FlowPools: Lock-Free Deterministic Concurrent Data-Flow Queues

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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

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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 $b = c \ \vee \ b.next = c \ \vee \ \exists b' \ : \ reachable(b, b') \ \wedge \ reachable(b', c)$. A **state changing** instruction is any atomic write or CAS instruction that changes an object that can be accessed from $pool.start$.

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

$\exists c, j \ : \ c.array(j) \in Terminal \land c.array(j).sealed = sealed \land reachable(pool.start, c)$.
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 scenario 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.

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

We begin by first proving that there are a finite number of execution steps before a consistency change occurs.

Lemma 1. *After invoking an operation op, if non-consistency changing CAS operations $CAS1$, $CAS3$, or $CAS4$, in the pseudocode fail, they must have already been successfully completed by another thread since op 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 since *op* began executing.

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 *op*.

Like above, $CAS4$ is the only CAS which can change the *current* reference, therefore in the case of a failure, some other thread must have already successfully completed $CAS4$ since *op* began. □

Lemma 2. *Invoking the expand operation will execute a non-consistency changing instruction after a finite number of steps. Furthermore, given a total number of blocks numBlocks reachable in a FlowPool pool before invoking expand, the number of blocks $numBlocks'$ after some finite number of steps is guaranteed to satisfy $numBlocks' > numBlocks$.*

Proof. From inspection of the pseudocode, it is clear that the only point at which *expand* can be invoked is under the condition that for some block *b*, $b.index > LASTELEMPOS$, where $LASTELEMPOS$ is the maximum size set aside for elements of type *Elem* in any block. Given this, we will proceed by showing that a new block will be created with all related references *b.next* and *current* correctly set.

There are two conditions under which a non-consistency changing CAS instruction will be carried out.

- **Case 1:** if $b.next = \perp$, a new block *nb* will be created and $CAS3$ will be executed. From Lemma 1, we know that $CAS3$ must complete successfully on some thread. Afterwards recursively calling *expand* on the original block b.

- **Case 2:** if $b.next \neq \perp$, $CAS4$ will be executed. Lemma 1 guarantees that $CAS4$ will update *current* to refer to $b.next$, which we will show can only be a new block. Likewise, Lemma 1 has shown that $CAS3$ is the only state changing instruction that can initiate a state change at location $b.next$, therefore, since $CAS3$ takes place within Case 1, the Case 2 can only be reachable after Case 1 has been executed successfully. Given that Case 1 always creates a new block, therefore, $b.next$ in this case, must always refer to a new block.

Therefore, since from Lemma 1 we know that both $CAS3$ and $CAS4$ can only fail if already completed, thus guaranteeing their finite completion, and since $CAS3$ and $CAS4$ are the only state changing operations invoked through *expand*, the *expand* operation must complete in a finite number of steps.

Finally, since we saw in Case 2 that a new block is always created and related references are always correctly set, that is both $b.next$ and *current* are correctly updated to refer to the new block, it follows that *numBlocks* strictly increases after some finite number of steps.

Lemma 3. *Each operation executes only a finite number of steps between each state changing instruction.*

Proof. We begin by inspecting each operation which contains a state changing instruction individually.

The *append* operation involves the following state changing instructions; $CAS1$, $CAS2$, $WRITE1$, $WRITE2$, $CAS3$, and $CAS4$.

Lemma 4. *Assume a concurrent operation op is started. After a finite number of state changing instructions, a consistency changing CAS instruction is guaranteed to be successfully completed.*

Proof.

Lemma 5. *Assume a concurrent operation is started. If a consistency changing CAS instruction completes, some concurrent operation is guaranteed to be completed.*

Proof.

Lock-freedom.

By We have to show that we'll update *current* after a finite number of steps.

The *expand* operation contains two CAS instructions; $CAS3$ and $CAS4$.

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

Proof. The *append* operation is restarted in three cases. Case 1: iff *check* returns $true \ \wedge \ CAS1$ fails. Case 2: . Case 3:

$expand$

$tryWriteSeal$

$asyncDoForAll$

Then, the operation corresponding to the consistency-changing CAS instruction is guaranteed to be eventually completed

If there's a CAS failing, then some other thread completes the CAS. Consistency change means progress.

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.