FlowPools: Lock-Free Deterministic Concurrent Data-Flow Queues

Authors

EPFL, Switzerland
{firstname.lastname}@epfl.ch
http://lamp.epfl.ch

Abstract. Implementing correct and deterministic parallel programs is hard (additional motivation sentence after this). We present the design and implementation of a fundamental data structure for deterministic parallel data-flow computation. Aditionally, we provide a proof of correctness, showing that the implementation is linearizable, lock-free, and deterministic. Finally, we provide microbenchmarks which compare our *flow pools* against corresponding operations on other popular concurrent data structures, in addition to performance benchmarks on a real *XYZ* application using real data. (Keep abstract between 70 and 150 words).

Keywords: data-flow, concurrent data-structure, determinism

1 Introduction

1.1 Motivation

- we want a deterministic model - we do not block in the programming model (i.e. there are no operations which cause blocking until a value becomes available) - we want a non-blocking data-structure (i.e. the operations on the data-structures should themselves be non-blocking) - programs run indefinitely =¿ we need to GC parts of the data structure we no longer need - we want to reduce heap allocation and inline the datastructure as much as possible =¿ lower memory consumption, better cache behaviour and fewer GC cycles

Obligatory multicore motivation paragraph.

Lock-free is better, and why.

Introduction and motivation for data-flow programming model.

2 Model of Computation

Producer-consumer parallelism. Description and image of queue/stream of values, producer, and multiple consumers.

3 Programming Model

The FlowPool suite supports the following operations:

- `Builder.<<(x: T): Builder`
  Inserts an element into the underlying FlowPool.
- `Builder.seal(n: Int): Unit`
  Seals the underlying FlowPool at `n` elements. The need for the size argument is explained below. A sealed FlowPool may only contain `n` elements. This allows for callback cleanup and termination.
- `FlowPool.doForAll(f: T => Unit): Future[Int]`
  Instructs the FlowPool to execute the closure `f` exactly once for each element inserted into the FlowPool (asynchronously). The returned future contains the number of elements in the FlowPool and completes once `f` has been executed for all elements.
- `FlowPool.mappedFold[U, V <: U](acc: V)(cmb: (U,V) => V)(map: T => U): Future[(Int, V)]` Reduces the FlowPool to a single value of type V, by first mapping each element to an internal representation using `map` and then aggregating using `cmb`. No guarantee is given about synchronization or order. Returns a future containing a tuple with number of elements in the FlowPool and the aggregated value.
- `FlowPool.builder`
  Returns a builder for this FlowPool.
- `Future.map[U](f: T => U)`
  Maps this future to another future executing the function `f` exactly once when the first future completes.
- `future[T](f: () => T): Future[T]`
  Asynchronously dispatch execution of `f` an return a future with its result.

Determinism of `seal` We will show that the final size of the FlowPool is required as an argument to the seal method in order to satisfy the determinism property of the FlowPool. Look at the following program:

```
val p = new FlowPool[Int]()
val b = p.builder

future {
  for (i <- 1 to 10) { b << i }
  b.seal
}

future { for (i <- 1 to 10) { b << i } }
```

Depending on which for-loop completes first, this program completes successfully or yields an error. A similar program with `b.seal(20)` will always succeed.

Generators In the following we'll present a couple of generators for FlowPools based on common generators in the Scala standard library.

```
def iterate[T](start: T, len: Int)(f: (T) => T) = {
  val p = new FlowPool[T]
  val b = p.builder
  future {
    var e = start
    for (i <- 1 to len) { b << e; e = f(e) }
    b.seal(len)
  }; p
}

def tabulate[T](n: Int)(f: (Int) => T) = {
  val p = new FlowPool[T]
  val b = p.builder
  future {
    for (i <- 0 to (n-1)) {
      b << f(i)
    }
    b.seal(n)
  }; p
}

def fill[T](n: Int)(elem: => T) = {
  val p = new FlowPool[T]
  val b = p.builder
  future {
    for (i <- 1 to n) { b << elem }
    b.seal(n)
  }; p
}
```

Monadic Operations In the following we'll present some monadic operations on top of the basic FlowPool operations. This will also show some use-cases of the futures as result type of `doForAll`.

```
def map[S](f: T => S) = {
  val fp = new FlowPool[S]
  val b  = fp.builder
  doForAll { x =>
    b << f(x)
  } map { b.seal _ }
  fp
}
```

```
def filter(f: T => Boolean) = {
  val fp = new FlowPool[T]
  val b  = fp.builder

  mappedFold(0)(_ + _) { x =>
    if (f(x)) { b << x; 1 } else 0
  } map { case (c,fc) => b.seal(fc) }

  fp
}

def flatMap[S](f: T => FlowPool[S]) = {
  val fp = new FlowPool[S]
  val b  = fp.builder

  mappedFold(future(0))(_ <+> _) { x =>
    f(x).doForAll(b << _)
  } map { case (c,cfut) => cfut.map(b.seal _) }

  fp
}
```

where `<+>` is the future of the sum of two `Future[Int]`.

4 Implementation

5 Proofs

5.1 Abstract Pool Semantics

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5.2 Linearizability

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5.3 Lock-Freedom

5.4 Determinism

6 Experimental Results

7 Related Work

Things to probably cite: Oz, gpars, Java CLQ, our futures writeup.

Things we should probably have a look at: Microsoft TPL, Dataflow Java, FlumeJava...

Forcing a bib, [1], [2], [3], [4], [5], [6]

8 Conclusion

References

1. M. Bowman, S. K. Debray, and L. L. Peterson. Reasoning about naming systems. *ACM Trans. Program. Lang. Syst.*, 15(5):795–825, November 1993.
2. J. Braams. Babel, a multilingual style-option system for use with latex's standard document styles. *TUGboat*, 12(2):291–301, June 1991.
3. M. Clark. Post congress tristesse. In *TeX90 Conference Proceedings*, pages 84–89. TeX Users Group, March 1991.
4. M. Herlihy. A methodology for implementing highly concurrent data objects. *ACM Trans. Program. Lang. Syst.*, 15(5):745–770, November 1993.
5. L. Lamport. *LaTeX User's Guide and Document Reference Manual*. Addison-Wesley Publishing Company, Reading, Massachusetts, 1986.
6. S. Salas and E. Hille. *Calculus: One and Several Variable*. John Wiley and Sons, New York, 1978.

A Proof of Correctness

Definition 1 (Data types). A **Block** b is an object which contains an array $b.array$, which itself can contain elements, $e \in Elem$, where **Elem** represents the type of e and can be any countable set. A given block b additionally contains an index $b.index$ which represents an index location in $b.array$, a unique index identifying the array $b.blockIndex$, and $b.next$, a reference to a successor block c where $c.blockIndex = b.blockIndex + 1$. A **Terminal** $term$ is a sentinel object, which contains an integer $term.sealed \in \{-1\} \cup \mathbb{N}$, and $term.callbacks$, a set of functions $f \in Elem \Rightarrow Unit$.

Definition 2 (FlowPool). A **FlowPool** $pool$ is an object that has a reference $pool.start$, to the first block b_0 (with $b_0.blockIndex = 0$), as well as a reference $pool.current$ typically pointing to some subsequent block b_n where $b_n = b_0$ or where b_n is reachable from b_0 following $next$ references. Initially, $pool.current = pool.start$. The pool **state** $\mathbb{S}$ is defined as the sequence of blocks reachable from $pool.start$ by following $next$ references within blocks. More formally, the relation $reachable(b, c)$ on two blocks b, c holds iff $b = c \ \vee \ b.next = c \ \vee \ \exists b' \ : \ reachable(b, b') \wedge reachable(b', c)$.

Definition 3 (Abstract state). An **abstract state** $\mathbb{A}$ is a tuple $(elems, sealed)$ such that $\mathbb{A} \in \{(elems, sealed) \mid elems \subset Elem, \ sealed \in \{-1\} \cup \mathbb{N}\}$. Abstract state operations on some abstract state $\mathbb{A}$ are $append(\mathbb{A}, e) = \mathbb{A}'$ where $\mathbb{A}' = (elems \cup \{e\}, sealed)$ if $\mathbb{A} = (elems, sealed)$, $seal(\mathbb{A}, sealSize) = \mathbb{A}''$ where $\mathbb{A}'' = (elems, sealSize) \ : \ sealSize \in \mathbb{N}$ if $\mathbb{A} = (elems, sealed)$ and $sealed = -1$, the unsealed state, or $sealed = sealSize$ already.

Definition 4 (Consistency). A FlowPool state $\mathbb{S}$ of $pool$ with starting block $pool.start$ is consistent with an abstract state $\mathbb{A} = (elems, sealed)$ iff some element $e \in elems \Leftrightarrow \exists b, i \ : \ reachable(pool.start, b) \ \wedge \ b.array(i) = e$, and $\exists c, j \ : \ c.array(j) \in Terminal \wedge c.array(j).sealed = sealed \wedge reachable(pool.start, c)$. A FlowPool operation op is **consistent** with the corresponding abstract state operation op' iff $\mathbb{S}' = op(\mathbb{S})$ is consistent with an abstract state $\mathbb{A}' = op'(\mathbb{A})$. A **consistency change** is a change from state $\mathbb{S}$ to state $\mathbb{S}'$ such that $\mathbb{S}$ is consistent with an abstract state $\mathbb{A}$ and $\mathbb{S}'$ is consistent with an abstract set $\mathbb{A}'$, where $\mathbb{A} \neq \mathbb{A}'$.

Definition 5 (Lock-freedom). In a situation where some finite number of threads are executing a concurrent operation, that concurrent operation is *lock-free* if and only if that concurrent operation is completed after a finite number of steps by some thread.

We proceed by...

Theorem 1 (Lock-freedom). *FlowPool operations append, seal, and doForAll are lock-free.*

Lemma 1. *In each operation there is a finite number of execution steps between consecutive CAS instructions..*

Proof. The *append* operation is restarted in two cases. Case 1: iff *check* returns $true \ \wedge \ CAS1$ fails.

$expand$

$tryWriteSeal$

$asyncDoForAll$

Lemma 1. *If non-consistency changing CAS operations $CAS1$ or $CAS3$, in the pseudocode fail, they must have already been successfully completed by another thread since their corresponding operation began.*

Proof. Trivial inspection of the pseudocode reveals that since $CAS1$ makes up a check that precedes $CAS2$, and since $CAS2$ is the only operation besides $CAS1$ which can change the expected value of $CAS1$, in the case of a failure of $CAS1$, $CAS2$ (and thus $CAS1$) must have already successfully completed or $CAS1$ must have already successfully completed by a different thread.

Likewise, by trivial inspection $CAS3$ is the only CAS which can update the $b(next)$ reference, therefore in the case of a failure, some other thread must have already successfully completed $CAS3$ since the beginning of the operation. □

Lemma 2. *Non-consistency changing CAS operation $CAS4$ must successfully complete after a finite number of steps.*

Expand must successfully complete after a finite number of steps.

OLD: *Proof.* Case 1: The failing $CAS4$ happens after a successful $CAS3$. From lemma 1, we know that $CAS3$, which is a check that precedes $CAS4$, is guaranteed to be successfully completed by some thread, so we focus on the implications of failure of $CAS4$. Case 2: $CAS5$ takes place if *nb* is $null$. Therefore, in both cases, $CAS4$ and $CAS5$ successfully complete.

Lemma 3. *consistency-changing CAS operations ... will successfully complete.*

Proof. Uses $\mathbb{A}$.

Lemma 4. *Assume that the FlowPool is consistent with some abstract state $\mathbb{A}$. If one of the operations advance or expand succeeds, the FlowPool will remain consistent with the abstract state $\mathbb{A}$ following the operation.*

Proof. The CAS operations, denoted $CAS3$, and $CAS4$ in the pseudo-code, within the *expand* operation neither affect *elems* nor *sealed*, thus by Definition 4, causes no consistency change. Likewise, the *advance* operation either calls *expand* once, or it invokes $CAS1$ it may update the index of the current block, neither of which cause a consistency change.

Lemma 5 (). *If a consistency changing CAS completes, then the operation is guaranteed to successfully complete.*

Lemma 6 (). append operation is lock-free.

Lemma 7 (). seal operation is lock-free.

Lemma 8 (). doForAll operation is lock-free.