Multicore Programming
Future Composition

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Master 1 computer science – Semester 8
Motivation

- Express multitask operations in a declarative way without writing the thread logic.
- Rely on *future composition* to limit synchronization code (since Java 8).
Outline

Blocking Problem

Future Composition

Summary and References
Outline

Blocking Problem With Thread Pools
  With Future

Future Composition

Summary and References
Context

- Tasks (or user threads) cannot be preempted.
- A (system) thread must finish a task before proceeding to another task.
- When a task is waiting for a blocking call, its thread is idle even though other tasks are ready.
- *Blocking/non-blocking* is also referred to as *synchronous/asynchronous*. 
Queued tasks

Five worker threads running five active tasks
Sizing Thread Pools: Problem

- A large number of tasks is submitted to a thread pool.
- Each task spends 75% of the time in a blocking operation.
- There are 2 cores.
- What is the minimum number of threads required in the pool to prevent any core from being idle?
Sizing Thread Pools: Solution

- In the best case, the periods for all blocking operations are well distributed (overlapping is minimum).
- The minimum number of necessary threads is 8: at any point in time, 75% of them (six) execute blocking tasks, while all cores are busy executing the remaining two.
- When tasks are waiting 90% of the time, 20 threads are necessary.
Gantt Chart with Blocking (2 threads)
Gantt Chart with Blocking (4 threads)

Thread pool

\[ P_1 \]

\[ P_2 \]

<table>
<thead>
<tr>
<th>4</th>
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<th>3</th>
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</thead>
<tbody>
<tr>
<td>3</td>
<td>3</td>
<td>2</td>
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<tr>
<td>2</td>
<td>1</td>
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</tbody>
</table>

0 1 2 3 4 time
Gantt Chart without Blocking (8 threads)

Thread pool

<p>| | | | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>8</td>
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<tr>
<td>2</td>
<td>1</td>
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</tr>
</tbody>
</table>

$P_2$:

| 5 | 6 | 7 | 8 |

$P_1$:

| 1 | 2 | 3 | 4 |
Threading Models

Kernel (or system) threads vs. user/application threads:

1:1 kernel-level threading (preemptive multitasking): native threads
n:1 user-level threading (cooperative multitasking)
m:n hybrid threading: thread pool, fiber (shared memory), green threads, virtual threads, etc.
Cooperative Multitasking

- The objective is to make each core busy with the minimum number of threads.
- Cooperation between tasks is needed to avoid blocking threads as much as possible.
- Solution 1 (Java): each task should avoid blocking operations.
- Solution 2 (Erlang): each task should frequently yield execution to a user scheduler and resumes it later (continuation-style).
Outline

Blocking Problem
  With Thread Pools
  With Future

Future Composition

Summary and References
Blocking Problem With Future

Asynchronous Operations

Asynchronous calls with future limit blocking and improve clarity:

▶ Launch multiple tasks as soon as possible to limit the time spent blocking while they complete.
▶ Objectives of Future:
  ▶ improve code clarity
  ▶ minimize blocking with asynchronous operations
  ▶ limit the number of threads (using executors)
Future Principle
Overcoming Future Limitation

- No way to specify how to react to a future completion without a blocking thread.
- Future *composition* allows minimizing blocking even more by chaining asynchronous operations and specifying how computations should proceed asynchronously.
- Eliminate the need of a supervising blocking thread.
Outline

Blocking Problem

Future Composition
Basic Interface and Example
Extended Interface

Summary and References
CompletionStage

Many available chaining methods:

```java
stage.thenApply(x -> square(x))
    .thenAccept(x -> System.out.print(x))
    .thenRun(() -> System.out.println());
```

Complete the stage, then compute a square root, then print it, then print an empty line.
Execution Diagram

\[ \sqrt{x} \rightarrow \text{print}(x) \rightarrow \text{println} \]

\text{thread} \quad \text{thread}

\text{then.}

\times

\text{square}(x)

\text{print}(x)

\text{println}()
Creation of CompletableFuture

- Implement Future and CompletionStage.
- Creation with a task (submitted to the default ForkJoinPool):
  
  ```java
  static CompletableFuture<Void> runAsync(Runnable runnable)
  static CompletableFuture<U> supplyAsync(Supplier<U> supplier)
  ```

- Creation by combining multiple CompletableFuture:
  
  ```java
  static CompletableFuture<Void> allOf(CompletableFuture<?>... cfs)
  static CompletableFuture<Object> anyOf(CompletableFuture<?>... cfs)
  ```
Creation of CompletableFuture
Creation of CompletableFuture

```java
cf1

<table>
<thead>
<tr>
<th>cf2</th>
</tr>
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<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>:</td>
</tr>
<tr>
<td>cfn</td>
</tr>
</tbody>
</table>
```

allOf
Completion of CompletableFuture

- Basic completions:
  ```java
  boolean complete(T value)
  T join()
  ```

- The name CompletableFuture comes from the method complete.

- Completion with a timeout:
  ```java
  CompletableFuture<T> completeOnTimeout(T value,
                                          long timeout, TimeUnit unit)
  CompletableFuture<T> orTimeout(long timeout,
                                   TimeUnit unit)
  ```
Parallel Streams vs. Futures

Assume a request needs to be processed with different arguments:

```java
List<Result> result = arguments.stream()
    .map(arg -> f(arg))
    .toList();
```

Two parallelization options: using a parallel stream, or asynchronous operations.
Parallelizing with Futures

```java
List<CompletableFuture<Result>> comps = arguments.stream()
    .map(arg -> CompletableFuture.supplyAsync(() -> f(arg)))
    .toList();

List<Result> result = comps.stream()
    .map(CompletableFuture::join)
    .toList();
```

Must be in two separate streams due to lazy evaluation (otherwise, there is no parallelism).
Parallelizing with Futures (Alternative)

If there is no result:

```java
arguments.stream()
    .map(arg -> CompletableFuture.runAsync(() -> f(arg)))
    .reduce(CompletableFuture::allOf)
    .get()
    .join();
```

Favor parallel streams for CPU-intensive tasks and streams of futures with I/O bound tasks.
Avoiding Blocking

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

CompletableFuture<Integer> c1 = new CompletableFuture<>();
CompletableFuture<Integer> c2 = new CompletableFuture<>();
c1.thenCombine(c2, (y, z) -> System.out.println(y + z));
executor.submit(() -> c1.complete(f(x)));
executor.submit(() -> c2.complete(g(x)));```

Future Compositon  Basic Interface and Example
Execution Diagram

\[ f(x) \]

\[ g(x) \]

\[ \text{println} \]

\[ \text{thread} \]

\[ \text{submit} \]

\[ \text{println} \]

\[ \text{submit} \]
Outline

Blocking Problem

Future Composition
  Basic Interface and Example
  Extended Interface

Summary and References
Sequence of CompletionStage<T>

<table>
<thead>
<tr>
<th>CompletionStage&lt;T&gt;</th>
<th>Method</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>CompletionStage&lt;Void&gt;</td>
<td>thenRun</td>
<td>Runnable</td>
</tr>
<tr>
<td>CompletionStage&lt;Void&gt;</td>
<td>thenAccept</td>
<td>Consumer&lt;T&gt;</td>
</tr>
<tr>
<td>CompletionStage&lt;U&gt;</td>
<td>thenApply</td>
<td>Function&lt;T,U&gt;</td>
</tr>
<tr>
<td>CompletionStage&lt;U&gt;</td>
<td>thenCompose</td>
<td>Func.&lt;T,CompletionStage&lt;U&gt;&gt;</td>
</tr>
</tbody>
</table>
## Composition of CompletionStage<T>

<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>runAfterEither(Compl.Stage&lt;?&gt;, Runnable)</code></td>
<td>Runs the given Runnable after the completion of the stage.</td>
</tr>
<tr>
<td><code>acceptEither (Compl.Stage&lt;T&gt;, Consumer&lt;T&gt;)</code></td>
<td>Accepts the completion of the stage and calls the Consumer.</td>
</tr>
<tr>
<td><code>applyToEither (Compl.Stage&lt;T&gt;, Function&lt;T,U&gt;)</code></td>
<td>Applies the Function to the completion of the stage.</td>
</tr>
<tr>
<td><code>runAfterBoth (Compl.Stage&lt;?&gt;, Runnable)</code></td>
<td>Runs the given Runnable after both stages complete.</td>
</tr>
<tr>
<td><code>thenAcceptBoth(Compl.Stage&lt;U&gt;, BiCons.&lt;T,U&gt;)</code></td>
<td>Calls the BiCons after both stages complete.</td>
</tr>
<tr>
<td><code>thenCombine (Compl.Stage&lt;U&gt;, BiFunc.&lt;T,U,V&gt;)</code></td>
<td>Combines the U values from both stages and applies the BiFunc.</td>
</tr>
</tbody>
</table>
Methods Nomenclature

- discard “then”, “after” and “to”
- type of computations:
  - run Runnable (no argument, no return value)
  - accept Consumer (one argument, no return value)
  - apply Function (one argument, one return value)
- type of compositions (suffix):
  - $\emptyset$ one stage
  - either any stage among two
  - both both stages
- exception for thenCombine, which could have been named thenApplyBoth or applyToBoth
Special Method: `thenCompose`

- Execute a function when a result becomes available (like `thenApply`).
- With `thenApply`, this function returns a value that is then implicitly incorporated into a `CompletionStage`.
- With `thenCompose`, this function returns a `CompletionStage` containing the value.
- The distinction is similar to the difference between `map` and `flatMap` (in the former, the function returns a value that will be incorporated into a stream, whereas in the latter, it returns a stream of values).
- Useful when using a function (from a third-party library for instance) returning a `CompletableFuture`. 
Example of `thenCompose`

```java
static class Util {
    static CompletableFuture<Long> add3(int a) {
        return CompletableFuture.supplyAsync(() -> a + 3);
    }
    static CompletableFuture<Long> mult3(int a) {
        return CompletableFuture.supplyAsync(() -> a * 3);
    }
}

Util.add3(10)
    .thenCompose(Util::mult3)
    .thenAccept(System.out::println);
```
Asynchronous Versions

Methods from CompletionStage are available in three versions:

1. A default one (no suffix): the following task is executed on the thread executing the previous task or the current thread (e.g. join).
2. An asynchronous one (suffix “async”): the following task is submitted to the executor of the current stage.
3. Another asynchronous one with another argument to specify the executor.
Exception Handling

From CompletionStage:

```java
Compl.Stage<T> exceptionally(Function<Throwable, T>)
Compl.Stage<U> handle (BiFunc.<T, Throwable, U>)
Compl.Stage<T> whenComplete (BiConsumer<T, Throwable>)
```

From CompletableFuture:

```java
boolean completeExceptionally(Throwable)
```
Not Only a Java Thing!

```cpp
id_rpc(&my_server).and_then(|id| {
    get_row(id)
}).map(|row| {
    json::encode(row)
}).and_then(|encoded| {
    write_string(my_socket, encoded)
})
```
Improved Example to Avoid Blocking

```java
CompletableFuture<Integer> c1 = new CompletableFuture<>();
CompletableFuture<Integer> c2 = new CompletableFuture<>();
c1.thenCombine(c2, (y, z) -> System.out.println(y + z));
executor.submit(() -> c1.complete(f(x)));
executor.submit(() -> c2.complete(g(x)));
```

```java
CompletableFuture<Integer> c1
    = CompletableFuture.supplyAsync(() -> f(x))
CompletableFuture<Integer> c2
    = CompletableFuture.supplyAsync(() -> g(x))
c1.thenAcceptBoth(c2, (y, z) -> System.out.println(y + z));
```
Outline

Blocking Problem

Future Compositon

Summary and References
Future Composition

- Making methods asynchronous (returning before all their work is done) allows additional parallelism and reduce blocking.
- The CompletableFuture class expresses one-shot asynchronous computations. Combinators can be used to compose asynchronous computations to reduce blocking.
- A CompletableFuture allows propagating and managing errors generated within an asynchronous task.
- A synchronous API can be asynchronously consumed by wrapping invocations into a CompletableFuture.
Official Documentation

- Documentation of class CompletableFuture
- Documentation of interface CompletionStage