the building blocks you need to begin building your understanding of threading and concurrency

Experienced with threading

Provide the necessary understanding of Java threading and concurrency to enable you apply your existing knowledge in Java

A Quick Look at the Basics

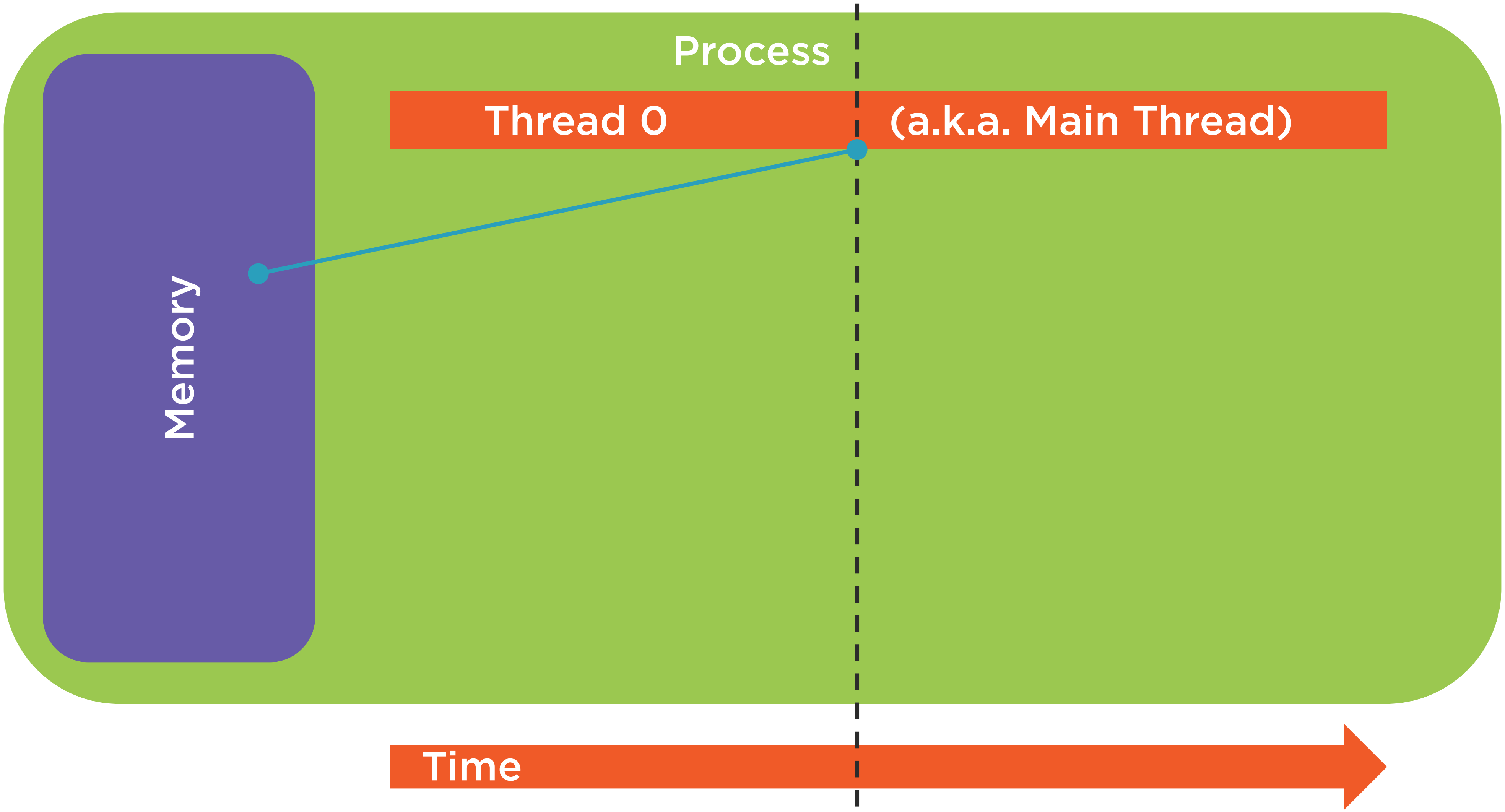
Process

- Instance of a program/application
- Has resources such as memory, etc.
- Has at least one thread

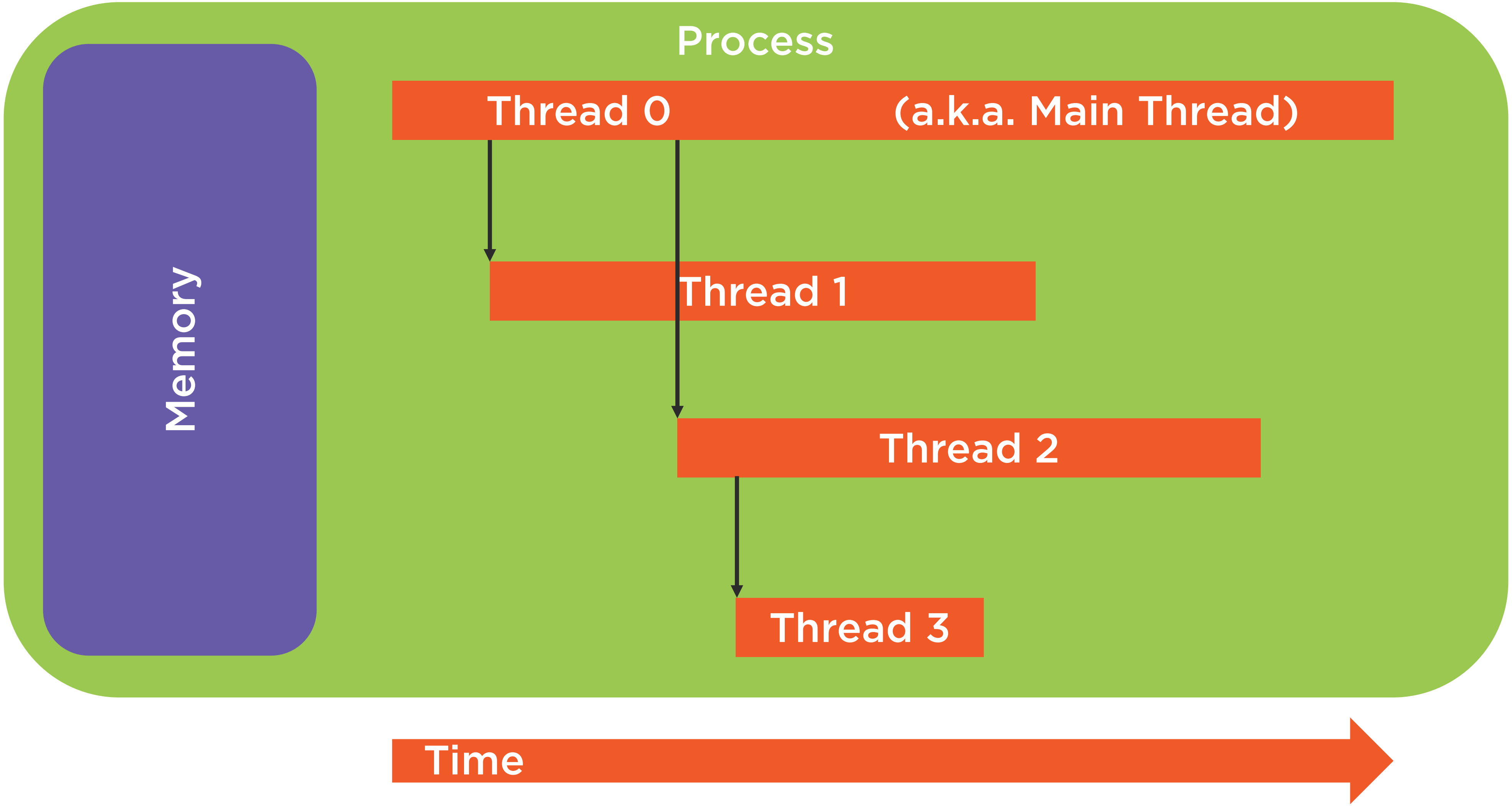
Thread

- Sequence of programmed instructions
- The thing that executes a program’s code
- Utilizes process resources

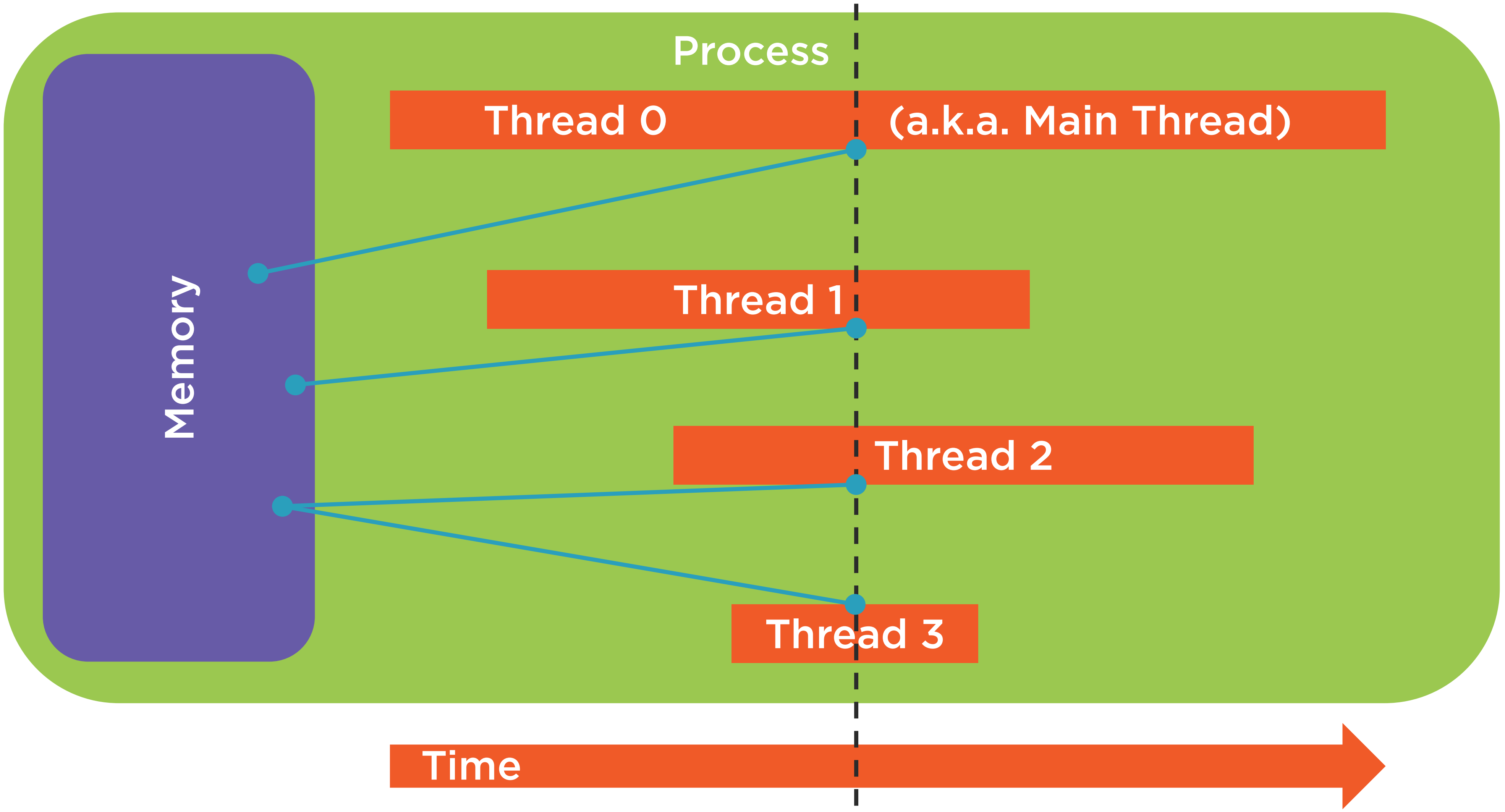
Single Threaded Process



Multithreading



Concurrency



The Case for Multithreading

Can enable more complete CPU use

- Threads often wait on non-CPU tasks
  - Interacting with storage, networks, etc.
- Most computers have multiple CPU cores
  - Allows things to run in parallel

Why does any of this matter?

- Can reduce perceived execution times
  - Less wall-clock time passes

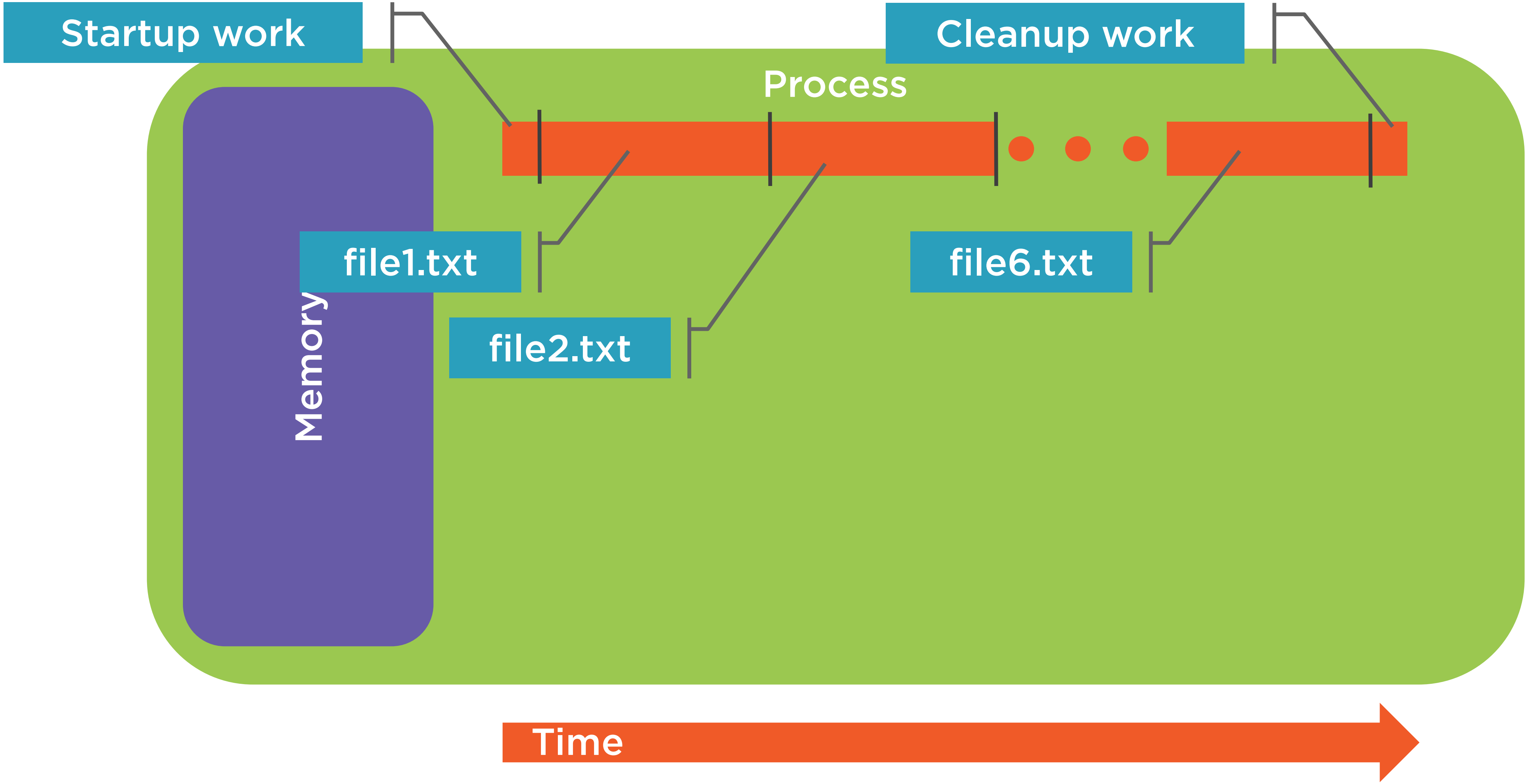
A Simple Adder Class

```
class Adder {
 private String inFile, outFile;
 public Adder(String inFile, String outFile) { /* assign filenames to member fields */ }

 public void doAdd()          throws IOException {
  int total = 0;
  String line = null;

  try (BufferedReader reader = Files.newBufferedReader(Paths.get(inFile))) {
   while ((line = reader.readLine()) != null)
    total += Integer.parseInt(inline);
  }

  try (BufferedWriter writer = Files.newBufferedWriter(Paths.get(outFile))) {
   writer.write("Total: " + total);
  }
 }
}
```

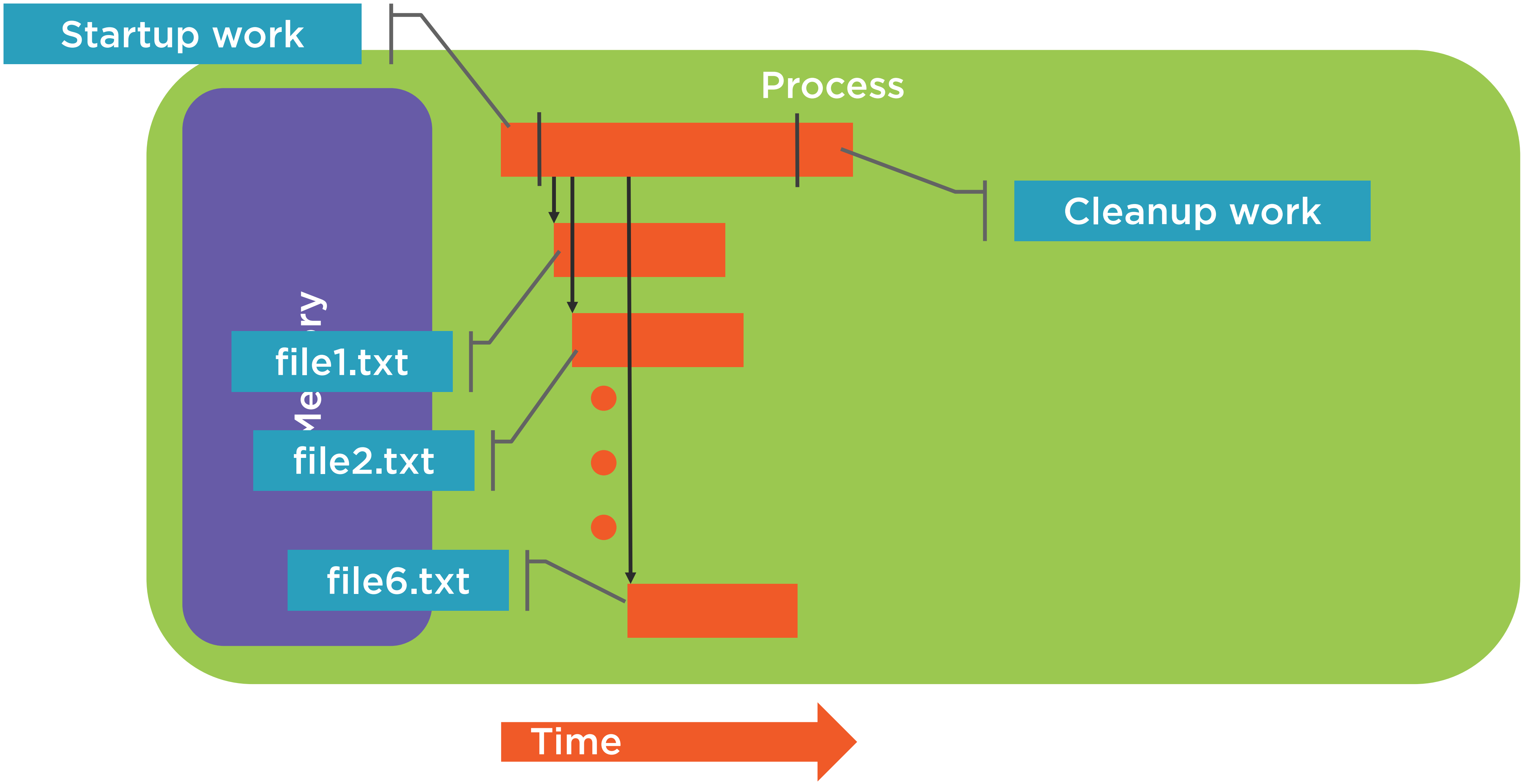
Using Simple Adder Class

```
String[] inFiles = {“./file1.txt”, . . . “./file6.txt”};
String[] outFiles = {“./file1.out.txt”, . . . “./file6.out.txt”};

try {
  for(int i=0; i < inFiles.length; i++) {
    Adder adder = new Adder(inFiles[i], outFiles[i]);
    adder.doAdd();

  }

} catch(IOException e) {

  // do something

}
```

Processing on a Single Thread



Processing on Multiple Threads



The Move to Multithreading

Multithreading is an explicit choice

- Must break the problem into parts
- Must handoff the parts for processing

Java provides differing levels of abstraction

- Supports very direct handling
  - Manual creation & coordination
- Supports higher level handling
  - Simplified creation & coordination

Java Threading Foundation

Limited threading abstraction

- Very close to the standard OS behavior
- Each thread started for a specific task
  - Terminates at end of task

Requires explicit management

- Responsible to manage coordination

Exceptions tied to thread

- Each thread must handle own exceptions

Threading Foundation Types

Runnable interface

- Represents a task to be run on a thread
- Only member is the run method

Thread class

- Represents a thread of execution
- Can interact with and effect thread state
- Begin execution with start method

Adder with Threading Support

```
class Adder      {implements Runnable {
  private String inFile, outFile;
  public Adder(String inFile, String outFile) { . . . }
  public void doAdd() throws IOException { . . . }
  public void run() {
    try {
      doAdd();
    } catch(IOException e) { . . . }
  }
}
```

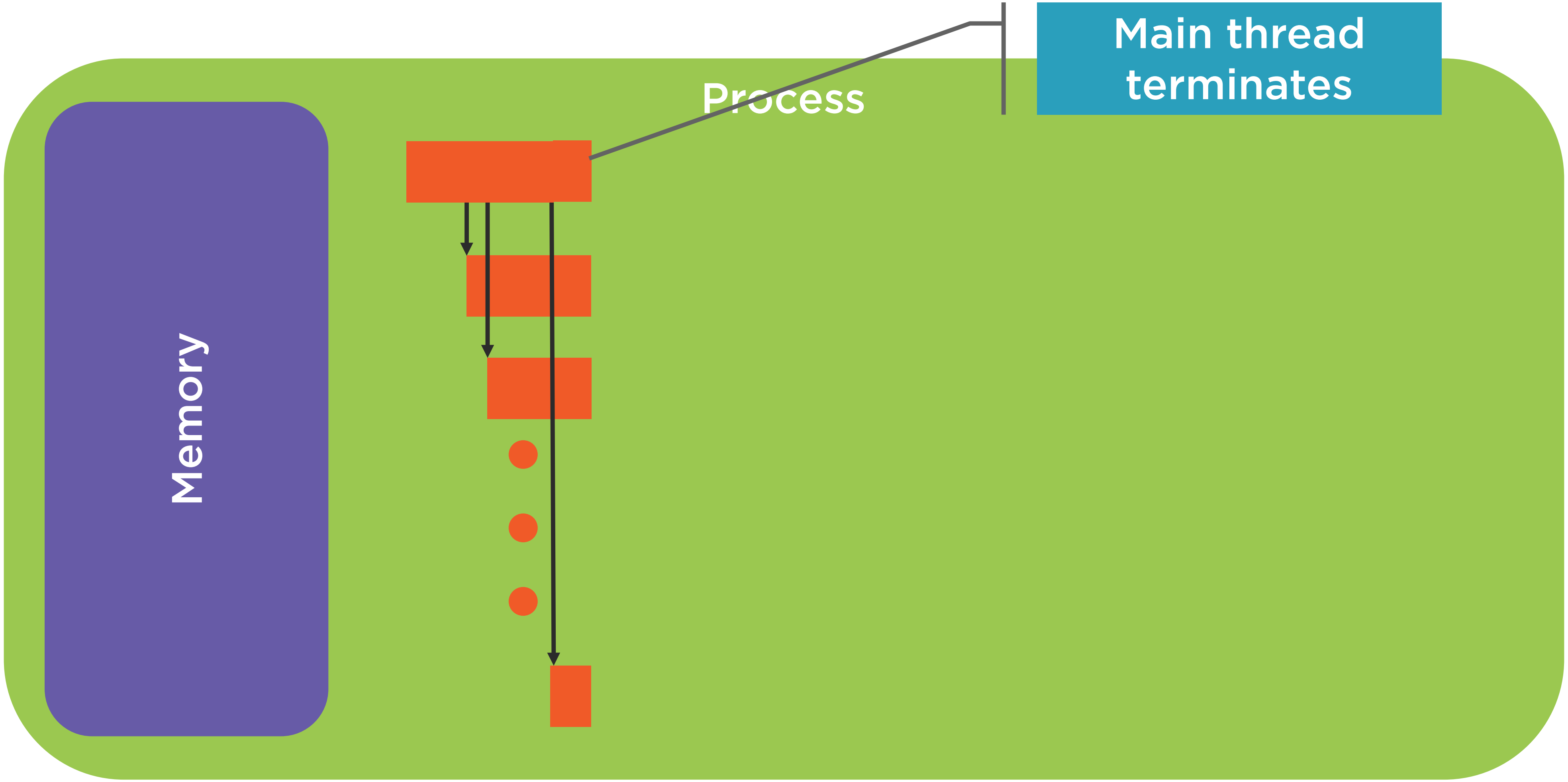
Running Adder on Separate Threads

```
String[] inFiles = {“./file1.txt”, . . . “./file6.txt”};
String[] outFiles = {“./file1.out.txt”, . . . “./file6.out.txt”};
try {
  for(int i=0; i < inFiles.length; i++) {
    Adder adder = new Adder(inFiles[i], outFiles[i]);
    adder.doAdd();


  }
} catch(IOException e) {
  // do something
}
```

Running Adder on Separate Threads

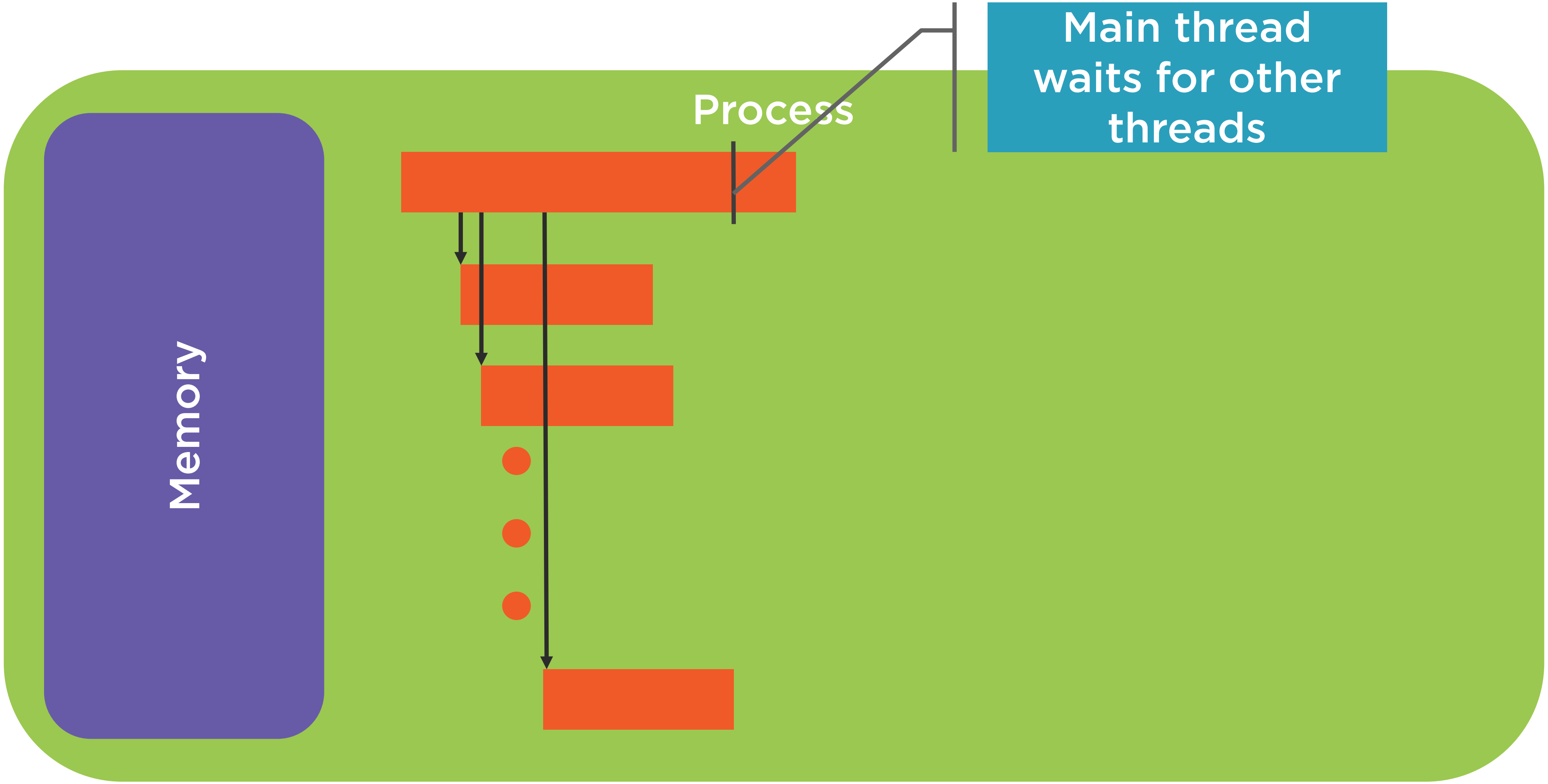
```
String[] inFiles = {“./file1.txt”, . . . “./file6.txt”};
String[] outFiles = {“./file1.out.txt”, . . . “./file6.out.txt”};
try {
  for(int i=0; i < inFiles.length; i++) {
    Adder adder = new Adder(inFiles[i], outFiles[i]);
    Thread thread = new Thread(adder);
    thread.start();
  }
} catch(IOException e) {
  // do something
}
```

Processing on Multiple Threads



Main thread terminates

Processing on Multiple Threads



Running Adder on Separate Threads

```
String[] inFiles = {“./file1.txt”, . . . “./file6.txt”};
String[] outFiles = {“./file1.out.txt”, . . . “./file6.out.txt”};
Thread[] threads = new Thread[inFiles.length];
for(int i=0; i < inFiles.length; i++) {
  Adder adder = new Adder(inFiles[i], outFiles[i]);
  Thread thread = new Thread(adder);
  thread.start();
}
```

Running Adder on Separate Threads

```
String[] inFiles = {“./file1.txt”, . . . “./file6.txt”};
String[] outFiles = {“./file1.out.txt”, . . . “./file6.out.txt”};
Thread[] threads = new Thread[inFiles.length];
for(int i=0; i < inFiles.length; i++) {
  Adder adder = new Adder(inFiles[i], outFiles[i]);
  threads[i] = new Thread(adder);
  threads[i].start();
}


for(Thread thread:threads)
  thread.join(); // Blocks waiting for thread completion
```

Thread Management Details

Value of the Thread class

- Allows direct control over thread startup, shutdown, & coordination

Challenge of the Thread class

- Responsible to efficiently manage thread startup, shutdown & coordination
- Easily misused

Abstracting Thread Management with Thread Pools

Java offers thread pools

- Creates a queue for tasks
- Assigns tasks into a pool of threads
- Handles details of managing threads

Thread Pool Types

ExecutorService interface

- Models thread pool behavior
- Can submit tasks
- Request and wait for pool shutdown

Executors class

- Methods for creating thread pools
  - Dynamically sized pools
  - Size limited pools
  - Pools that schedule tasks for later

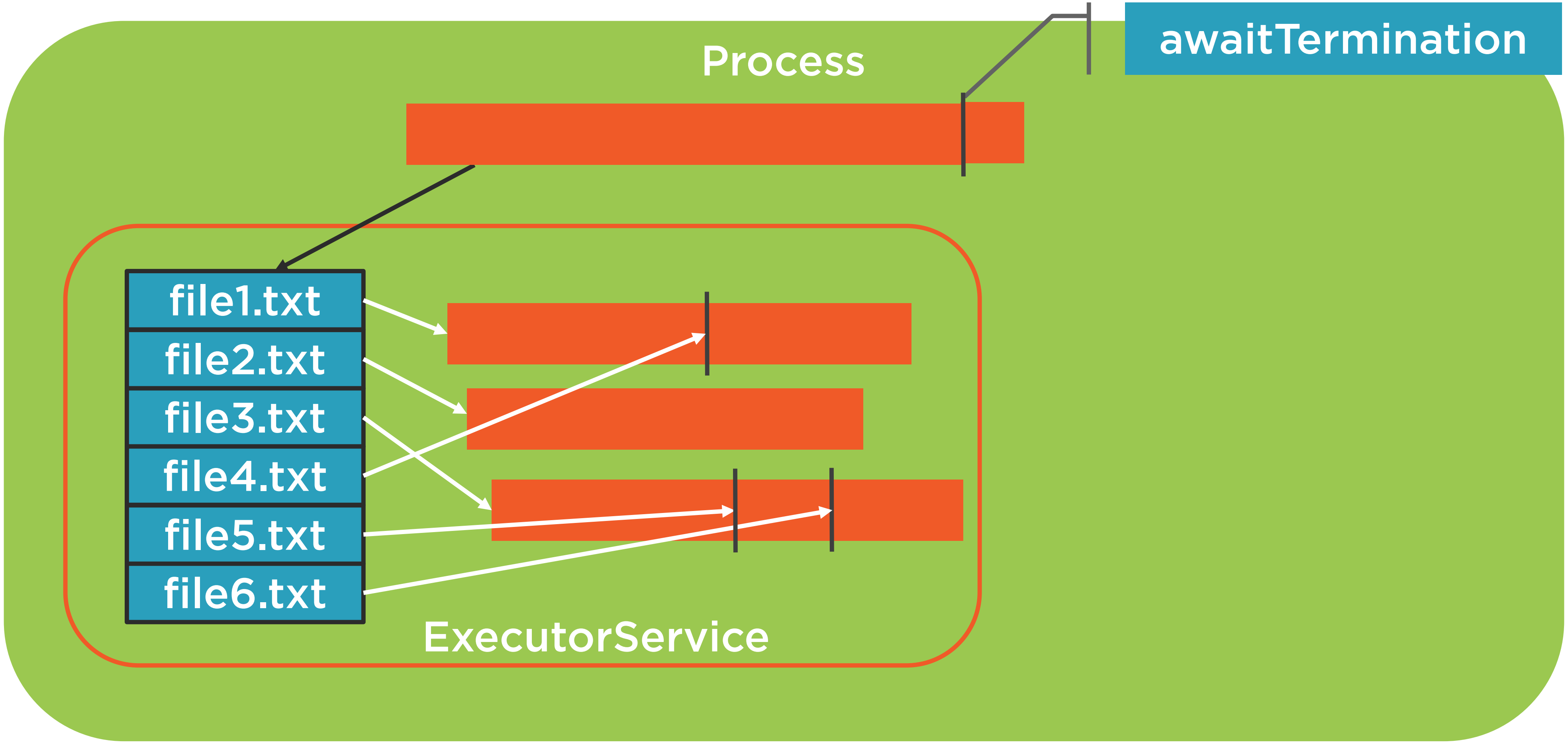
Running Adder on Separate Threads

```
String[] inFiles = {“./file1.txt”, . . . “./file6.txt”};
String[] outFiles = {“./file1.out.txt”, . . . “./file6.out.txt”};
Thread[] threads = new Thread[inFiles.length];
for(int i=0; i < inFiles.length; i++) {
  Adder adder = new Adder(inFiles[i], outFiles[i]);
  threads[i] = new Thread(adder);
  threads[i].start();
}
for(Thread thread:threads)
  thread.join(); // Blocks waiting for thread completion
```

Running Adder in a Thread Pool

```
String[] inFiles = {“./file1.txt”, . . . “./file6.txt”};
String[] outFiles = {“./file1.out.txt”, . . . “./file6.out.txt”};
ExecutorService es = Exec
for(int i=0; i < inFiles.length; i++) {
  Adder adder = new Adder(inFiles[i], outFiles[i]);
  es.submit(adder);


}
try {
  es.shutdown();
  es.awaitTermination(60, TimeUnit.SECONDS);
} catch(Exception e) { . . . }
```

Processing in a Thread Pool

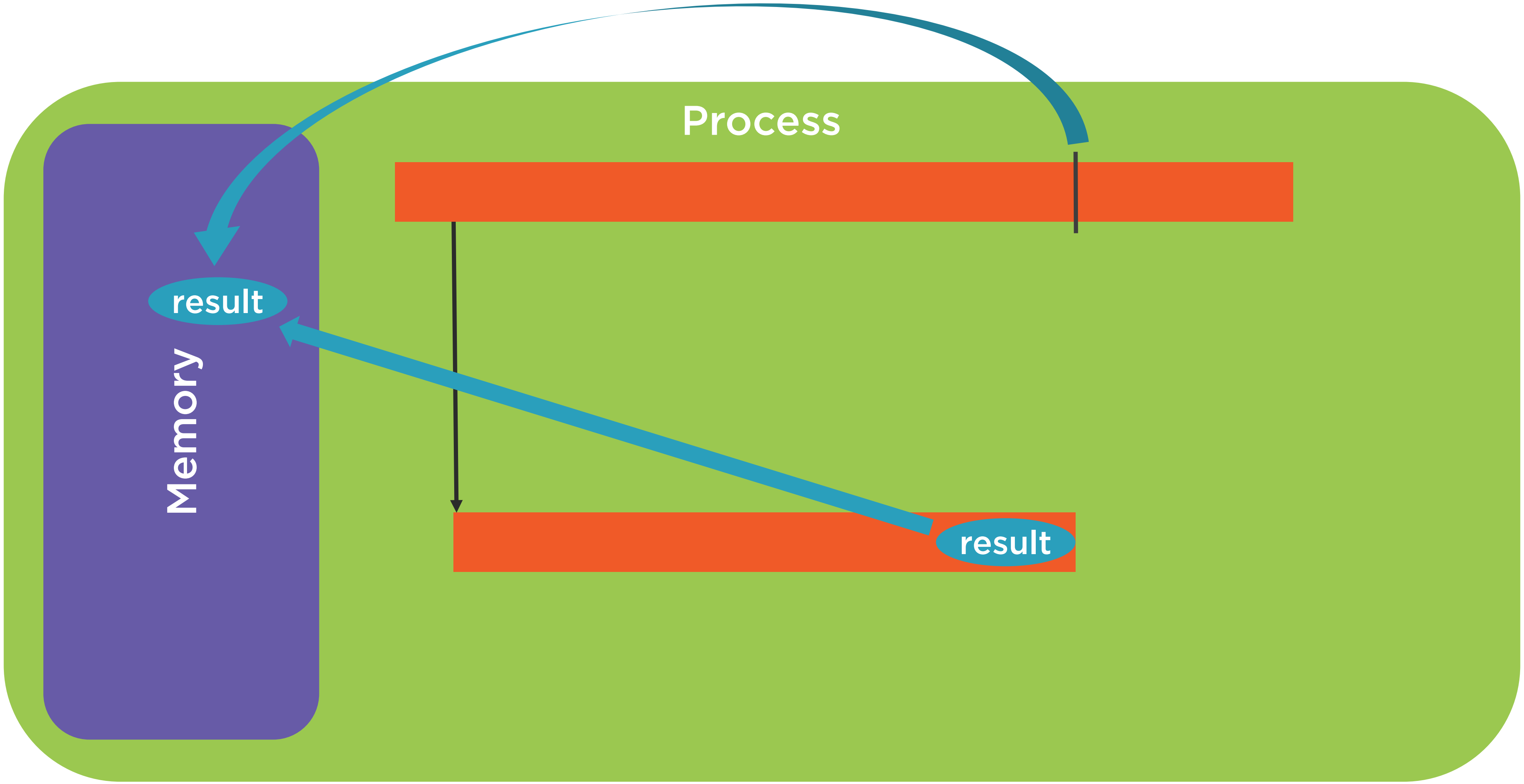


Creating a Closer Relationship Between Thread Tasks

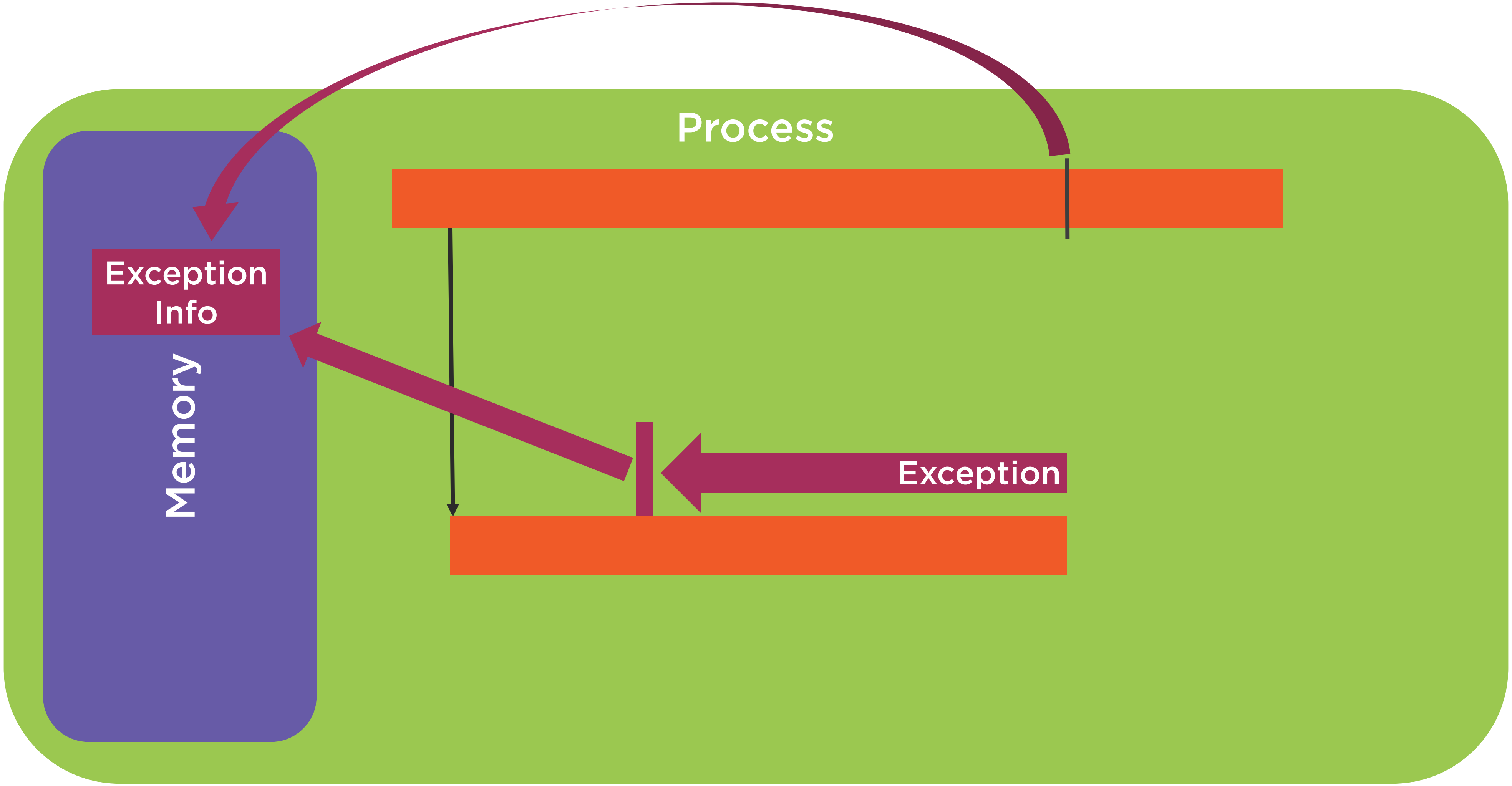
Multithreading not always loosely coupled

- Caller may need results from worker
- May need to know if task succeeded

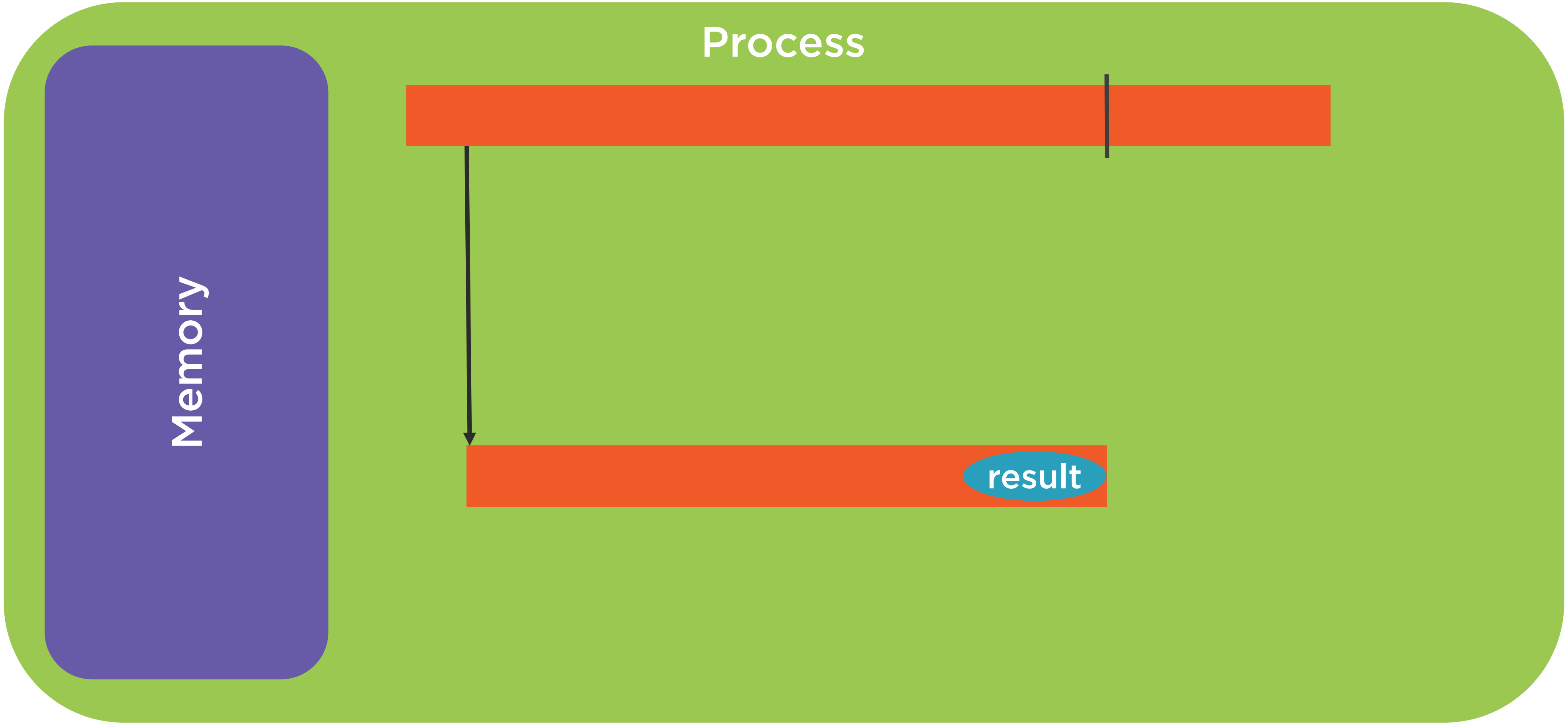
Thread Result Manual Handling



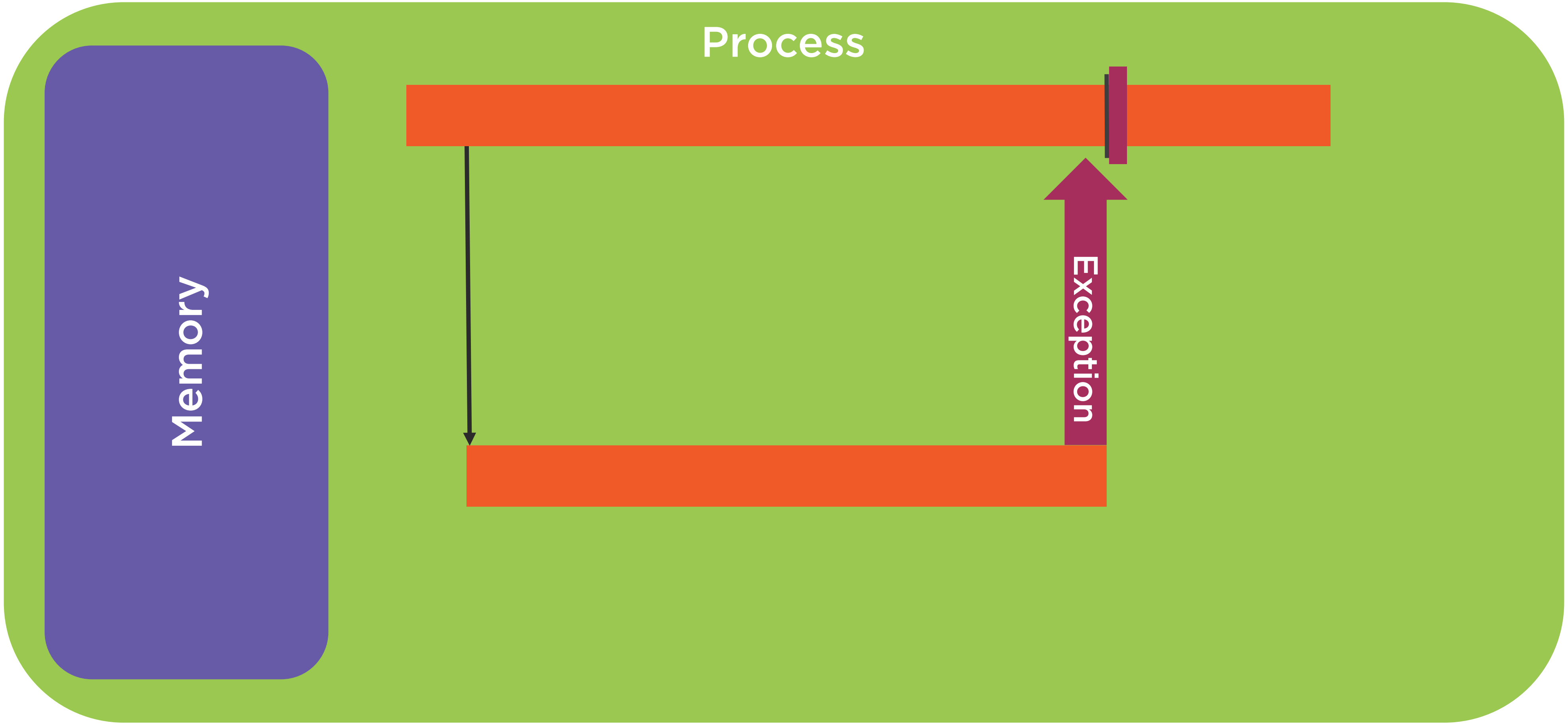
Thread Exception Manual Handling



Thread Result Handling Desired



Thread Exception Handling Desired



Threading Relationship Types

Callable interface

- Represents a task to be run on a thread
  - Can return results
  - Can throw exceptions
- Only member is the call method

Future interface

- Represents results a thread task
  - Returned by ExecutorService.submit
- The key method is get
  - Blocks until task completes
  - Returns Callable interface result
  - Throws Callable interface exception

Adder Method Returning a Value

```
public void doAdd() throws IOException
  int total = 0;
  String line = null;
  try (BufferedReader reader = Files.newBufferedReader(Paths.get(inFile))) {
    while ((line = reader.readLine()) != null)
      total += Integer.parseInt(inline);
  }
  try (BufferedWriter writer = Files.newBufferedWriter(Paths.get(outFile))) {
    writer.write(“Total: " + total);
  }
}
```

Adder Method Returning a Value

```
public      int     l() throws IOException
  int total = 0;
  String line = null;
  try (BufferedReader reader = Files.newBufferedReader(Paths.get(inFile))) {
    while ((line = reader.readLine()) != null)
      total += Integer.parseInt(inline);
  }
  try (BufferedWriter writer = Files.newBufferedWriter(Paths.get(outFile))) {
    writer.write(“Total: " + total);
  }
}
```

Adder Method Returning a Value

```
public      int     l() throws IOException
  int total = 0;
  String line = null;

  try (BufferedReader reader = Files.newBufferedReader(Paths.get(inFile))) {
    while ((line = reader.readLine()) != null)
      total += Integer.parseInt(inline);
  }


  return total;


}
```

Adder Implementing Callable

```
class Adder implements          Runnable {
  private String inFile;
  public Adder(String inFile) { . . . }
  public int doAdd() throws IOException { . . . }
  public       void    run() {
    try {
         doAdd();
    } catch(IOException e) { . . . }
  }
}
```

Adder Implementing Callable

```
class Adder implements          Runnable {   <Integer> {
  private String inFile;
  public Adder(String inFile) { . . . }

  public int doAdd() throws IOException { . . . }

  public      Integer     call()       throws IOException {


           return doAdd();


  }
}
```

Start Adder Processing

```
String[] inFiles = {“./file1.txt”, . . . “./file6.txt”};
ExecutorService es = Executors.newFixedThreadPool(3);

for(int i=0; i < inFiles.length; i++) {
  Adder adder = new Adder(inFiles[i]);
    es.submit(adder);
}
```

Start Adder Processing

```
String[] inFiles = {"./file1.txt", . . . "./file6.txt"};
ExecutorService es = Executors.newFixedThreadPool(3);
Future<Integer>[] results = new Future[inFiles.length];
for(int i=0; i < inFiles.length; i++) {
  Adder adder = new Adder(inFiles[i]);
    results[i]          = es.submit(adder);
}
```

Retrieving Adder Class Results

```
for(Future<Integer> result:results) {
  try {
    int value = result.get(); // blocks until return value available
    System.out.println(“Total: “ + value);
  } catch(ExecutionException e) { // Exception raised in Adder
    Throwable adderEx = e.getCause(); // Get the Adder exception
    // Do something with adderEx
  } catch(Exception e) { . . . } // Non-Adder exceptions
}
es.shutdown();
```

Concurrency Issues

The challenge of concurrency

- Threads sometimes share resources
- No problem if resources only read
- Changes must be coordinated

Failure to coordinate can create problems

- Receive wrong results
- Crash the program

A Simple Bank Account Class

```
public class BankAccount {
  private int balance;
  public BankAccount(int startBalance) {
    balance = startBalance;
  }

  public int getBalance() {
    return balance;
  }

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

A Class to Update the Bank Account

```
public class Worker implements Runnable {
  private BankAccount account;
  public Worker(BankAccount account) {
    this.account = account;
  }
  public void run() {
    for(int i=0; i < 10; i++) {
      int startBalance = account.getBalance();
      account.deposit(10);
      int endBalance = account.getBalance();
    }
  }
}
```

Running on a Single Thread

```
ExecutorService es = Executors.newFixedThreadPool(5);
BankAccount account = new BankAccount(100);

  Worker worker = new Worker(account);
  es.submit(worker);

// Shutdown es and wait
```

```
End Balance: 110  StartBalance: 100
End Balance: 120  StartBalance: 110
End Balance: 130  StartBalance: 120
End Balance: 140  StartBalance: 130
End Balance: 150  StartBalance: 140
End Balance: 160  StartBalance: 150
End Balance: 170  StartBalance: 160
End Balance: 180  StartBalance: 170
End Balance: 190  StartBalance: 180
End Balance: 200  StartBalance: 190
```

Running on Multiple Threads

```
ExecutorService es = Executors.newFixedThreadPool(5);
BankAccount account = new BankAccount(100);
for(int i = 0; i < 5; i++) {
  Worker worker = new Worker(account);
  es.submit(worker);
}
// Shutdown es and wait
```

1 Thread vs. 5 Threads

$$100 \qquad \underbrace{+10 \quad +10 \quad +10 \quad +10 \quad +10 \quad +10 \quad +10 \quad +10 \quad +10 \quad +10}_{\text{1 Thread}} \quad = 200$$

$$100 \qquad \underbrace{\begin{matrix} +10 & +10 & +10 & +10 & +10 & +10 & +10 & +10 & +10 & +10 \\ +10 & +10 & +10 & +10 & +10 & +10 & +10 & +10 & +10 & +10 \\ +10 & +10 & +10 & +10 & +10 & +10 & +10 & +10 & +10 & +10 \\ +10 & +10 & +10 & +10 & +10 & +10 & +10 & +10 & +10 & +10 \\ +10 & +10 & +10 & +10 & +10 & +10 & +10 & +10 & +10 & +10 \end{matrix}}_{\text{5 Threads}} \quad = \cancel{6\text{[illegible]}0} \quad \cancel{5\text{[illegible]}0} \quad \cancel{5\text{[illegible]}0} \quad \cancel{5\text{[illegible]}0}$$

?

What Happened on the 5 Threads

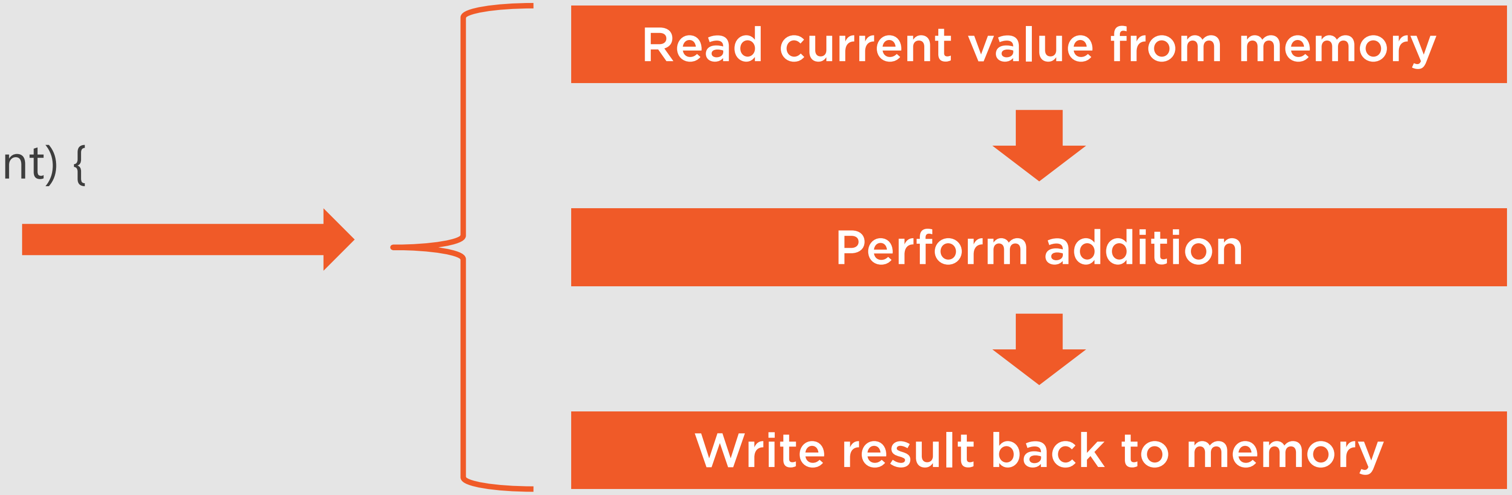
```
End Balance: 110  Start Balance: 100  Worker: 1
End Balance: 120  Start Balance: 110  Worker: 2
End Balance: 130  Start Balance: 120  Worker: 3
End Balance: 140  Start Balance: 130  Worker: 4
End Balance: 150  Start Balance: 140  Worker: 5
End Balance: 160  Start Balance: 150  Worker: 5
End Balance: 170  Start Balance: 160  Worker: 3
End Balance: 170  Start Balance: 160  Worker: 2
```

⋮

```
End Balance: 510  Start Balance: 500  Worker: 4
End Balance: 520  Start Balance: 510  Worker: 5
End Balance: 520  Start Balance: 510  Worker: 1
End Balance: 530  Start Balance: 520  Worker: 2
End Balance: 540  Start Balance: 530  Worker: 3
End Balance: 550  Start Balance: 540  Worker: 3
```

There’s More Than Meets the Eye

```
public class BankAccount {
  private int balance;
  public BankAccount(int startBalance) {
    balance = startBalance;
  }

  public int getBalance() {
    return balance;
  }

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

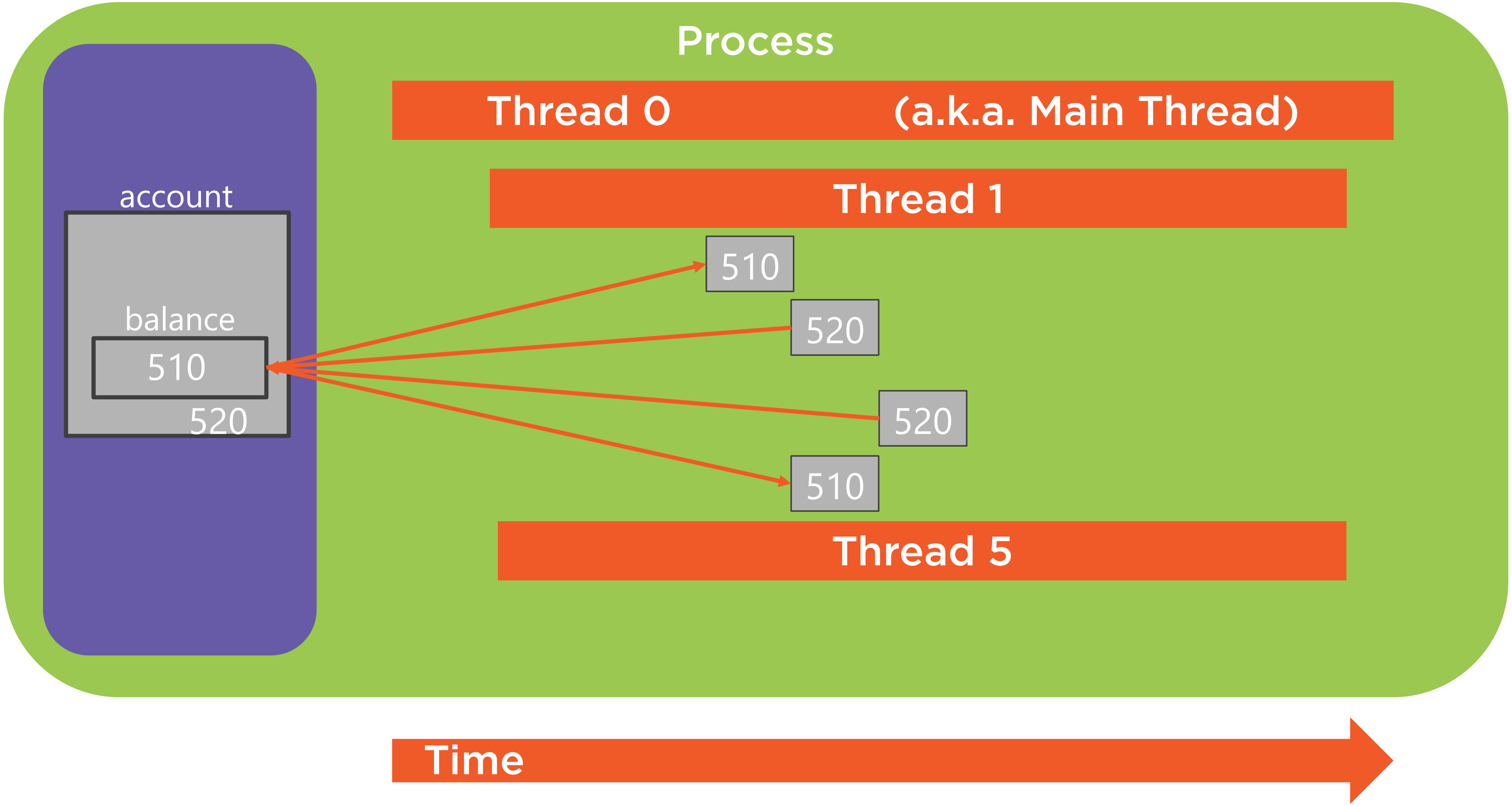


Read current value from memory

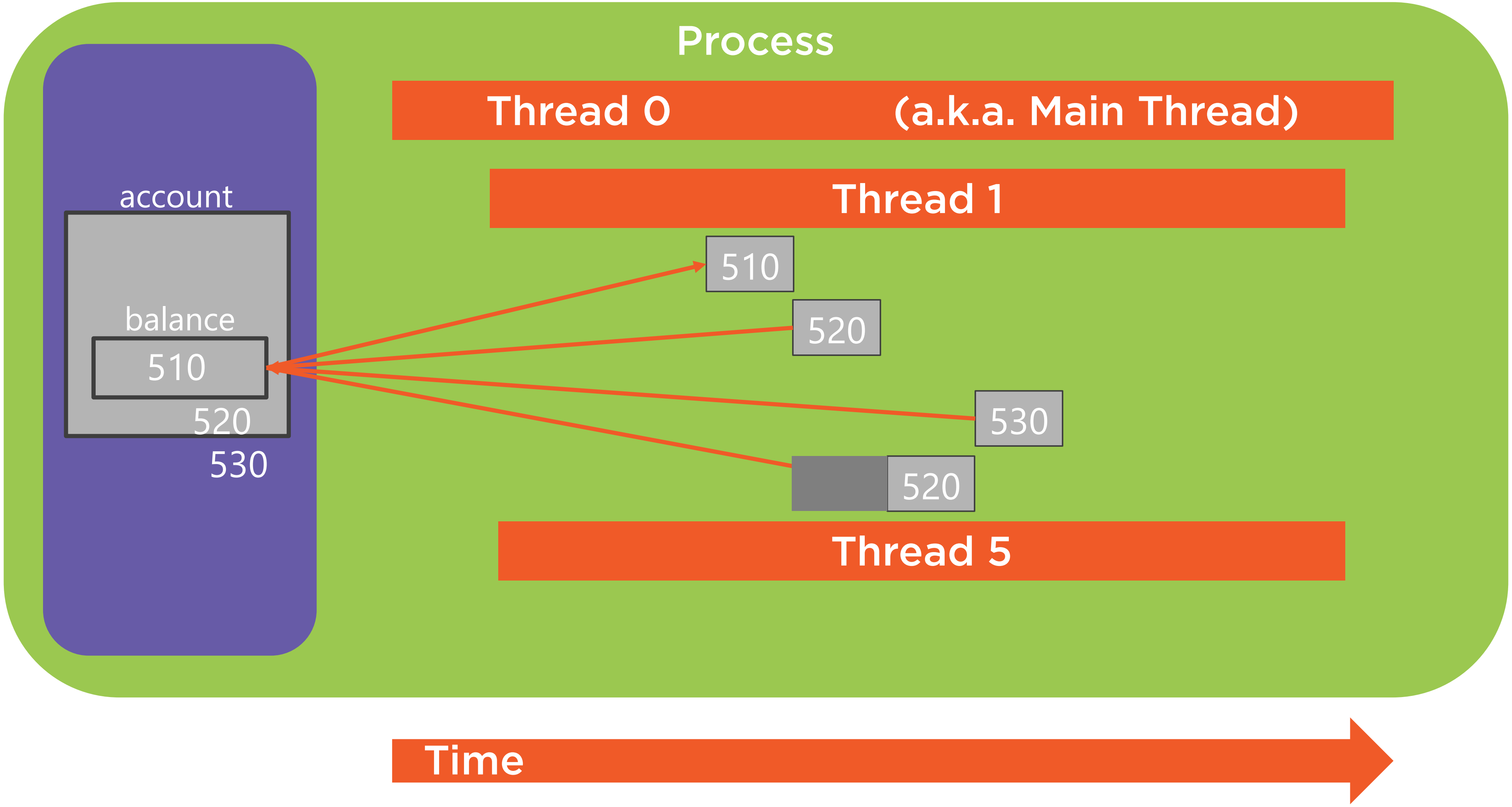
Perform addition

Write result back to memory

Unprotected Concurrency



Coordinated Concurrency



Coordinating Method Access

Synchronized methods

- Coordinate thread access to methods
- Use synchronized method modifier
  - Class can have as many as needed

Synchronization managed per instance

- No more than one thread can be in any synchronized method at a time

Using Synchronized Methods

When to use synchronized

- Protect modification by multiple threads
- Reading value that might be modified by another thread

Why not always synchronize methods

- Has significant overhead
- Use only in multithreading scenarios

Constructors are never synchronized

- A given object instance always created on exactly one thread

Synchronized Methods on Bank Account Class

```
public class BankAccount {
  private int balance;
  public BankAccount(int startBalance) {
    balance = startBalance;
  }

  public      synchronized      int getBalance() {
    return balance;
  }

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

5 Threads Running Correctly

100 +10 +10 +10 +10 +10 +10 +10 +10 +10 +10

+10 +10 +10 +10 +10 +10 +10 +10 +10 +10

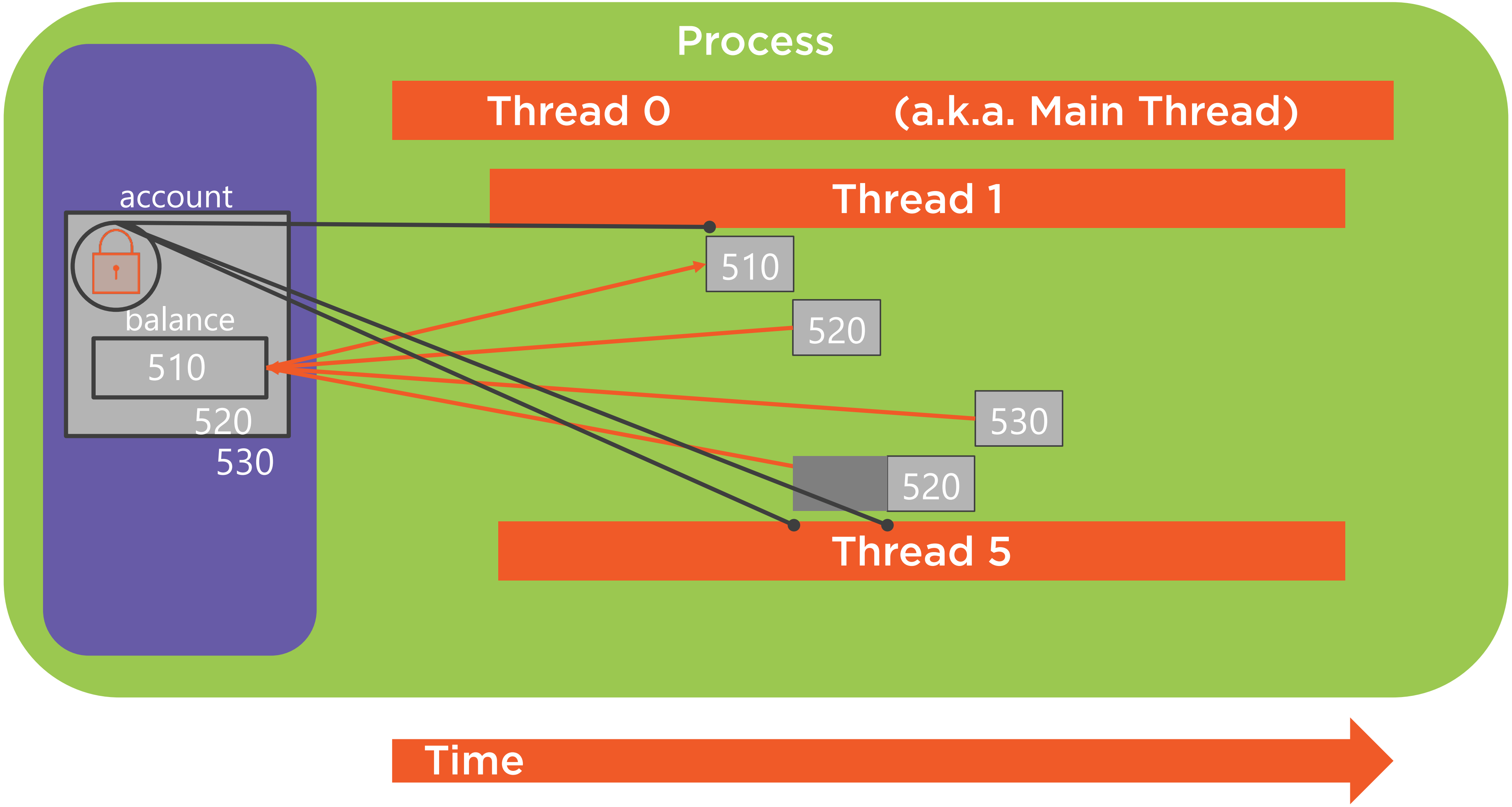
+10 +10 +10 +10 +10 +10 +10 +10 +10 +10

+10 +10 +10 +10 +10 +10 +10 +10 +10 +10

+10 +10 +10 +10 +10 +10 +10 +10 +10 +10 = 600

5 Threads

Behavior of Synchronized Methods



Manual Synchronization

Synchronized methods

- Automated concurrency management
- Used lock of current object instance

All Java objects have a lock

- Can manually acquire that lock
  - Use synchronized statement block
  - Available to any code with a reference

Synchronized Method

```
class BankAccount {
  private int balance;
  // other members elided for clarity
  public synchronized void deposit(int amount) {
    balance += amount;
  }
}
```

```
class Worker implements Runnable {
  private BankAccount        ;     account
  // other members elided for clarity
  public void run() {
    for(int i=0; i<10; i++) {
             account deposit(10);
    }
  }
}
```

Synchronized Statement Block

```
class BankAccount {
  private int balance;
  // other members elided for clarity

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

```
class Worker implements Runnable {
  private BankAccount       ;     account
  // other members elided for clarity

  public void run() {
    for(int i=0; i<10; i++) {
      synchronized(      ) {   account
              .deposit(10);  account
      }
    }
  }
}
```

Why Use Synchronized Statement Blocks

Synchronized blocks provide flexibility

- Enables use of non-thread safe classes
- Can protect complex blocks of code
- Sometimes synchronized methods just aren't enough

Bank Account Class Revisited

```
public class BankAccount {
  private int balance;
  public BankAccount(int startBalance) { balance = startBalance; }
  public synchronized int getBalance() {
    return balance;
  }
  public synchronized void deposit(int amount) {
    balance += amount;
  }
  public synchronized void withdrawal(int amount) {
    balance -= amount;
  }
}
```

Transaction Worker

```
public class TxWorker implements Runnable {
  protected BankAccount account;
  protected char txType; // ‘w’ -> withdrawal, ‘d’ -> deposit
  protected int amt;
  public TxWorker(BankAccount account, char txType, int amt) { . . . }

  public void run() {
    if (txType == ‘w’)
      account.withdrawal(amt);
    else if (txType == ‘d’)
      account.deposit(amt);
  }
}
```

Dispatching Transactions

```
ExecutorService es = Executors.newFixedThreadPool(5);
TxWorker[] workers = // Retrieve TxWorker instances

for(TxWorker worker:workers)
  es.submit(worker);

// Shutdown es and wait
```

Transaction Worker

```
public class TxWorker implements Runnable {
  protected BankAccount account;
  protected char txType; // ‘w’ -> withdrawal, ‘d’ -> deposit
  protected int amt;
  public TxWorker(BankAccount account, char txType, int amt) { . . . }

  public void run() {
    if (txType == ‘w’)
      account.withdrawal(amt);
    else if (txType == ‘d’)
      account.deposit(amt);
  }
}
```

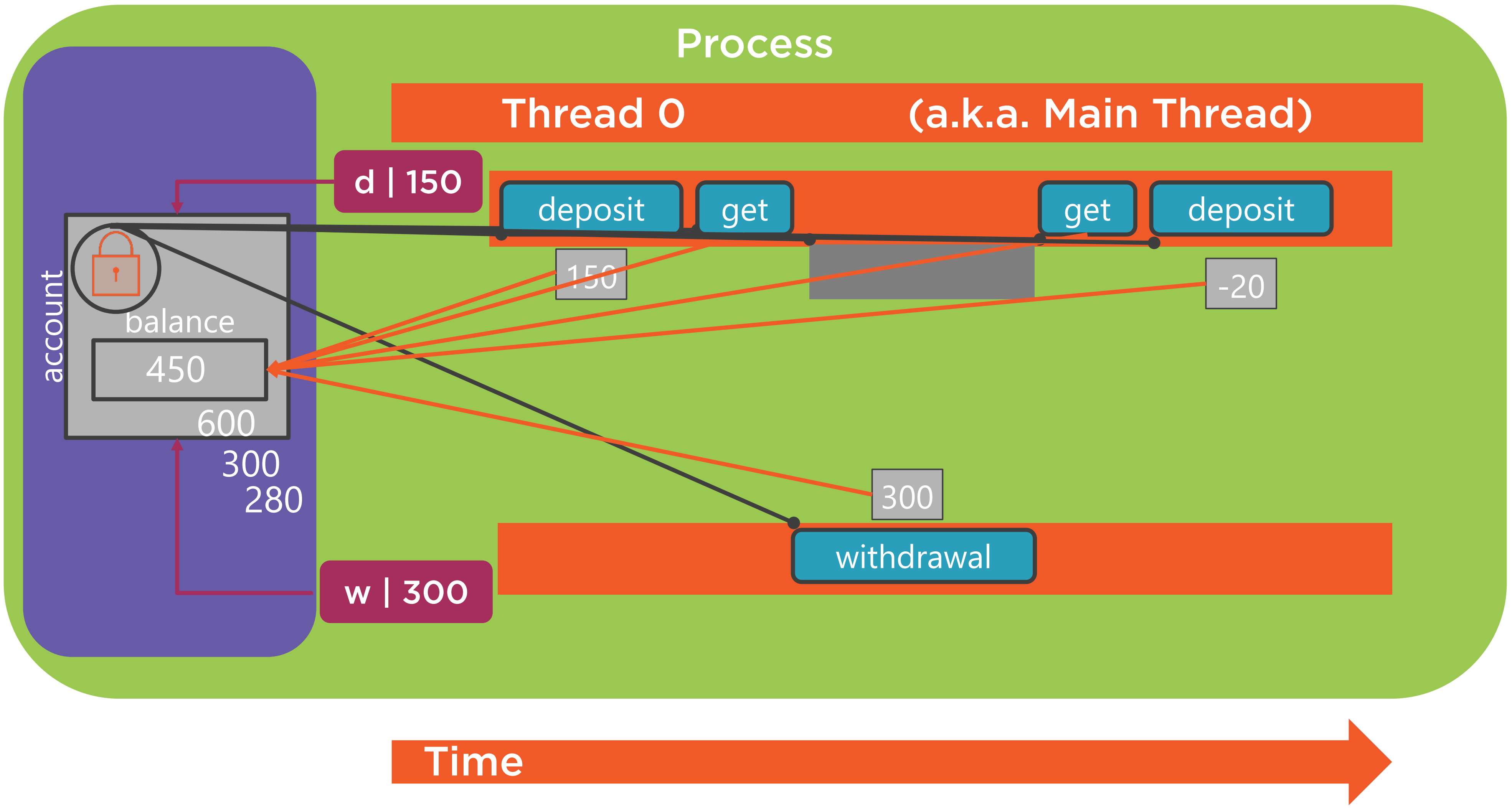
Transaction Promo Worker

```
public class TxPromoWorker extends TxWorker {
  public TxPromoWorker(BankAccount account, char txType, int amt) { super(. . .) }

  public void run() {
    if (txType == ‘w’)
      account.withdrawal(amt);

    else if (txType == ‘d’) {
      account.deposit(amt);
      if(account.getBalance() > 500) {
        int bonus = (int)((account.getBalance() – 500) * 0.1);
        account.deposit(bonus);
      }
    }
  }
}
```

Dispatching Transactions

```
ExecutorService es = Executors.newFixedThreadPool(5);
TxWorker[] workers =          // Retrieve TxPromoWorker instances

for(TxWorker worker:workers)
  es.submit(worker);

// Shutdown es and wait
```

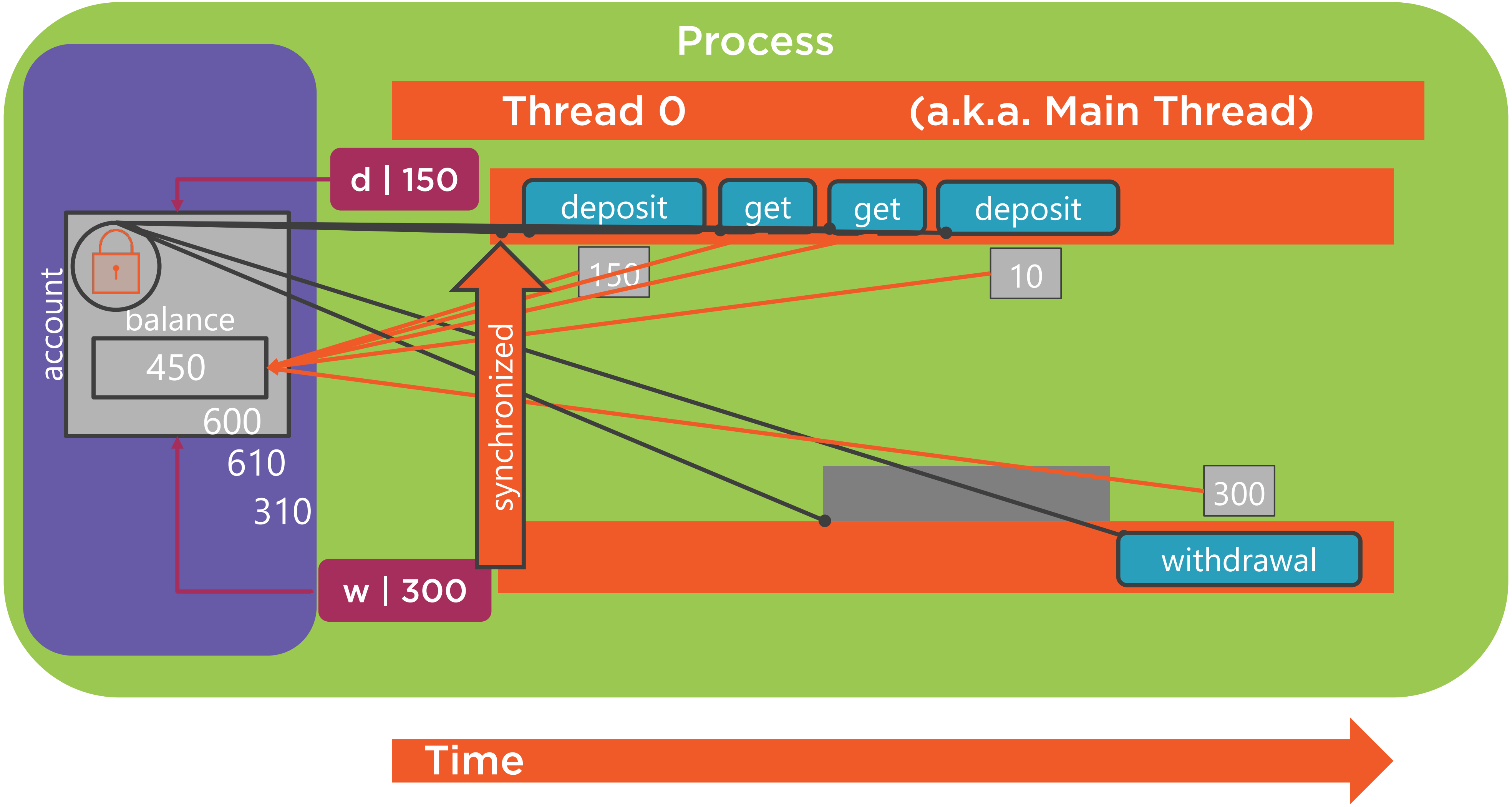
Behavior of Synchronized Methods



Thread Safe Transaction Promo Worker

```
public void run() {
  if (txType == ‘w’)
    account.withdrawal(amt);
  else if (txType == ‘d’) {
    synchronized(account) {
      account.deposit(amt);
      if(account.getBalance() > 500) {
        int bonus = (int)((account.getBalance() – 500) * 0.1);
        account.deposit(bonus);
      }
    }
  }
}
```

Behavior of Synchronized Methods



Collections and Concurrency

Concurrency and collections

- Concurrency safe collection access
- Blocking collections

Concurrency Safe Collection Access

Synchronized collection wrappers

- Most collections are not thread safe
- Can create thread safe wrapper
    - Use Collection class static methods
        - synchronizedList
        - synchronizedMap
        - Etc.
    - Wrapper is a thread safe proxy
        - Actual work occurs in original object

Blocking Collections

Coordinating producers and consumers

- One or more threads produce content
- One or more other threads consume
    - Must wait for content if not available

Java provides blocking queues

- Attempt to read blocks if empty
    - Wakes up when content available
- Examples
    - LinkedBlockingQueue
    - PriorityBlockingQueue
    - Etc.

Java Provides Still More

java.util.concurrent

- Types for managing concurrency
  - Has much of what we’ve talked about
- Semaphores
  - Coordinate access to multiple resources
- Lots more

java.util.concurrent.atomic

- Types providing atomic operations
  - set, get, getAndAdd, compareAndSet

Summary

Thread class

- Represents a thread of execution
- Similar to most OS thread representations
- Responsible to handle most details

Runnable interface

- Represents a task to run on a thread
- Simply override run method
- Can’t return results
- Exceptions responsibility of thread

Summary

ExecutorService

- Abstracts thread management details
- Can interact with thread pools

Callable interface

- Represents a task to be run on a thread
- Can return results
- Can throw exceptions

Future interface

- Represents results of a thread task
- Can access results from task
- Can throw exceptions from thread task

Summary

All Java objects have a lock

- Can access with synchronized methods
    - Acquires lock of target instance of call
    - Only one active at a time on an object
- Can manually acquire lock
    - Use synchronized statement block
    - Available to any code referencing object