Multicore Programming

Executors

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Motivation

- Express multitask operations without writing the thread logic.
- Rely on *thread pools* to limit thread management overhead (since Java 5).
Outline

Generality

Multicore Architecture

Classic Threads
Problems with Threads

Thread Pool

Summary and References
Machine (31GB)

Package P#0

L3 (8192KB)

L2 (256KB)

L1d (32KB)

L1i (32KB)

Core P#0

PU P#0

PU P#4

Core P#1

PU P#1

PU P#5

Core P#2

PU P#2

PU P#6

Core P#3

PU P#3

PU P#7
How Hyper-Threading Technology Works

- **Physical Processors**
- **Logical processor visible to OS**
- **Physical processor resource allocation**
- **Throughput**

**WITHOUT HT Technology**

- Thread 2
- Thread 1

**WITH HT Technology**

- Thread 1
- Thread 2

Resource allocation and throughput comparison.
Outline

Generality
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Thread Pool

Summary and References
Thread API

Interface Runnable:

```java
void run()
```

Class Thread:

```java
Thread()
Thread(Runnable command)
static Thread currentThread()
void join() // synchronous
void run() // synchronous
static void sleep(long millis)
void start() // asynchronous
```
Example of Thread Creation

class ExaRun implements Runnable {
    public void run() {
        System.out.println("Hello");
    }
}
new Thread(new ExaRun()).start();
new Thread(() -> System.out.println("Hello")).start();

From now on, we avoid new Thread() and start, except when implementing an executor.
Thread Creation

main

start()

Thread-0

"Hello"
Outline

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Summary and References
Problem 1: C10k Problem

As a motivational example, a server dealing with multiple requests:

- 1 connection: easy without thread
- 10/100 connections: easy with threads, possible without
- 1k connections: technical with threads, difficult without
- 10k connections: problem with only threads, easy with Erlang (green threads)
Thread Costs

Maximum number of concurrent threads:
- around 1 MB for each stack for recursive calls
- at most 10k with 10 GB of RAM

Maximum rate of thread creations:
- around 0.1 ms per creation
- costly creation and destruction
Problem 2: Code Clarity

Low-level thread logic is:

- hard to reason with (difficult to debug)
- heavy to write (lot of synchronizations)
Example of Boilerplate Thread Code

```java
int y = f(x);
int z = g(x);
System.out.println(y + z);

Result result = new Result();
Thread t1 = new Thread(() -> { result.left = f(x); });
Thread t2 = new Thread(() -> { result.right = g(x); });
t1.start();
t2.start();
t1.join();
t2.join();
System.out.println(result.left + result.right);
```
Thread Synchronization

main

start()

Thread-0

start()

Thread-1

join()

f(x)

join()

g(x)

blocked
Outline

Generality

ThreadPool

Overview

Future and Task Interface
Executors Interface
ForkJoinPool: a Special ThreadPool

Summary and References
Solution

Thread pool:
- one or a few long-running threads per core with several tasks to execute sequentially
- reuse threads (limited number of threads and fewer creations)
- provide features for synchronization
- alleviate both cost and clarity problems
Preemption

- Each thread can be interrupted by the operating system for concurrency (to let others have a time-share of a CPU core).
- A task cannot be paused and goes back in the queue to let another task executes.
Outline

Generality

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Summary and References
Future

- Placeholder (like Optional) for a result that will be computed later.
- Similar to promises.
- Inspired by the conflict between RPC and message passing paradigm:
  - **RPC** Remote Procedure Call: easy to program with (close to sequential programming) but synchronous (blocking).
  - **Message passing** Asynchronous but harder to reason about.
- Futures/promises can be seen as messages to future self.
Future\(<V>\)

Class Future:

```java
boolean cancel(boolean mayInterruptIfRunning)
V get() // synchronous
V get(long timeout, TimeUnit unit) // synchronous
boolean isCancelled()
boolean isDone()
```
Example of Code Clarity

```
int y = f(x);
int z = g(x);
System.out.println(y + z);
```

Parallel version with asynchronous functions (f’ and g’):

```
Future<Integer> y = f'(x);
Future<Integer> z = g'(x);
System.out.println(y.get() + z.get());
```
Thread Synchronization

main

Thread-0

Thread-1

\[
f'(x) \quad \text{f}(x) \quad \text{g}'(x) \quad \text{g}(x)
\]

y.get()

z.get()

blocked
Task API

A *task* is either:

- an action: interface `Runnable` defining the method `void run()`
- or a function: interface `Callable<V>` defining the method `V call()`
Outline

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Summary and References
Executor

Interface Executor:

```java
void execute(Runnable command) // asynchronous
```

Example:

```java
Executor executor = anExecutor();
executor.execute(new RunnableTask());
executor.execute(() -> { processing(); });
```

Limitation: not possible to check task completions.
ExecutorService

Interface:

```
Future<?> submit(Runnable command) // asynchronous
Future<V> submit(Callable<V> callable) // asynchronous
List<Future<V>> invokeAll(Collection<Callable<V>> callables) // sync.
```

Alternative invocation methods with timeout (preferable when possible).
Example

```java
int y = f(x);
int z = g(x);
System.out.println(y + z);

Future<Integer> y = executor.submit(() -> f(x));
Future<Integer> z = executor.submit(() -> g(x));
System.out.println(y.get() + z.get());
```
Executors

Convenience class to easily create an ExecutorService:

```java
Executors.newSingleThreadExecutor();
Executors.newFixedThreadPool(10);
Executors.newCachedThreadPool();
```

Different types of thread pools:

- **single thread**  execution of a single task at a time
- **fixed thread**  the maximum number of threads is fixed (threads are not reclaimed)
- **cached thread**  expandable thread pool (suitable with many short-lived tasks)

More customized executors may be created by instantiating class ThreadPoolExecutor.
Pool Termination

Methods from interface ExecutorService for termination:

```java
boolean awaitTermination(long timeout, TimeUnit unit)
void shutdown()
List<Runnable> shutdownNow()
```

Effects:

- `awaitTermination` blocks until all tasks are terminated (with timeout)
- `shutdown` prevent the executor from accepting new tasks
- `shutdownNow` as `shutdown` but cancel waiting tasks and try interrupting executing tasks (return unfinished tasks)
Java: Task Interruption

- Interrupting a thread is done cooperatively.
- The method `interrupt` is called on a given thread.
- The task executed by this thread must regularly check if it has been interrupted with `Thread.interrupted()`.
- Alternatively, the task frequently calls a method that may throw `InterruptedException`.
Thread Pool  Executors Interface

Complete Example

```java
List<Callable<String>> callables = Arrays.asList(
    () -> "task1",
    () -> "task2",
    () -> "task3";

List<Future<String>> results =
    executor.invokeAll(callables);

executor.shutdown();
executor.awaitTermination(1, TimeUnit.SECONDS);

results.stream()
    .map(future -> future.get(1, TimeUnit.SECONDS)).
    forEach(System.out::println);
```
Thread Synchronization

- main
- Thread-0
- Thread-1

invokeAll()

"task1"

"task2"

"task3"

get()

get()
ScheduledExecutorService – part 1

To specify the execution of a task in the future (asynchronous):

```
Future<?> schedule(Runnable command, long delay, TimeUnit unit)
Future<V> schedule(Callable<V> callable, long delay, TimeUnit unit)
```
ScheduledExecutorService – part 2

To specify that a task must be repeated (every few time units or with a minimum delay between each termination and start):

```
Future<?> scheduleAtFixedRate(Runnable command,
long initialDelay, long period, TimeUnit unit)
Future<?> scheduleWithFixedDelay(Runnable command,
long initialDelay, long delay, TimeUnit unit)
```

Scheduled versions of most previous methods exist for Executors. Moreover, class ScheduledThreadPoolExecutor allows creating a customized scheduled executor.
Avoiding Sleeps

```java
work1();
Thread.sleep(10000);
work2();

work1();
ScheduledExecutorService scheduler =
    Executors.newScheduledThreadPool(1);
scheduler.schedule(work2, 10, TimeUnit.SECONDS);
scheduler.shutdown();
```
Sequence Diagram
Other Non-Covered Features

- daemon and non-daemon threads
- `ExecutionException`, `RejectedExecutionException`
- `ThreadFactory`, `RejectedExecutionHandler`
- `ThreadLocal`, `ThreadGroup`, `ThreadInfo`
Outline

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Thread Pool
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Summary and References
A Special Executor

- Designed for tasks that can be decomposed recursively (forked and then joined): ForkJoinTask.
- Rely on a work-stealing algorithm: when a thread is free, it steals tasks from other threads.
- Used by parallel streams and Arrays.parallelSort().
ForkJoinPool

Same behavior as Executor for execute (asynchronous execution without result) and as ExecutorService for submit (asynchronous execution with a future).
Tasks can be submitted synchronously:

```java
T invoke(ForkJoinTask<T> task) // synchronous
```

A static common fork/join pool is available:

```java
static ForkJoinPool commonPool()
```

Numerous possible customizations.
Fork recursively a task in smaller subtask until each subtask is small enough.

Evaluate all subtasks in parallel.

Recombine the partial results.
ForkJoinTask\(\langle V \rangle\)

Asynchronous execution:

\[
\text{ForkJoinTask}\langle V \rangle \, \text{fork()} \quad // \quad \text{asynchronous} \\
V \, \text{join()} \quad // \quad \text{synchronous}
\]

Synchronous execution:

\[
V \, \text{invoke()} \quad // \quad \text{synchronous} \\
\text{static} \quad \text{Collection}\langle \text{ForkJoinTask}\langle ? \rangle \rangle \\
\quad \text{invokeAll(Collection}\langle \text{ForkJoinTask}\langle ? \rangle \rangle \, \text{tasks})} \quad // \quad \text{synchronous} \\
\text{static} \quad \text{void} \quad \text{invokeAll(ForkJoinTask}\langle ? \rangle \ldots \text{tasks})} \quad // \quad \text{synchronous}
\]

Concrete implementations of abstract class ForkJoinTask:

- RecursiveTask\(\langle V \rangle\) with one method to implement: \(V \, \text{compute()}\)
- RecursiveAction with one method to implement: \(\text{void} \, \text{compute}()\)
Task Division Algorithm

Divide work until it is small enough:

```java
if (currentPortion() <= THRESHOLD)
    // do the work directly
else
    // split current work into two pieces
    // fork a piece (incurring additional recursive splits)
    // execute the other piece (incurring additional recursive splits)
    // wait for the result of the first piece
    // combine the results
```

Alternative for the division (with a blocking thread):

```java
// split current work into two pieces
// invoke the two pieces (incurring additional recursive splits)
// wait for both results
// combine the results
```
Example with a RecursiveTask<V>

```java
protected Double compute() {
    if (length <= THRESHOLD)
        return computeSequentially();

    int half = length / 2;

    RecTask leftTask = new RecTask(half);
    leftTask.fork();

    RecTask rightTask = new RecTask(length - half);
    Double rightResult = rightTask.compute();

    Double leftResult = leftTask.join();
    return leftResult + rightResult;
}
```
Example with a RecursiveAction

```java
protected void compute() {
    if (length < THRESHOLD) {
        computeSequentially();
        return;
    }

    int half = length / 2;

    invokeAll(new RecAction(half),
              new RecAction(length - half));
}
```
Submission Example to ForkJoinPool

```java
Long res = new ForkJoinPool()
    .invoke(new RecTask(1_000_000));
new ForkJoinPool()
    .invoke(new RecAction(1_000_000));
```
Threshold Selection

Select threshold by testing and measuring performance:

- Too much divisions (low \texttt{THRESHOLD}) leads to task management overhead: fine grain.
- Not enough divisions (high \texttt{THRESHOLD}) leads to work imbalance among the threads (some will finish earlier than others): coarse grain.
Work Imbalance

Coarse grain:

Fine grain:

\[ C_{\text{max}} \]
Complete Example (Sequential Part)

```java
public class RecPiTask extends RecursiveTask<Double> {
    static long THRESHOLD = 1_000_000;
    long MC;

    public RecPiTask(long MC) {
        this.MC = MC;
    }

    protected Double computeSequentially() {
        Supplier<double[]> supplier = () -> new double[] {
            ThreadLocalRandom.current().nextDouble(),
            ThreadLocalRandom.current().nextDouble()
        };
        return Stream.generate(supplier)
            .limit(MC)
            .filter(x -> x[0] * x[0] + x[1] * x[1] < 1)
            .count() * 4. / MC;
    }
}
```
Complete Example (Parallel Part)

```java
protected Double compute() {
    if (MC <= THRESHOLD)
        return computeSequentially();

    long half = MC / 2;

    RecPiTask leftTask = new RecPiTask(half);
    leftTask.fork();

    RecPiTask rightTask = new RecPiTask(MC - half);
    Double right = rightTask.compute();

    Double left = leftTask.join();
    return (half * left + (MC - half) * right) / MC;
}
```
Complete Example (Invocation Part)

```java
long MC = 100_000_000;
// Sequentially
Double pi1 = new RecPiTask(MC)
    .computeSequentially();

// In parallel
Double pi2 = ForkJoinPool.commonPool()
    .invoke(new RecPiTask(MC));
```
Outline

Generality

ThreadPool

Summary and References
Thread Pools

- Support for concurrency in Java has evolved and continues to evolve.
- Thread pools are generally helpful but can cause problems when many tasks are blocking.
- The fork/join framework lets you recursively split a parallelizable task into smaller tasks, execute them on different threads, and then combine the result of each subtask in order to produce the overall result.
Official Documentation

- Documentation of package concurrent
- Documentation of interface ExecutorService
- Documentation of class Executors
- Documentation of class ForkJoinPool
- Documentation of class ForkJoinTask
- Java Tutorial on Executors