Technical Report: Asymmetric Mutual Exclusion for RDMA

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"New instances of the mutual exclusion problem can still arise that make currently impractical algorithms useful, or that require new algorithms. One source of those instances is new hardware designs." – Leslie Lamport [16]

Abstract

Coordinating concurrent access to a shared resource using mutual exclusion is a fundamental problem in computation. In this paper, we present a novel approach to mutual exclusion designed specifically for distributed systems leveraging a popular network communication technology, remote direct memory access (RDMA). Our approach enables local processes to avoid using RDMA operations entirely, limits the number of RDMA operations required by remote processes, and guarantees both starvation-freedom and fairness.

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1 Introduction

Remote direct memory access (RDMA) is a popular network communication technology that directly implements the shared memory abstraction in the distributed setting by allowing a process to access memory on a remote machine without interacting with another process [24, 11, 25]. In addition to the ability to read and write shared memory on another machine, RDMA also enables processes to perform atomic read-modify-write (RMW) operations on remote memory, like compare-and-swap (CAS) and fetch-and-add (FAA). Hence, the API closely resembles that of modern shared-memory architectures.

Also similar to modern architectures, the memory semantics of RDMA is not sequentially consistent. Since remote operations complete asynchronously, local and remote access to a given memory location may be reordered [7]. Thus, the programming model requires that programmers wait until remote operations complete and use the provided RDMA memory fences, along with local ones, to guarantee ordering [11].

Moreover, atomicity between local and remote accesses is not guaranteed. For instance, RDMA reads and writes are only atomic with their local counterparts for accesses within a cache line [9]. Also, remote RMW operations are

| Access (8B) | Remote (RDMA) |
|-------------|---------------|
| Read | Yes | Yes | Yes |
| Write | Yes | Yes | No |
| RMW | Yes | Yes | No |

Table 1 Atomicity between 8-byte local and remote accesses.

1 Both of these behaviors are assumed throughout the paper.
not atomic with local RMW operations in commodity hardware without global atomicity support (i.e., atomicity among all operations – see Table 1). For instance, many RDMA implementations enforce atomicity of the remote RMW operations in the RDMA-capable network interface controller (RNIC) [13], precluding global atomicity. An upshot of the lack of atomicity for RMW operations is that synchronizing local and remote processes becomes more difficult and costly. In practice, RDMA RWM operations are frequently used in RDMA-based distributed systems when synchronizing concurrent access among processes (e.g., [6, 15, 29, 28]). In these systems, all processes rely on the RNIC to provide consistency. More precisely, local processes must use the loopback mechanism, which allows a process to access memory on its own machine by passing through the RNIC. Although fast compared to other network communication, RDMA is still at least an order of magnitude slower than local accesses [22, 13], degrading performance for local processes. Additionally, the RDMA loopback mechanism can cause poor performance due to internal congestion [15]. Alternatively, systems can leverage remote procedure calls (RPCs) to allow all synchronization to be handled exclusively with local processes. However, sending messages nullifies the performance benefit of directly accessing remote memory that RDMA provides. The prevalence of RPCs in RDMA-based systems (e.g., [9, 30, 14, 21, 26]) is attributed in part to the challenges associated with synchronizing local and remote processes.

In this paper, we describe a new mutual exclusion algorithm designed to capture the nuanced requirements of synchronizing local and remote processes in RDMA-aware systems without using loopback or RPCs. First, we define a model to precisely capture the interaction between local and remote processes and formalize the concept of operation asymmetry, a property that captures how processes interact with registers. This model motivates and informs the design of our RDMA-aware synchronization primitive that jointly optimizes behavior for both local and remote processes by eliminating RDMA use in local processes and limiting the number of RDMA operations required by remote processes. To the best of our knowledge, we are the first to solve mutual exclusion specifically for RDMA in a manner that does not require loopback or RPC handling for local processes, is starvation-free (i.e., a calling process eventually executes its critical section [10]), and is fair (i.e., lock acquisitions are first-come-first-served [10]).

To achieve our goal, we draw from lock cohorting [8] and the classic Peterson’s lock algorithm [23] to guarantee mutual exclusion between a local process \( p_L \) and remote process \( p_R \). The processes \( p_L \) and \( p_R \) are elected by the set of local processes and remote processes, respectively, via orthogonal mechanisms that we embed directly into Peterson’s lock. Thus, we reduce the \( n \)-process mutual exclusion problem to synchronizing a single local process and a single remote process. Compared to our approach, previous strategies to synchronize local and remote processes without RPCs are not starvation-free, entail further hardware support, or require RDMA loopback, which we discuss later. Finally, to verify the correctness of our solution we model check a TLA+ specification translated from a PlusCal algorithm.

2 System Model

We model an RDMA-based distributed system as a set of nodes \( N \) and processes \( P \), for which \( p_i^j \) is a process running on node \( n_i \) with a process identifier \( j \). All processes can access an RDMA-accessible shared memory \( M \) partitioned among the nodes, where each partition \( m_i \) on node \( n_i \) is composed of atomic registers. A register \( r^j_i \) resides in memory partition \( m_i \) and is identified by \( j \). Similar to previous RDMA system models [2], we assume that processes are asynchronous and that accesses to memory are failure free.

We define locality as a relation between the set of processes and the set of registers in
our system. A process is local if and only if it resides on the same node as the given register. Otherwise, it is remote. A local access is the means by which a local process accesses a register via the traditional memory subsystem of a machine (i.e., no RDMA operation). Alternatively, a remote access is an operation on a register that passes through the RNIC. For a given process, an operation on a register is enabled if the process is able to access the register using the given operation. Intuitively, local accesses are only enabled for local processes. However, remote accesses are enabled for all processes because RDMA allows processes to access a local register using RDMA loopback.

For each class of access (local or remote), a register supports three operations: read, write and compare-and-swap. We denote the local operations using Read, Write and CAS, and the remote operations with rRead, rWrite and rCAS. Recall from Table 1, the atomicity of operations between classes is not guaranteed. Due to this behavior, an rCAS operation appears to a local process as if it were a Read then Write. Without loss of generality, we define an object as operation asymmetric if, given two processes, the intersection of their respective enabled operations on the object is not equal to their union. In our model, registers are operation asymmetric since remote processes are constrained to remote accesses.

3 Mutual Exclusion Under Operation Asymmetry

Mutual exclusion is a known problem in which access to a shared resource is coordinated among two or more concurrent processes [19]. A naive solution to mutual exclusion is to implement a lock by enforcing that all processes, including the local ones, utilize rCAS to guarantee atomicity. As discussed in Section 1, RDMA loopback adds overhead and may exhibit anomalous performance bugs, causing the RNIC to become a bottleneck. To avoid these performance pitfalls, in our solution we enforce that local processes only use local operations. However, since atomicity is not guaranteed among local and remote RMW operations we must reassess how to implement a mutual exclusion primitive. Due to operation asymmetry, we require an algorithm solely built from the greatest common denominator: read-write registers. A natural choice is to look to Peterson’s lock for inspiration.

Peterson’s lock [23] is a well-known starvation-free mutual exclusion primitive for two processes. Because remotely accessible memory is composed of atomic read-write registers, Peterson’s lock can be implemented directly over RDMA, with the appropriate memory fences, to coordinate access between a local and a remote process. To allow multi-process synchronization, we modify the original Peterson’s lock algorithm to embed an orthogonal mutual exclusion primitive whereby a process participates in the Peterson’s lock protocol by first obtaining the embedded lock. Since we wish to limit the number of remote operations required for remote processes (e.g., spinning on remote memory), we embed the widely used MCS queue lock [24], allowing processes to spin locally while waiting in a queue of processes to acquire the lock. This combination of locks has similar characteristics to lock cohorting [8], which decouples the synchronization of cohorts of processes with global synchronization. The locks used for each step are called the cohort and global locks respectively, a nomenclature that we adopt. In our approach, processes of the same locality (local or remote) compete amongst themselves using a MCS queue cohort lock to determine a leader that then participates in the global Peterson’s lock protocol.

Note that a naive solution to multi-processes mutual exclusion is a filter lock [23], which extends Peterson’s lock for multiple processes. Briefly, processes compete for access to successive levels that each hold back one process. The number of levels is equal to one less than the number of processes that might acquire the lock. Unfortunately, this would require both remote spinning and a number of remote accesses proportional to the number of
processes that might contend for the lock, even if a process executes in isolation. Lamport’s Bakery algorithm [10] also demonstrates the same undesirable behavior for remote processes.

Below, we first discuss our modified Peterson’s lock mechanism, then describe our MCS queue lock design. Subsequently, we address fairness by extending the Peterson’s lock API and incorporating a budget into the cohort lock. Finally, we compare our technique to lock cohorting and other RDMA-based mutual exclusion approaches. Algorithm [1] and Algorithm [2] provide the pseudo-code for our modified Peterson’s lock and RDMA-based MCS queue lock implementations, respectively. Appendix [A] contains a PlusCal version of our design that can be translated to a TLA+ specification, which we model checked.

### Algorithm 1 Modified Peterson’s Lock

```plaintext
Data: (global) cohort[2], victim

pLock() begin
  id ← getCid() // Get ID of process class
  other ← 1− id
  isLeader ← cohort[id].qLock()
  if isLeader then
    victim ← id
    while cohort[other].qIsLocked() and victim = id do wait
  end
pUnlock() begin
  id ← getCid()
  cohort[id].qUnlock()
pReacquire() begin
  id ← getCid()
  other ← 1− id
  victim ← id // Yield lock to waiting process
  while cohort[other].qIsLocked() and victim = id do wait // Reacquire lock
```

### 3.1 Algorithm Description

Our modified Peterson’s lock algorithm (Algorithm [1]) has two global variables: cohort, which is a two element array of cohort locks, and victim, which decides which process yields execution. In pLock(), a process first announces interest in executing its critical section by locking the appropriate cohort lock. When the cohort lock acquisition returns true, the calling process directly acquired the lock from another member of its cohort and may enter the critical section without additional steps. Otherwise, the process must engage in the Peterson’s lock protocol, in which case the wait condition (Line 7) is nearly identical to the original algorithm other than the calling process checking whether the other cohort lock is held. pUnlock() simply unlocks the cohort lock corresponding to the calling process’s class, allowing a waiting process to proceed. Crucially, any interleaving of instructions in concurrent calls to pLock() will only allow a single process access to the critical section, assuming that sequential consistency is enforced.

Next, we describe our modified MCS queue algorithm (Algorithm [2]) for remote processes. It should be noted that the local version of the algorithm can be obtained by directly replacing each remote access with a local one. This algorithm maintains two global variables: glock is a remote reference to the global lock, tail is a remote reference to the corresponding slot in the cohort array of Algorithm [1] which acts as the tail of the lock queue. In qLock(), a process atomically swaps a new descriptor into tail then waits until the process is at the head of the queue, finally returning whether the queue was empty at its outset. The value swapped into the tail of the queue contains an address of the remotely accessible descriptor desc, which is local to the locking process. If tail was not previously set, the call returns
## Algorithm 2 Budgeted MCS Queue Lock for Remote Process

**Data:** (constants) $k_{\text{InitBudget}}$; (global) $g\text{lock}$, $t\text{ail}$; (process-local) $\text{desc}$, $\text{leader}$

```
q\text{Lock}() begin
1 desc ← MCSDescriptor($k_{\text{InitBudget}}$, nullptr) // Remotely accessible
2 curr ← nullptr
3 while true do
4   // Note: curr updated on rCAS
5   if rCAS(tail, /*expected=*/curr, /*swap=*/&desc) = curr then
6     if curr = nullptr then return true
7     break
8   desc.budget ← −1
9   rWrite(&(curr->next), &desc) // Busy wait locally
10  while desc.budget = −1 do wait
11  if desc.budget = 0 then
12     g\text{lock}.p\text{Reacquire}() // Provides fairness
13     desc.budget ← $k_{\text{InitBudget}}$
14     return false
15 q\text{Unlock}() begin
16  if desc.next = nullptr then
17     if rCAS(tail, &desc, nullptr) = &desc then return
18  while desc.next = nullptr do wait
19  rWrite(\text{desc.next}−>budget), desc.budget − 1) // Pass the lock
20 q\text{IsLocked}() begin
21  return rRead(tail) ≠ nullptr
```

false since the cohort lock was not passed to the calling process. Otherwise, desc allows
the locking process to spin locally while waiting for another process to pass the lock via an
rWrite operation, returning true once the lock is passed. When the queue is empty, a lone
process requires only a single rCAS to acquire the lock. Otherwise, if the queue is not empty,
a lone process requires an additional rWrite to set its predecessor’s next value. Note that
once the descriptor is enqueued the calling process avoids remote spinning, thus reducing
network traffic.

After acquiring the lock and performing its critical section, a process attempts to release
the lock following the conventional MCS queue algorithm, which tries to CAS the back of
the queue back to a null value. Recall that if the CAS operation in the MCS queue lock
q\text{Unlock}() is successful, then it also releases the Peterson’s lock, since the corresponding
cohort is now unset. Otherwise, the process passes the lock to the next waiting process by
performing a rWrite to the location returned by the attempted CAS. At worst, a process
requires an rCAS operation followed by an rWrite when unlocking.

The above algorithm is unfair because the lock may be passed indefinitely among processes
of the same class. To address this, we extend the Peterson’s lock to support p\text{Reacquire}()
(Algorithm 1 Line 12), which releases the lock by setting itself as the victim then immediately
reacquires the lock. We also alter the original MCS queue algorithm to support a budget,
similar to the technique used by Dice et al. \cite{8}. A lock is passed by setting the budget of
a waiting process to a non-negative integer that represents the number of remaining lock
acquisitions. When the budget reaches zero, an acquiring process must call p\text{Reacquire}()
on the global lock. If there is a waiting process of the opposite class, it will be allowed to
proceed. Otherwise, the calling process reacquires the global lock and resets the budget.
Since the global lock is released after a bounded number of cohort lock acquisitions, and
the global lock is itself fair (i.e., a waiting process cannot be overtaken), our approach is fair \cite{5}.

In summary, our technique enables local and remote processes to synchronize via inde-
pendent mutual exclusion primitives embedded in a modified Peterson’s lock algorithm. By
using a budgeted MCS queue lock as the embedded lock, we can provide fairness. Lastly, our
approach is RDMA-aware since local processes avoid RDMA loopback and remote processes
avoid remote spinning, both important factors in RDMA-enabled system performance.

4 Related Work

Similar to lock cohorting [8], a strategy for NUMA-aware synchronization, our approach allows a group of processes to compete amongst itself before acquiring a global lock. Our technique explicitly couples the global and cohort locks to achieve behavior tailored to the respective processes in our system. By embedding the cohort lock in the global lock, we avoid an additional remote access for remote processes while maintaining the integrity of the global lock. The application of lock cohorting in a distributed setting is a natural extension of the technique but it requires rethinking the design to optimize for operation asymmetry between local and remote processes, yielding a lock primitive that is of independent interest.

To the best of our knowledge, our approach is the first mutual exclusion primitive designed for RDMA that provides local-only access for local processes while maintaining fairness and avoiding RPCs. A notable alternative is the technique pioneered by Wei et al. [27], which allows local accesses to be protected by hardware transactional memory (HTM) while remote accesses acquire a lock using RDMA CAS. This technique only applies to architectures supporting HTM, which is increasingly disabled due to security concerns [17, 12]. Due to cache coherent I/O, a local hardware transaction is aborted whenever a remote process acquires the lock. Local operations use local accesses in the common case but a fallback path using RDMA is also needed. Another potential option is to leverage RDMA-accessible memory permissioning, which atomically revokes remote access [3, 11], to devise a mutual exclusion algorithm. However, this approach is known to be slow [4] and is not easily made starvation-free since remote access may be continuously revoked by local processes.

Finally, our notion of operation asymmetry is a useful property to capture the relative capabilities of processes. While in our model asymmetry stems from the operations with which a process accesses a register, this notion can also capture the behavior of asymmetric multiprocessing (AMP). AMP is a recent architectural innovation in which cores on the same processor offer different power characteristics [18]. So called large cores specialize in higher performance while small cores are energy efficient. The adoption of AMP in commodity hardware has led to new techniques to balance their respective needs [15, 1]. We leave a more detailed analysis of the application of operation asymmetry to other domains for future work but we believe it is a practical tool to capture asymmetry in process capabilities, especially as it pertains to recent trends in heterogenous architectures.

5 Conclusion

In this paper we present a new model for describing the atomicity of memory for RDMA-based systems and we define operation asymmetry to capture how processes do not operate on a register equally. Based on our model, we propose a fair mutual exclusion mechanism inspired by lock cohorting to enable local and remote processes to synchronize while optimizing for their individual behavioral constraints. Our design embeds an RDMA-aware MCS queue lock into a modified version of Peterson’s lock protocol to achieve our design goals. To the best of our knowledge, our technique is the first mutual exclusion solution that allows synchronizing local and remote processes while avoiding both RDMA loopback and RPCs.
Appendix

A PlusCal Algorithm

MODULE qplock

EXTENDS Integers, Sequences, TLC

CONSTANTS NumProcesses, InitialBudget

ASSUME NumProcesses > 0

ASSUME InitialBudget > 0

NP \triangleq NumProcesses

B \triangleq InitialBudget

--algorithm qplock

variables

\begin{align*}
\text{Global} & \quad \text{victim} \in \{1, 2\}, \\
\text{cohort} & \quad = [x \in \{1, 2\} \mapsto 0], \\
\text{descriptor} & \quad = [x \in \text{ProcSet} \mapsto \text{budget} \mapsto -1, \text{next} \mapsto 0], \\
\text{Process-local} & \quad \text{passed} = [x \in \text{ProcSet} \mapsto \text{FALSE}], \\
\end{align*}

define

\begin{align*}
\text{Us}(\text{pid}) & \triangleq (\text{pid} \% 2) + 1 \\
\text{Them}(\text{pid}) & \triangleq ((\text{pid} + 1) \% 2) + 1 \\
\text{Budget}(\text{pid}) & \triangleq \text{descriptor}[\text{pid}].\text{budget}
\end{align*}

end define ;

procedure AcquireGlobal()

begin

\begin{align*}
g1: & \quad \text{victim} := \text{self} ; \\
gwait: & \quad \text{while TRUE do} \\
g2: & \quad \text{if cohort}[\text{Them}(\text{self})] = 0 \text{ then} \\
& \quad \quad \text{goto g4} ; \\
& \quad \text{end if} ; \\
g3: & \quad \text{if victim} \neq \text{self} \text{ then} \\
& \quad \quad \text{goto g4} ; \\
& \quad \text{end if} ; \\
& \quad \text{end while} ; \\
g4: & \quad \text{return ;}
\end{align*}

end procedure ;

procedure AcquireCohort()

variables \text{pred}

begin

\begin{align*}
c1: & \quad \text{descriptor}[\text{self}] := [\text{budget} \mapsto -1, \text{next} \mapsto 0] ; \\
\text{swap}: & \quad \text{pred} := \text{cohort}[\text{Us}(\text{self})] ; \text{cohort}[\text{Us}(\text{self})] := \text{self} ; \\
cwait: & \quad \text{if} -(\text{pred} = 0) \text{ then} \\
c2: & \quad \text{descriptor}[\text{pred}].\text{next} := \text{self} ; \\
c3: & \quad \text{await} \text{Budget}(\text{self}) \geq 0 ; \\
c4: & \quad \text{if} \text{Budget}(\text{self}) = 0 \text{ then} \\
& \quad \quad \text{c5:} \quad \text{call AcquireGlobal()} ; \\
& \quad \quad \text{c6:} \quad \text{descriptor}[\text{self}].\text{budget} := B ; \\
& \quad \text{end if} ; \\
c7: & \quad \text{passed}[\text{self}] := \text{TRUE} ; \\
\text{else} & \quad \text{c8:} \quad \text{descriptor}[\text{self}].\text{budget} := B ;
\end{align*}

\end{procedure
procedure ReleaseCohort()
variables size, next
begin
  cas: if cohort[Us(self)] = self then
    cohort[Us(self)] := 0;
  else
    r1: await ¬(descriptor[self].next = 0);
    r2: descriptor[descriptor[self].next].budget := Budget(self) − 1;
  end if;
  r3: return;
end procedure;

fair process p ∈ 1 . . NP
begin
  p1: while TRUE do
    Non-critical section
    ncs: skip;
    Acquire the cohort lock
    enter: call AcquireCohort();
    Acquire the global lock, maybe
    p2: if ¬passed[self] then
      call AcquireGlobal();
    end if;
    Critical section
    cs: skip;
    Release the cohort lock
    exit: call ReleaseCohort();
  end while;
end process;
end algorithm;

Safety
MutualExclusion ⊩ (∀ i, k ∈ ProcSet : (i ≠ k) ⇒ ¬(pc[i] = “cs” ∧ pc[k] = “cs”))

Liveness
ExecsCriticalSectionInfinitelyOften ⊩ ∀ i ∈ ProcSet : □◇(pc[i] = “cs”)
StarvationFree ⊩ ∀ i ∈ ProcSet : (pc[i] = “enter”) □¬(pc[i] = “cs”)
DeadAndLivelockFree ⊩ (∃ i ∈ ProcSet : pc[i] = “enter”) □¬ (∃ i ∈ ProcSet : pc[i] = “cs”)

Fairness
CohortFairness ⊩ ∀ i, j ∈ ProcSet : (pc[i] = “cwait” ∧ pc[j] = “enter”) ⇒ (pc[i] = “cs” □¬ pc[j] = “cs”)
GlobalFairness ⊩ ∀ i, j ∈ ProcSet : (pc[i] = “gwait” ∧ pc[j] = “enter”) ⇒ (pc[i] = “cs” □¬ pc[j] = “cs”)
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