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Advanced Programming

Purely Functional Parallelism

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Parallel Data Structures (Motivation)

- Consider a regular list: `val list=(1 to 100).toList`
- And a regular list computation: `list map f`
- What if `f` is very slow but referentially transparent?
- We can parallelize the mapping!
- In Scala standard library we can: `list.par.map (f)`
- `list.par : collection.parallel.immutable.ParSeq[Int] =ParVector(1,...`
- Scala has parallelized versions for `ParArray`, `ParVector`, `mutable.ParHashMap`, `mutable.ParHashSet`, `immutable.ParHashMap`, `immutable.ParHashSet`, `ParRange`, `ParTrieMap`
- **Similarities** with `Par`: enable parallelism at the level of processing data structures without low level concurrency primitives (**parallel programming for the masses!**)
- **Differences** from `Par`: Scala's parallel collections are **eager**. We separate construction of the computation from execution. This gives more flexibility.
- Similar facilities exist in LINQ (C#) and in F#

http://docs.scala-lang.org/overviews/parallel-collections/overview.html

Parallel Collections in Spark

- Spark has seemingly similar facilities:

```
val data =Array(1, 2, 3, 4, 5)
val distData =sc.parallelize(data)
```

- Constructs an `RDD` from a collection.
- RDD resembles a parallel collection, but it can **also** be distributed
- **RDD constructions are lazy**. As long as transformations are applied to an RDD, no computation is executed.
- Allows Spark schedulers to control the computation better
- This is more like `Par` than Scala's native parallel collections
- Today we look at a design of such general APIs (and even better!)

http://spark.apache.org/docs/latest/programming-guide.html#parallelized-collections

API for functional parallelism

How to read this chapter?

Chapter 7

- No right answers in design
- You will see a collection of design choices
- You are to understand their trade-offs, and think critically.
- The lecture explains the key design, but not all the meanders of the story — not the full learning experience!

Agenda for Today

- Motivation for Par [Done]
- Usage & Design of Par
- Continuation Passing Style (A general pattern)
- Implementation of Par
- Extension methods / Pimp Your Library Pattern (A general Pattern)

map2 for Option and Par

```scala
def map2 (oa: Option[A], ob: =>Option[B]) (f: (A,B) =>C): Option[C] =
  oa.map (a =>ob.map (b =>f(a,b)))
```

- Why is `oa` by-value and `ob` by-name?
- Now a version for `Par`:

```scala
def map2[A,B,C] (pa: =>Par[A], pb: =>Par[B]) (f: (A,B)=>C): Par[C]
```

- Why are both `pa` and `pb` by name?
- An example of use, parallel summation of list:

```scala
def sum (ints: IndexedSeq[Int]): Par[Int] =                // Returns immediately
  if (ints.size <= 1)
    Par.unit (ints.headOption.getOrElse (0))
  else {
    val (l,r) = ints.splitAt (ints.length/2)
    Par.map2 (Par.fork (sum(l)), Par.fork (sum(r)) ) (_+_) // After forking don't wait explicitly!
  }                                                        // We can apply _+_ to computations!
```

The Par Type

- `Par[A]`: a **pure data structure** describing a **parallel computation**
  - Some similarity to `Stream` which describes computations happening in sequence
  - `Par` is Java's `Callable` with a better API
  - Allows expanding the computation, without waiting for results
  - Separates construction and parallelization of computation from scheduling and execution
  - First decide what runs in separate threads, then on what resource (Executor) to run it
- `unit[A] (a: A): Par[A]` promote a constant to `Par` eagerly (trivial, return `a` immediately)
- `map2[A,B,C] (pa: Par[B],pb: Par[C]) (f: (A,B) => C): Par[C]` combines results of two computations with a binary function. Does not introduce new threads.
- `fork[A](a: => Par[A]): Par[A]` marks a computation for concurrent evaluation (separate thread). No evaluation until forced by `run`. Introduce a new thread.
- `lazyUnit[A] (a: =>A): Par[A]` wraps its unevaluated argument in a `Par` and marks it for concurrent evaluation (so it combines `unit` and `fork`).
- `run[A] (es: ExecutorService) (p: Par[A]): A` extracts a value from a `Par` by actually performing the computation (the non-blocking version)

Other Combinators

- `def map[A,B] (pa: Par[A]) (f: A => B): Par[B] = map2 (pa, unit (())) ((a,_) => f (a))`
  - `map` extends the definition of a parallel computation with a new step (`f`)
  - Example: `def sortPar (parList: Par[List[Int]]) = map (parList) (_.sorted)`
  - Q. What does `sortPar` do?
  - It changes a parallel computation producing a list, into one whose resulting list is sorted. Nothing is run at this stage!
  - An example how we an build a computation without committing to where and how to execute
  - Choose to use a different number of threads or a different scheduling policy in different places
  - For example UI vs background batch processing
- `def asyncF[A,B] (f: A => B): A => Par[B]` change `f` to run in parallel (exercise)
- `def sequence[A] (ps: List[Par[A]]) : Par[List[A]]`
  - Recomposes a list of parallel computations of `A` into a single parallel computation of a list of `A`s
  - Example: schedule `n` downloads, get a list of downloaded files in parallel (exercise)
  - Familiar from `State`
- We can use it to implement parMap (that maps over list in parallel):

```
def parMap[A,B] (as: List[A]) (f: A => B): Par[List[B]] =
  sequence (as map (asyncF (f)))
```

Mentimeter

- `def map[A,B] (pa: Par[A]) (f: A =>B): Par[B] = map2 (pa, unit (())) ((a,_) => f (a))`
- `def asyncF[A,B] (f: A =>B): A =>Par[B]`
- `def sequence[A] (ps: List[Par[A]) : Par[List[A]]`
- `def parMap[A,B] (as: List[A]) (f: A =>B): Par[List[B]] =`
  `sequence (as.map (asyncF (f)))`

Question. Why is `asyncF` called? What would happen if we did:

```
def parMap[A,B] (as: List[A]) (f: A =>B): Par[List[B]] =
  sequence (as.map (f))
```

Continuation Passing Style

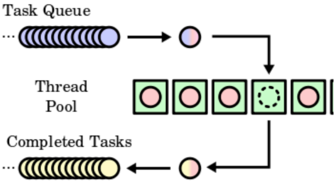
```
def f (x: X): Y                                     // Consider two functions
def g (y: Y): Z
// Normally this is how we compose them:
g (f (x)): Z                                        // f (x) first returns, then we call 'g' on the outcome

def f (x: X) (cont: Y => Unit): Unit = {          // Rewrite f to call a *continuation* instead of returning
  val y_result = ... // the original body of f
  cont (y_result)
}
def g (y: Y) (cont: Z => Unit): Unit = {          // Do the same to 'g;
  val z_result = ... // the original body of g
  cont (z_result)
}
// Let 'consumer: Z => Unit' execute what we shall do with g's result
f (x) (y => g (y) (z => consumer (z)))            // Compose 'f' and 'g' in the continuation passing style
```

- All returning via argument passing; `Unit` inessential, consumer could be pure and return value
- The last thing each function does is calling the next function
- A peculiar generalization of tail recursion and accumulator style
- Use to implement `Par` so that handing over from one to another can reuse same thread

Background: Java's ExecutorService and Future API

```scala
class ExecutorService {
  def submit[A](a: Callable[A]): Future[A]
}
trait Future[A] {
  def get: A
}
```



https://www.slideshare.net/afkham_azeez/java-colombo-developing-highly-scalable-apps

```
public interface ExecutorService
extends Executor
```

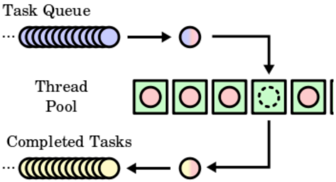
An `Executor` that provides methods to manage termination and methods that can produce a `Future` for tracking progress of one or more asynchronous tasks.

The thread pool execution uses a blocking queue. It keeps storing all the tasks that you have submitted to the **executor service**, and all threads (workers) are always running and performing the same steps:

- Take the Task from the queue
- Execute it
- Take the next or wait until a task will be added to the queue

Typical usage of ExecutorService

```
class ExecutorService {
  def submit[A](a: Callable[A]): Future[A]
}
trait Future[A] {
  def get: A
}
```



Typical usage1

```
val service: ExecutorService =
Executors.newFixedThreadPool(2)
service.submit(t1)
service.submit(t2)
service.submit(t3)
```

Typical usage2

```
val es=Executors.newWorkStealingPool()
val fut=es.submit(new Callable[Int] {
  override def call(): Int = (1 to 10).sum
})
val res=fut.get
```


The Implementation of Par [1/3]

The non-blocking CPS-based variant (Section 7.4.4)

```
// We use futures to represent an asynchronous calculation of a value.

trait Future[+A] {                                              // Java futures deadlock, own  design
  private def apply (k: A => Unit): Unit                        // The future calls 'k' when A ready
}

// Futures (also in Java) don't have a way to continue computation without waiting for A. Par has.

type Par[A] = ExecutorService => Future[A]                      // Just an alias, using Java's Executors

// Normally we do not execute Par, but compose it with new calculations (using map,map2,chooser,etc.)
// Once we have a representation of the whole thing we can run it:

def run[A] (es: ExecutorService) (p: Par[A]): A = {
  val ref = new java.util.concurrent.atomic.AtomicReference[A] // Mutable threadsafe cell (local!)
  val latch = new CountDownLatch(1)                             // Create a lock
  p (es) { a => ref.set(a); latch.countDown }                   // Continuation sets ref and unlocks
  latch.await                                                   // Wait for unlock (never if p crashes)
  ref.get                                                       // Return value of p set by continuation
}
```


The Implementation of Par [2/3]

The non-blocking CPS-based variant (Section 7.4.4)

```
def unit[A] (a: A): Par[A] =                                          // A strict unit
  es => new Future[A] { def apply (cb: A => Unit) = cb(a) } // Return 'a' immediately to continuation

def eval (es: ExecutorService) (r: => Unit): Unit =           // A helper function
  es.submit (new Callable[Unit] { def call = r })             // Submit a unit computation to an executor

def fork[A] (a: => Par[A]): Par[A] =                          // Marks 'a' for parallel execution
  es => new Future[A] {                                       // Do not evaluate, but delay in a Future
    def apply (cb: A => Unit) =                               //   (like unit)
      eval (es) (a (es) (cb))                                 // Eval 'a' and 'cb' via 'es' (parallel)
  }

def lazyUnit[A] (a: =>A) : Par[A] =                          // A lazy (by-name) version of unit
  fork (unit (a))                                             // Mark 'a' for parallel, wrap in unit
                                                              // NB. fork is by-name in the first arg.
```

The Implementation of Par [3/3]

The non-blocking CPS-based variant (Section 7.4.4)

```
 1 def map2[A,B,C] (p: Par[A], p2: Par[B]) (f: (A,B) => C): Par[C] =
 2   es => new Future[C] {                         // 1. Create a Par
 3     def apply (cb: C => Unit): Unit = {
 4       var ar: Option[A] = None                  // 2. A mutable cell to store result of p
 5       var br: Option[B] = None                  // 3. A mutable cell to store result of p2
 6       val combiner = Actor[Either[A,B]] (es) {  // 4. An actor to receive results from p,p2
 7         case Left (a) =>                        // 7. When p is done
 8           if (br.isDefined)                     // 8. If p2 has already finished (br is set)
 9             eval (es) (cb (f (a, br.get)))      // 9. Eval the callback with the merged result
10           else ar = Some (a)                    // 10. Otherwise store and finish
11                                                 // NB. No race, an actor handles 1 message at a time
12         case Right (b) =>                       // 11. When p2 is done
13           if (ar.isDefined)                     // 12. If p has already finished (ar is set)
14             eval(es) (cb (f (ar.get, b)))       // 13. Eval the callback with the merged result
15           else br = Some(b)                     // 14. Otherwise store and finish
16       }
17       p (es) (a => combiner ! Left (a))         // 5. Spawn ’p’, notify ’combiner’ with result when done
18       p2 (es) (b => combiner ! Right (b))       // 6. Spawn ’p2’, notify ’combiner’ with result on done
19     }                                           // NB. If ’p’ has a fork, then line 17 will exit
20   }                                             //     immediately and continue with ’p2’ in parallel
```

Other operators are derived
(see exercises)

Extension Methods (C# vs Scala)

```csharp
namespace ExtensionMethods {
  public static class MyExtensions {
    public static int WordCount(this String str)
    {
      return str.Split(
          new char[] { ' ', '.', '?' },
          StringSplitOptions.RemoveEmptyEntries
        ).Length;
    }
  }
}
using ExtensionMethods;
"Hello Extension Methods".WordCount();
```

```scala
case class MyStringOps (val str: String) {
  def wordCount = str.split (" .?".toArray)
                     .filter { !_.isEmpty }
                     .length
}

implicit def myStringOps (s: String) =
  MyStringOps (s)

...
...
"Hello Extension Methods".wordCount
...
```

- **Extension methods** C#, F#, Xtend, Kotlin: define static methods, call like instance method
- **Pimp my library pattern** Scala: define an **auxiliary class** with **new methods and fields** and an **implicit conversion** to this class
- That's why `String` in Scala has **more methods** than in Java, even though it is the **same class**!
- In fact, `split` is a method on `StringOps` not on `String` (see above)

source: https://docs.microsoft.com/en-us/dotnet/csharp/programming-guide/classes-and-structs/extension-methods

Extension Methods and Pimp My Library Pattern

- Two mechanisms to **extend an existing library**
- When you **cannot change the source** code
- Add methods to classes **without recompiling** the source
- **Even to Java classes from 1995!**
- Add methods to classes at **call location**, not at class definition location
- Even **objects** produced by **old code** (factories) get the new methods
- When you **read** someone else's code you need to know that you have to search **not only for class methods** but also for extension methods
- In Scala, extensions are often placed in the `*Ops` classes, e.g. https://www.scala-lang.org/api/2.12.3/scala/collection/immutable/StringOps.html
- **Exercises:** use this pattern to add methods to `Par` which is a function type alias! Not even an explicitly a class!

source: https://docs.microsoft.com/en-us/dotnet/csharp/programming-guide/classes-and-structs/extension-methods