Non-Blocking Inter-Partition Communication with Wait-Free Pair Transactions

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Wait-Free Pair Transactions

A communication mechanism that is:

- Lightweight
- Transactional
- Non-blocking
- One-way
- Safe
- “Natural”

WFPTs Cont'd

WFPTs are a shared-memory mechanism.
Transactions are explicit:

- Writers commit
- Readers update

Referential integrity is guaranteed.
Access to transaction fields requires no application changes.

Motivation

Real-time systems may contain tasks of differing priority.
Communication among such tasks must bound priority inversion.
Traditional solutions for this are:

- Priority Inheritance Protocol
- Priority Ceiling Protocol
- Asynchrony (not easy in Java!)

The scene is complicated by tasks of differing criticality.

Mixed-Criticality Systems

The Fiji Multi-VM allows multiple independent Java VMs to execute, isolated in time and space.

This complicates safe, low-overhead communication.

WFPTs are ideal for crossing VM partitions!

Wait-Free Pair Transaction Semantics

WFPT objects provide two contexts, reader and writer.
Both contexts:

- Never block
- Never lose coherence
- Have $O(1)$ access to transaction fields

Writers:

- Can commit their changes
- Never share changes without committing

Readers:

- Can update to the writer's committed changes
- Never share their changes

Java Language WFPT Semantics

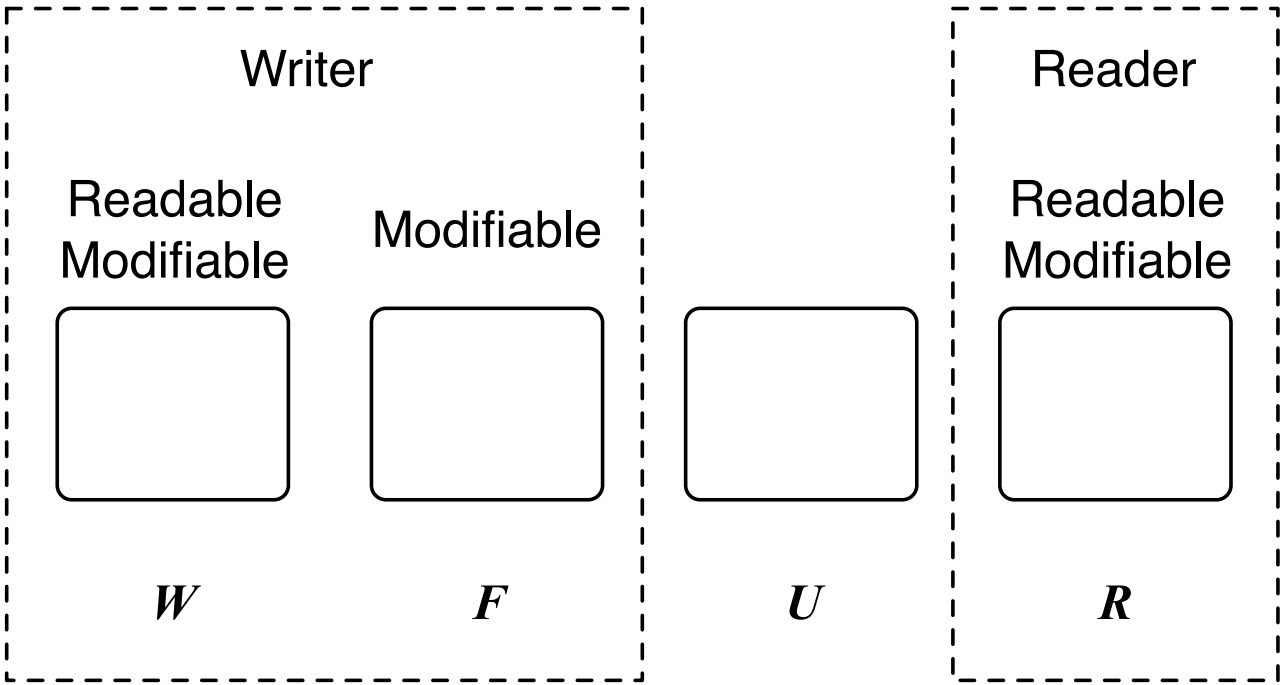
- WFPT objects subclass `WaitFreePairTransaction`
- Static fields are not subject to WFPT semantics.
- Static fields are not shared between partitions for inter-partition WFPT.
- WFPT object field accesses behave like “regular” objects.
- The commit and update operations are provided by final methods on `WaitFreePairTransaction`.

WFPT Object Model

WFPT Objects don't use the "normal" Fiji VM Java object model

- WFPT object fields are replicated four times.
  - These replicas are named by mutable indexes W, F, U, and R.
  - Each index has a different role in the transaction.
  - The replica at W is currently being written by the writer.
  - F will receive the writer's next commit.
  - U will become the read index on the next update.
  - R is currently being read by the reader.
- An update flag indicates whether there has been a commit since the last update.
- A tracking structure is used for each WFPT object to store WFPT state and facilitate transactions.

WFPT Replicas

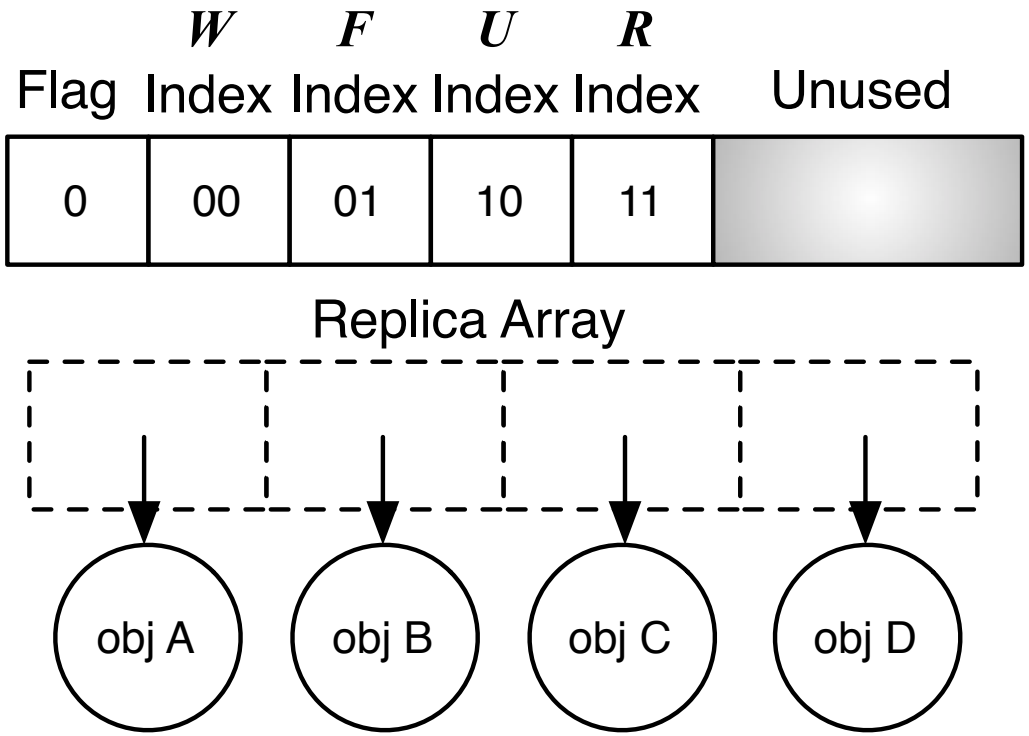


Commit

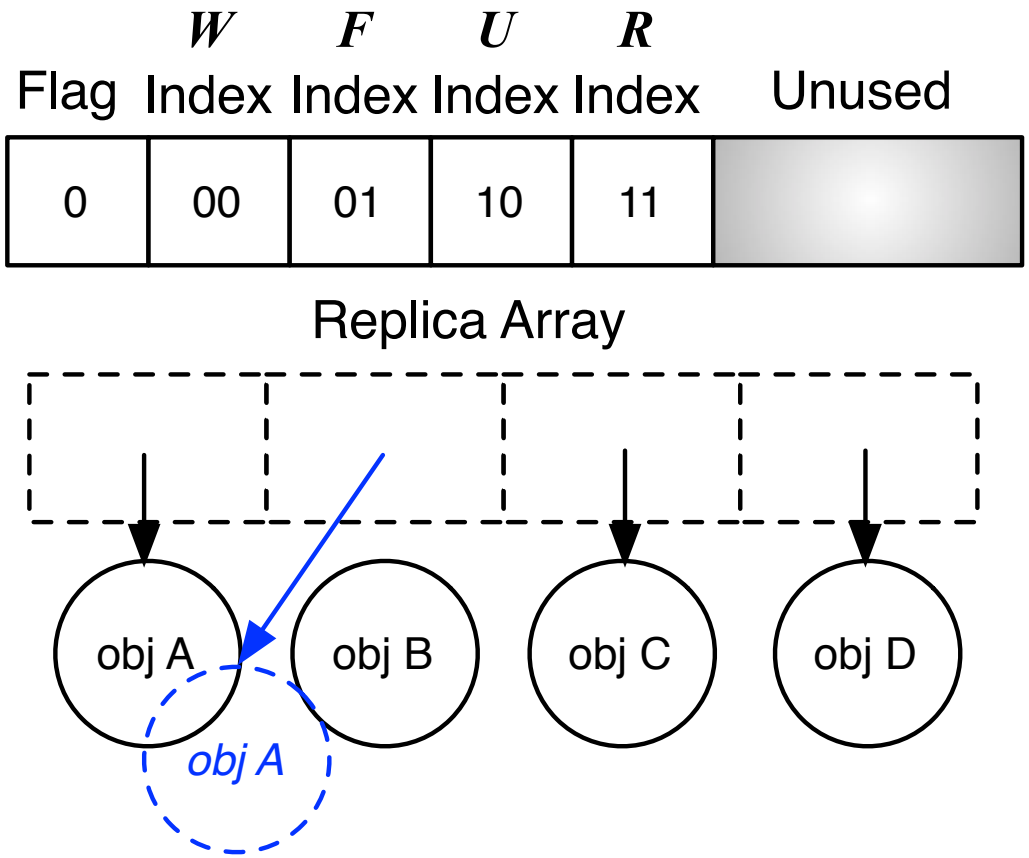
1. Copy the contents of the replica at W to the replica at F.
2. Atomically swap the indexes U and F while setting the update flag.

Note that this operation modifies only the replica at F (before the swap) and affects only the indexes F and U.

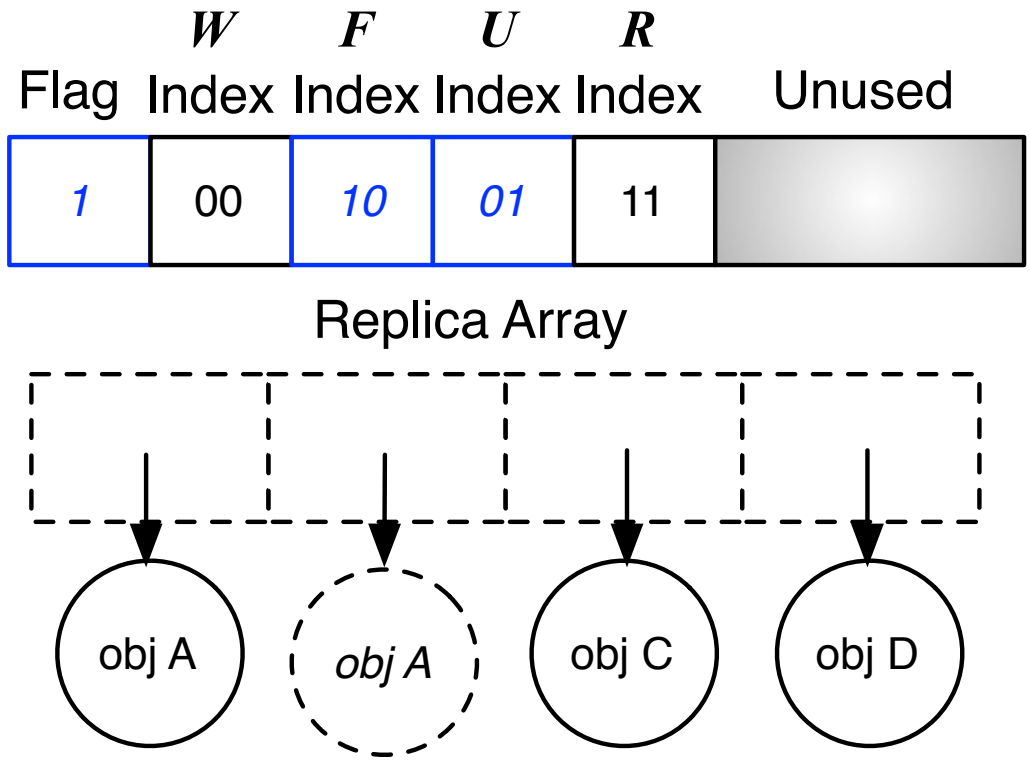
Replica State Prior to Commit



Replica State After Commit Phase I



Replica State After Commit Phase II

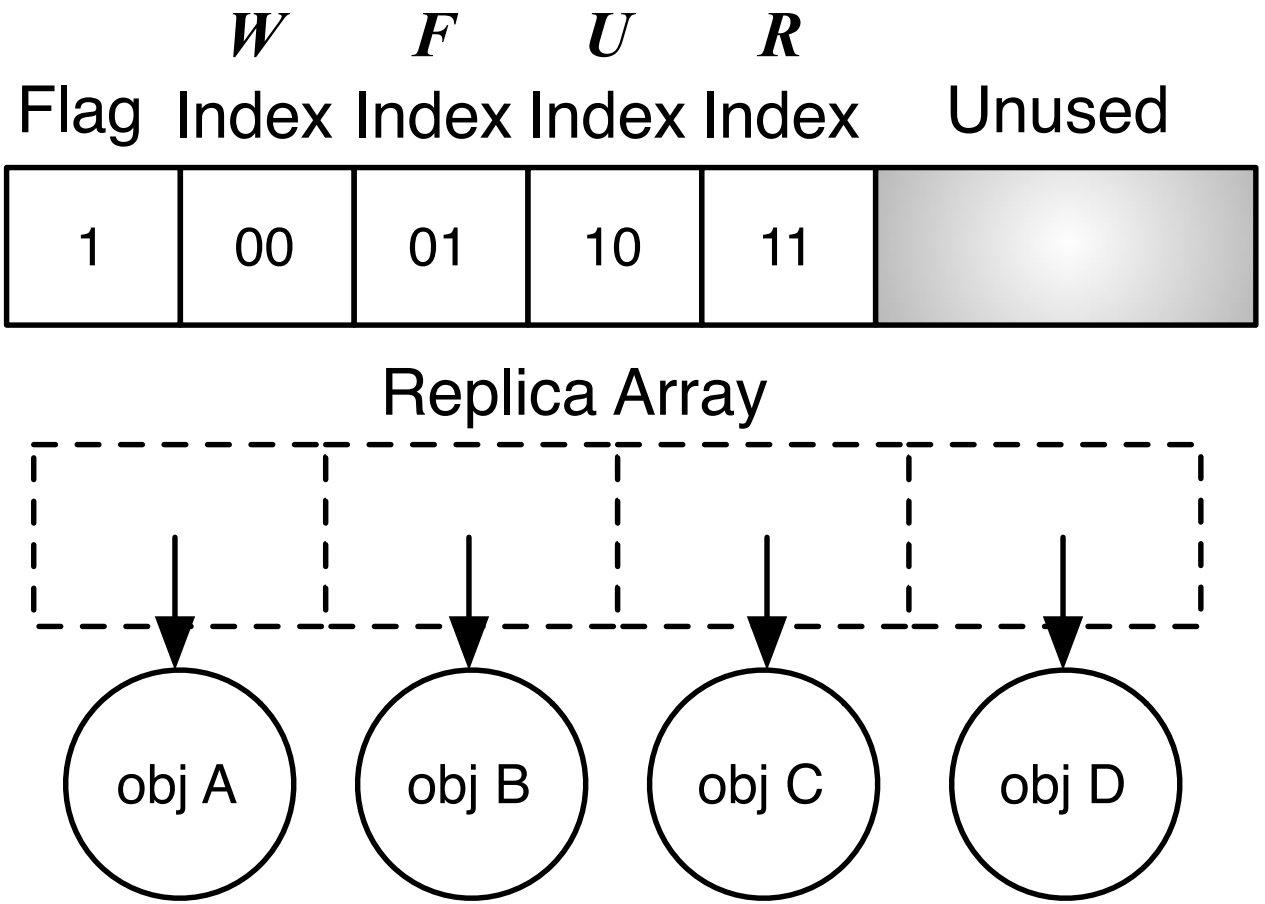


Update

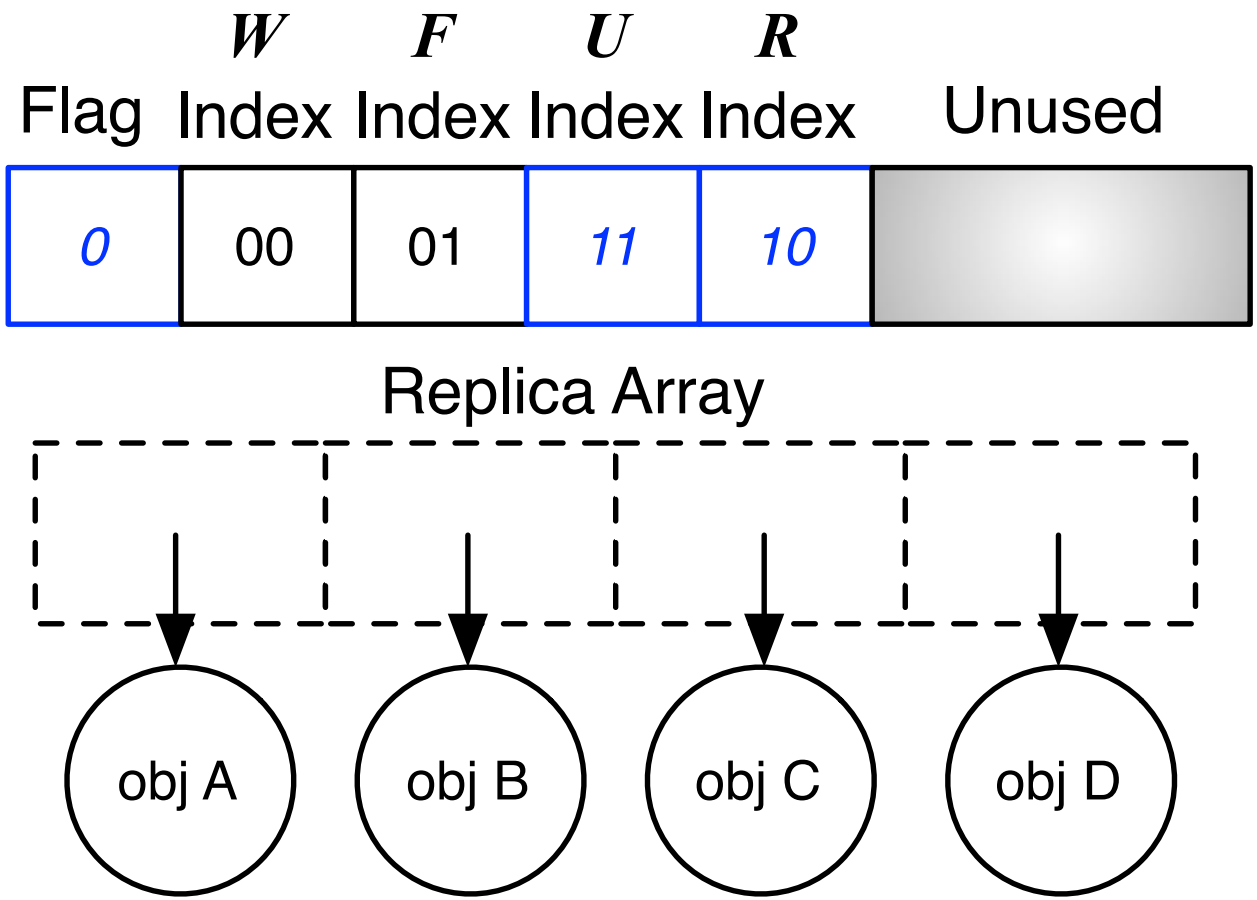
1. Check the update flag, return if clear.
2. Atomically swap the indexes U and R while clearing the update flag.

Note that this operation modifies no replicas, and affects only the indexes U and R.

Replica State Prior to Update



Replica State After Update



Complexity

For the higher priority context on a WFPT:

- update runs in $O(1)$ time.
- commit runs in time proportional to the size of the object.
- All operations are completely independent of the other context's state.

For the lower-priority context on a WFPT:

- Transaction complexity remains the same.
- Field accesses are completely independent of the other context's state.
- Transactions may be affected by the other context.

Safety and Correctness

The safety and correctness of WFPT transactions are predicated upon:

- The replica at U is never modified.
- The writer only reads or modifies W and F.
- The reader only reads or modifies R.
- F and U are swapped only when all of the following are true:
  - The update flag is set,
  - F contains the newest commit, and
  - U contains the most recent previous commit, if it exists.

Safety and Correctness, cont'd

Thus:

- Neither context can "see" the other context's current replica.
- The reader is always guaranteed to update to either:
  - The most recent commit, or
  - The immediately previous commit.

Implementation Overview

WFPT involves changes to both the runtime and compiler.
Compiler:

- Four new classes
- Almost entirely self-contained
- < 500 lines

Runtime:

- WFPT objects replaced with `WFPTProxy` tracking objects
- One new exception
- Trivial change to `newInstance()`

Compiler Changes

- Tracking structure allocation at `new` time
- Method lookasides
- Cast replacements to hide `WFPTProxy`
- Access barriers to perform context lookups

Proxy Objects

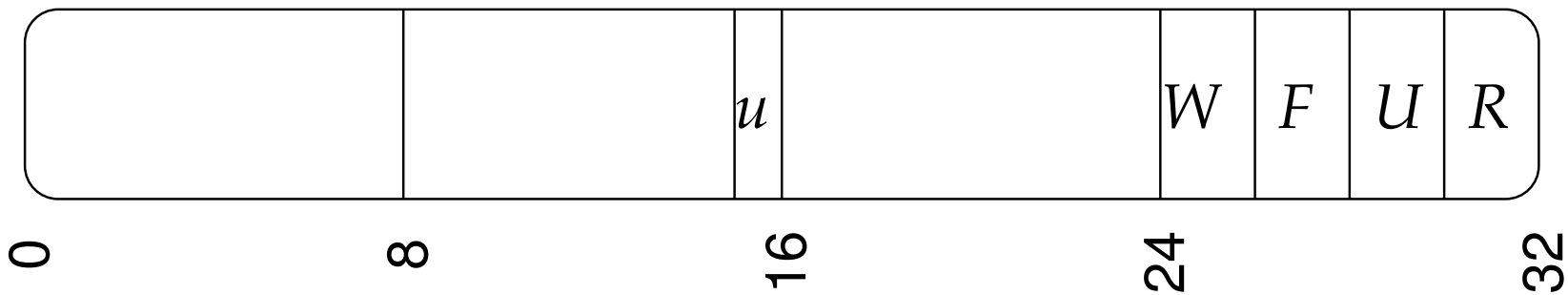
The proxy object contains four items:

- One word for index values and update flag
- Array of four WFPT objects
- Reader context object
- Writer context object

The context objects are entirely uninteresting.

Index Field

All four index values and the update flag are packed into a single 32-bit word:



Index updates are then performed by strong CAS.

Inter-partition Communication

Some restrictions must be levied for inter-partition WFPT:

- IP-WFPT objects must be negotiated *a priori* and are allocated in “immortal” memory.
- Reference fields are forbidden.
- WFPT object structure must be identical in size and layout across partitions.
- Concurrent access to IP-WFPT objects does not guarantee coherency within a partition.

WFPT Overhead

Worst-case micro-benchmarks:

```
public synchronized void set(int value) {
    this.value = value;
}

public void set(int value) {
    this.value = value;
}
```

Micro-benchmark Results

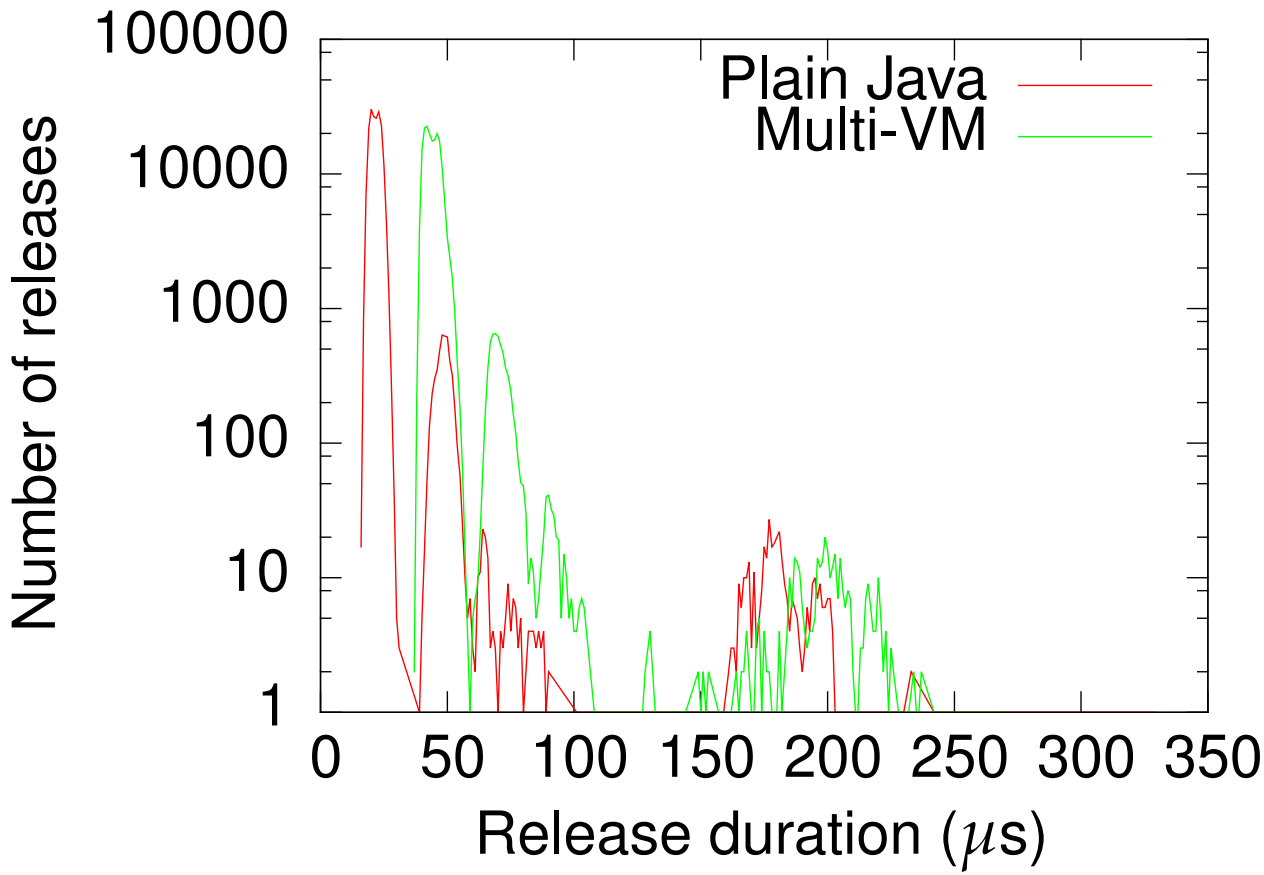
Configuration	ARM	LEON3
Monitors	123	5107
WFPT	260	6557
WFPT w/ Commit	653	14107

All values are in nanoseconds.

Multi-VM jPapaBench

- jPapaBench consists of three major modules:
  - Autopilot
  - Simulator
  - Fly-by-Wire (FBW)
- We placed the FBW module in its own VM.
- Communication between VMs is via three WFPT objects.

Stabilization Release Durations



Conclusions

- WFPT is a viable mechanism for both inter- and intra-partition communication.
- Optimization for elision of context checks is wanted for performance, to bring overheads closer to monitors.
- Inter-partition WFPT is viable in a Multi-VM, but safety requires restrictions that should be carefully examined.

Questions?

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