A Verified High-Performance Composable Object Library for Remote Direct Memory Access

POPL 2026

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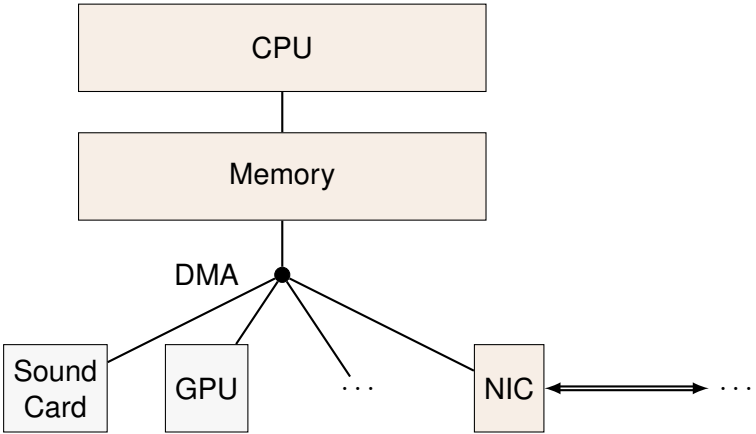
January 16, 2026

Remote Direct Memory Access (RDMA)



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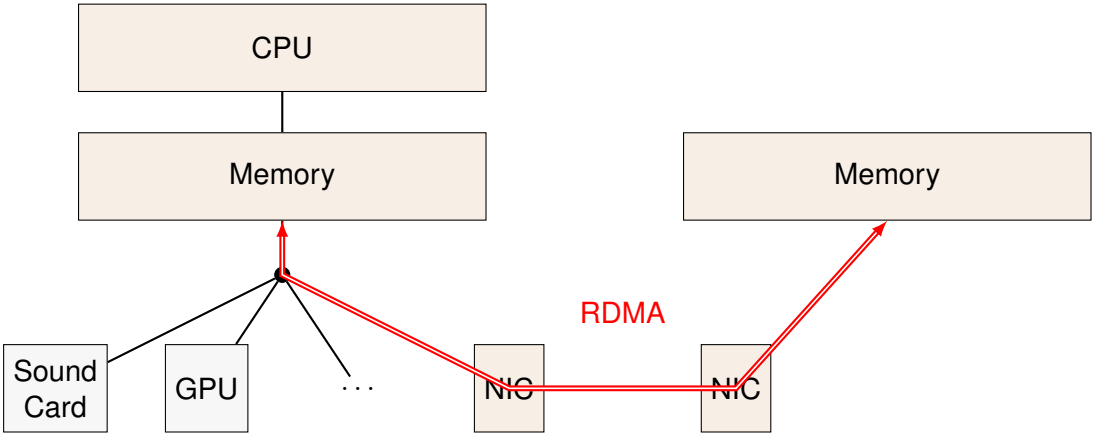

RDMA: Data-transfer protocol for High-Performance Computing
Low Latency: $\sim \mu$s

RDMA^{TSO} [OOPSLA 24]

Two nodes, one thread

$x = 0$	$z = 0$
$\widetilde{z} := x$ $x := 1$	

$z = 0$ ✓ $z = 1$**?**

Can the output be $z = 1$?

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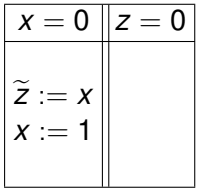
$z = 0$ ✓ $z = 1$ ✓

Can the output be $z = 1$?

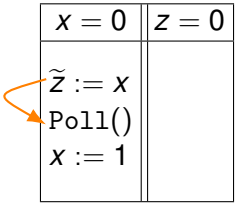
Yes! like this:

- CPU offloads "$\widetilde{z} := x$" to the NIC
- CPU executes "$x := 1$"
- NIC picks up "$\widetilde{z} := x$" and reads 1
- ...

RDMA^{TSO} [OOPSLA 24]



$z = 1$ ✓



$z = 1$ ✗

Can prevent this!

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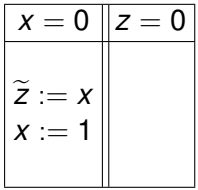

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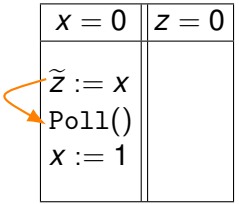

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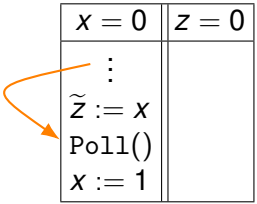

$z = 1$ ✓

Can prevent this!

But it's context-dependent...

Problems and Contributions

Problems with current RDMA programs:

- Low-level non-modular code (no libraries)
- No formalisation or verification

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Our contributions:

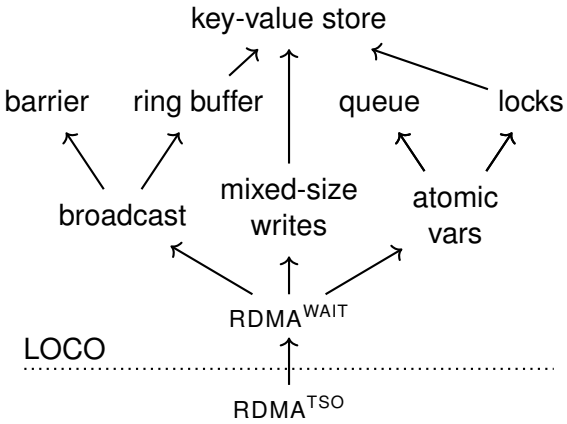
- Generalised RDMA^{TSO} to $\text{RDMA}^{\text{WAIT}}$ as a modular alternative
- LOCO: High-performance Modular RDMA Libraries
- Mowgli: Framework for Libraries in (very) weak settings such as RDMA
- Local soundness result for simpler verification
- Specified and verified a large fragment of LOCO using Mowgli

LOCO: Overview

LOCO (Library of Composable Objects)

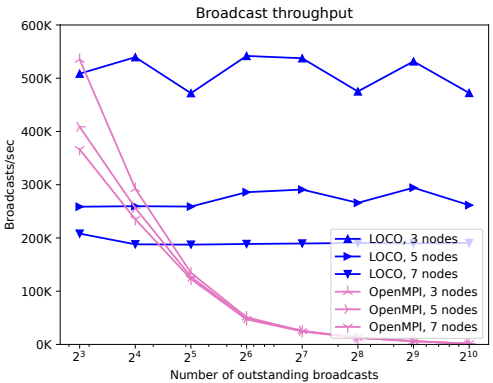
One manager thread talks to the hardware
$\Rightarrow$ RDMA$^{\text{WAIT}}$ (context independent code)

Tower of libraries, allowing programming RDMA similarly to shared-memory

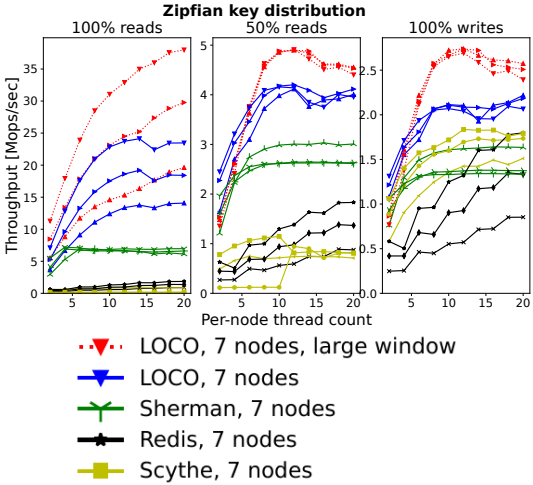


LOCO: High-Performance Libraries

Broadcast Benchmark



Key-Values Store Benchmark



Specification: Ring Buffer Library

Example 1: Ring Buffer (single-writer-multiple-reader, FIFO)

$$\texttt{Send}\colon \mathsf{Loc} \times \mathsf{Val} \to () \quad \text{and} \quad \texttt{Recv}\colon \mathsf{Loc} \to \mathsf{Val} \cup \{\bot\}$$

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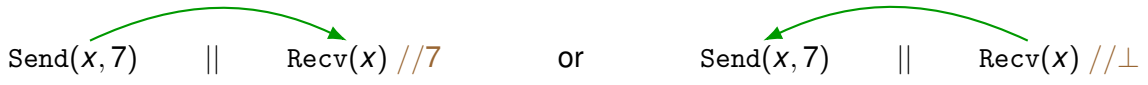

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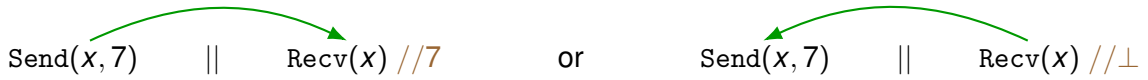

Ring Buffer library spec (wishlist, first draft, version 0)

- Syntax (`Send`, `Recv`)
- Behaviour constraints (e.g. FIFO)
- Synchronisation dependencies ($\longrightarrow$)

Specification: Barrier Library

Example 2: Barrier library

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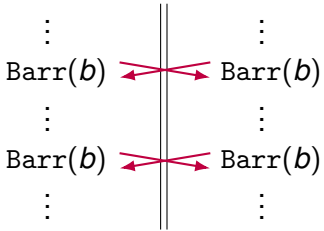
Thread synchronisation:

All threads reach the barrier before any can continue past.



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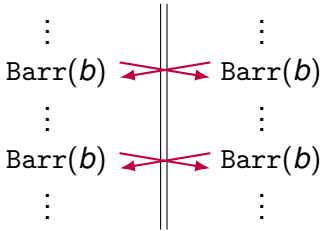
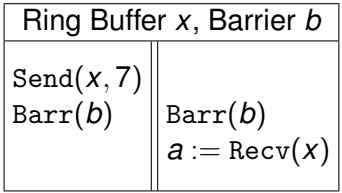


Barrier library specification (wishlist, first draft, version 0)

- Syntax (`Barr`)
- Behaviour constraints (e.g. used same number of times by each thread)
- Synchronisation dependencies ($\longrightarrow$)

Execution



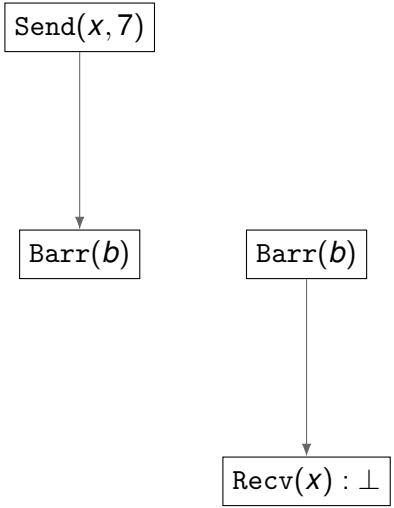
A global execution is allowed if it:

- respects the semantics of every library
- doesn't create dependency cycles

Execution

Ring Buffer x, Barrier b	
$\texttt{Send}(x, 7)$ $\texttt{Barr}(b)$	$\texttt{Barr}(b)$ $a := \texttt{Recv}(x)$

Claim: $a \neq \bot$



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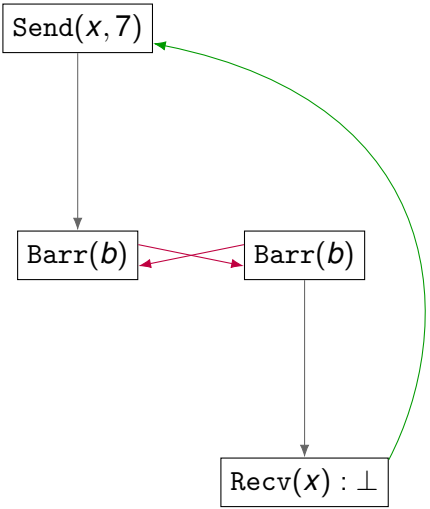

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Execution (First Try)

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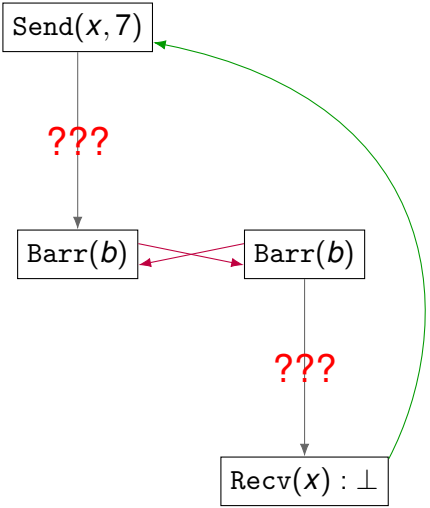

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Program Order Dependencies???

Remember the first example:

$x = 0$	$z = 0$
$\widetilde{z} := x$ $x := 1$	

$z = 1$ ✓

Program order is **not** always respected...

When is it respected?

Stamp ordering for RDMA

Previous documented hardware (re)orderings:

Second Stamp

First Stamp			Ordered?	single					families					
				1	2	3	4	5	6	7	8	9	10	11
				aCR	aCW	aCAS	aMF	aWT	aNLR$_n$	aNRW$_n$	aNRR$_n$	aNLW$_n$	aRF$_n$	aGF$_n$
single	A	aCR		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	B	aCW		✗	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓
	C	aCAS		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	D	aMF		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	E	aWT		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
families	F	aNLR$_n$		✗	✗	✗	✗	✗	SN	SN	SN	SN	SN	SN
	G	aNRW$_n$		✗	✗	✗	✗	✗	✗	SN	SN	SN	✗	SN
	H	aNRR$_n$		✗	✗	✗	✗	✗	✗	✗	✗	SN	SN	SN
	I	aNLW$_n$		✗	✗	✗	✗	✗	✗	✗	✗	SN	✗	SN
	J	aRF$_n$		✗	✗	✗	✗	✗	SN	SN	SN	SN	SN	SN
	K	aGF$_n$		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

11 **stamps** (**categories** of operations) define when ordering is preserved.

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Reorderings for (independent) libraries?

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Reorderings for (independent) libraries?

Mowgli solution:

- Use hardware behaviours as categories (stamps).
- Libraries specify the effects of each function.

Mowgli Ring Buffer library specification

- like before: syntax, semantics, $\longrightarrow$
- `Send` is in the "NIC write" category
- `Recv` is in the "CPU read" category

Mowgli Barrier library specification

- like before: syntax, semantics, $\longrightarrow$
- `Barr` has Fence and Read behaviours

Mowgli Execution (Fixed)

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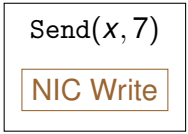

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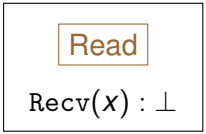

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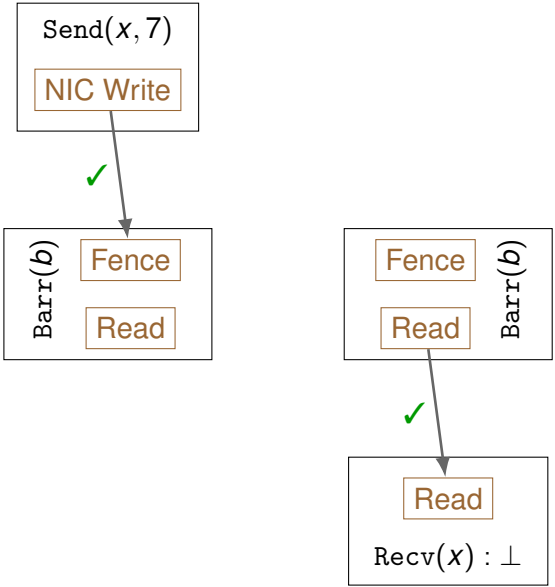

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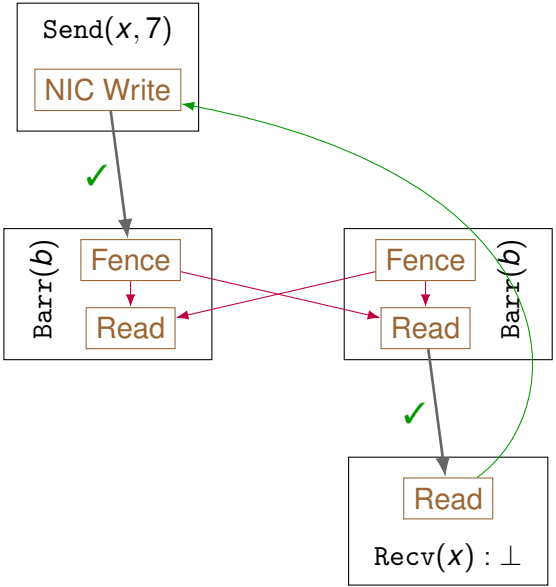

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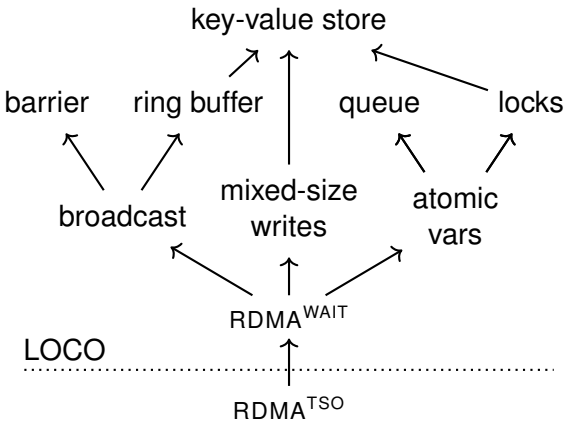
Verifying Library Implementations



Libraries can be implemented using other libraries

Programs can use a set Λ of libraries

Inlining an implementation I (of library L) **should be fine**

Implementation Soundness

How do we prove correct an implementation I for a library L?

- **Soundness** [general, hard to show]:
  Outcomes of the implementation are valid, in **all** contexts:
  $\forall \Lambda, P.\ \texttt{outcome}_{\Lambda}(I(P)) \subseteq \texttt{outcome}_{\Lambda \uplus \{L\}}(P)$

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  Considers I and L in isolation.

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Programmers prove local soundness, Mowgli gives soundness for free.

Conclusion

Summary:

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Thanks for listening!

Poll vs Wait Semantics

Base RDMA (RDMA^{TSO}):

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$z = 1$ ✓

$x = 0$	$z = 0$
$\widetilde{z} := x$ `Poll()` $x := 1$	

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$z = 1$ ✓

$x = 0$	$z = 0$
$\widetilde{z} :=^{d} x$ $\texttt{Wait}(d)$ $x := 1$	

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