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Āpta: Fault-tolerant object-granular CXL disaggregated memory for accelerating FaaS

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informatics

arm

NVIDIA

Āpta
Reliable
CXL.mem

Function-as-a-Service or “Serverless”

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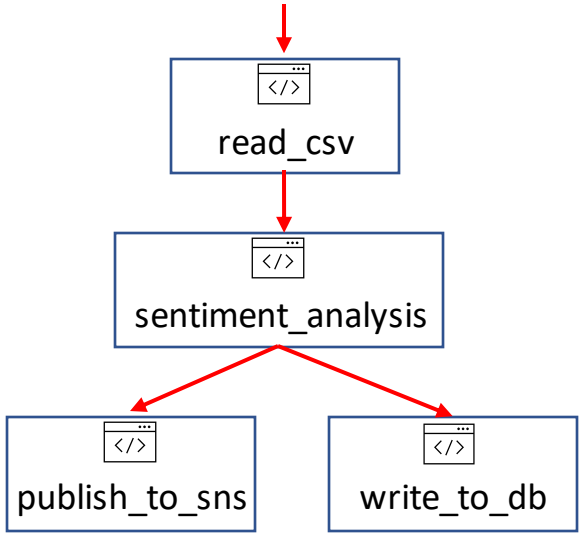
FaaS applications

- State machine workflow of *stateless* functions



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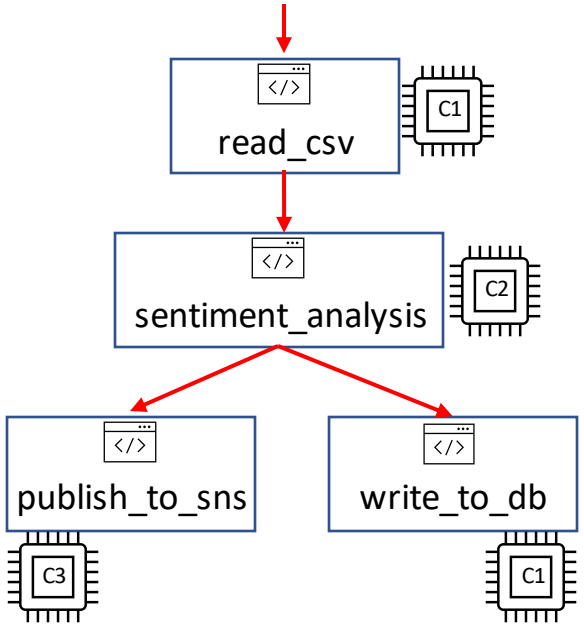

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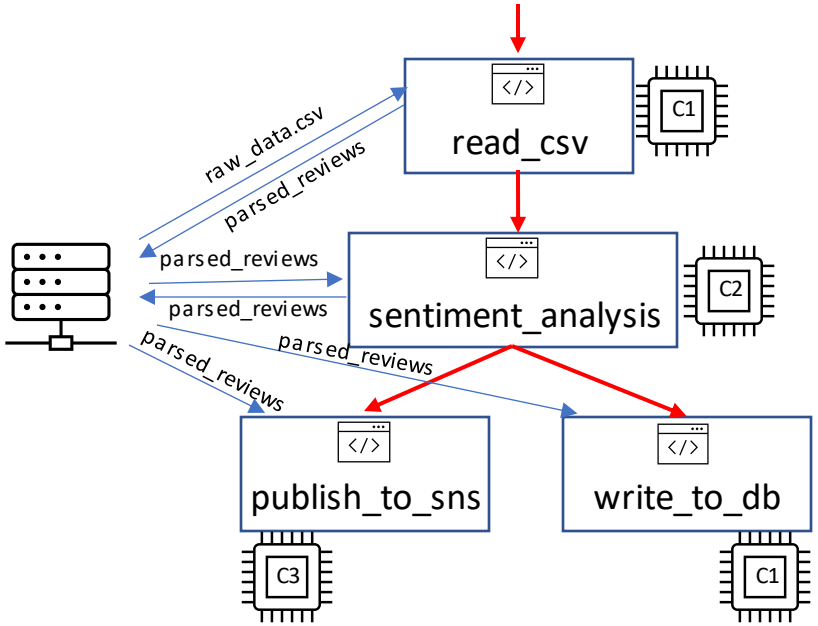
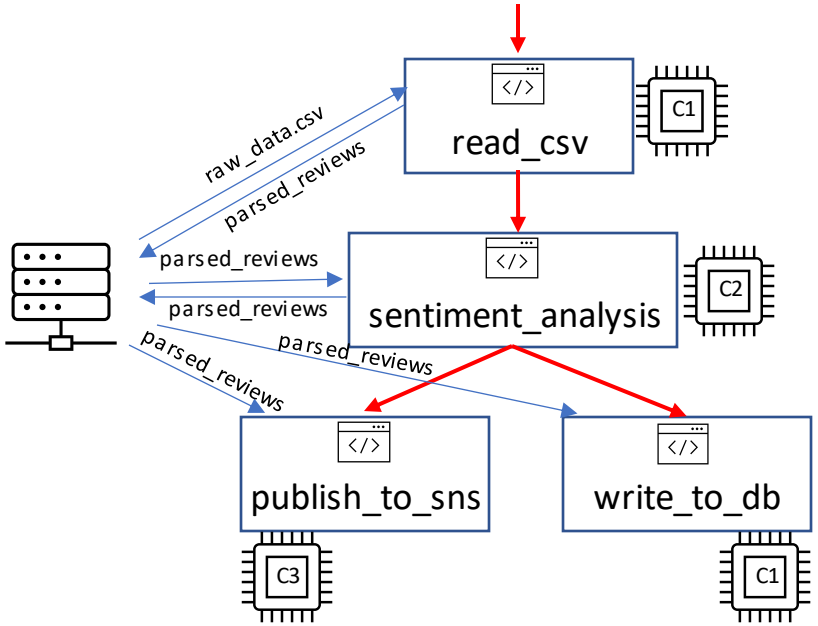


FaaS applications

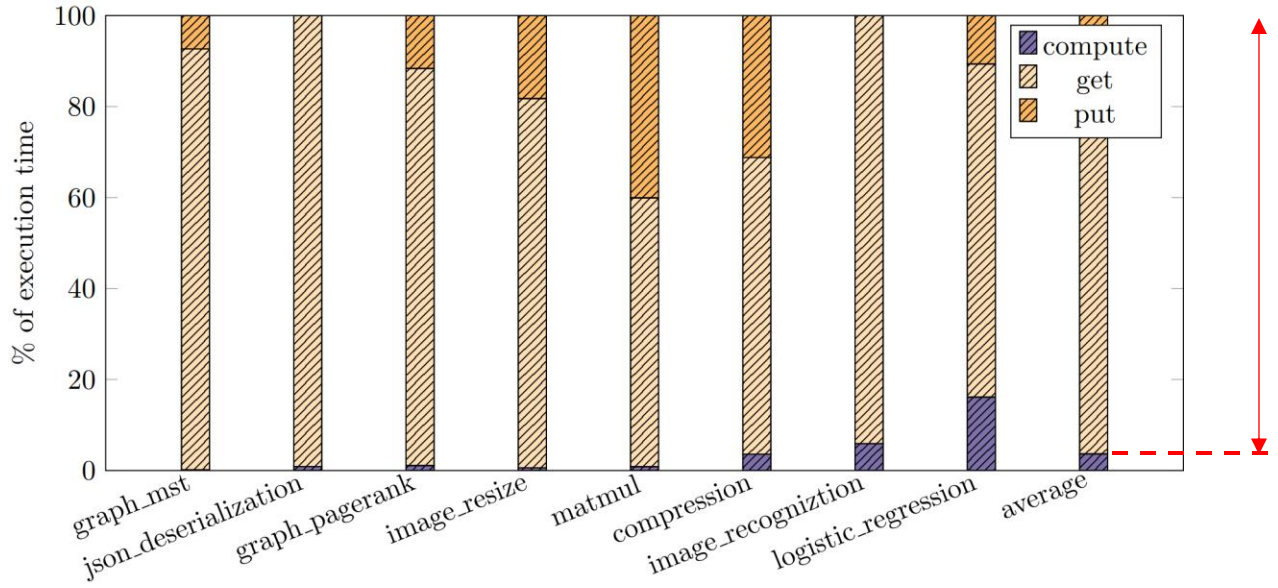
- State machine workflow of *stateless* functions
- Cloud provider dynamically orchestrates and schedules functions on a fleet of compute servers
- State maintained externally as objects in a remote data store
  - × Splitting state-compute adds communication overheads

How much?



Quantifying communication overheads

- Functions from FunctionBench and SeBS benchmark suites
- Compute - Optimized with Intel OneAPI, run on 16-core Skylake CPUs
- Communication - Amazon S3 object store (median of 100 executions)

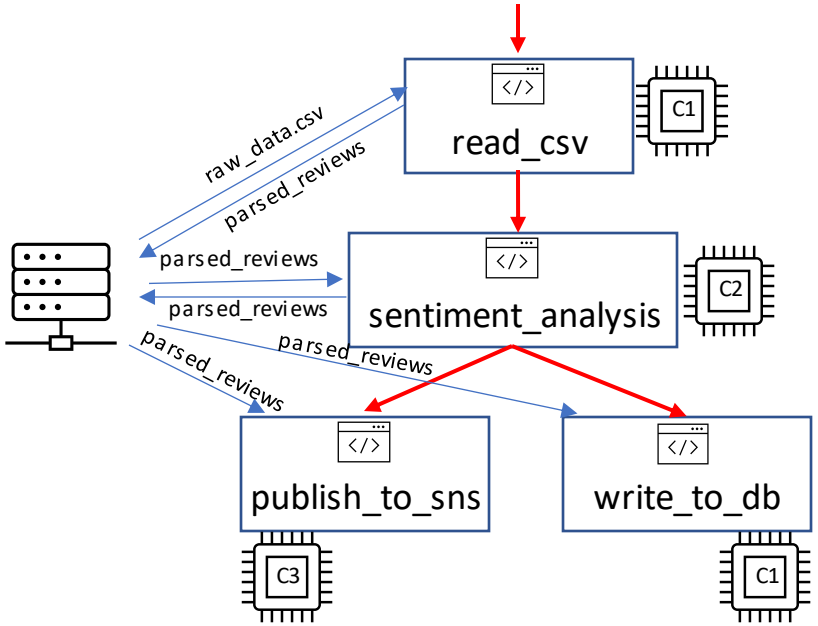


96% of execution time is spent in retrieving data from S3

Inefficiency of FaaS applications

- State machine workflow of *stateless* functions
- Cloud provider dynamically orchestrates and schedules functions on a fleet of compute servers
- State maintained externally as objects in a remote data store
  - × Splitting state-compute adds communication overheads
  - × Communication overheads severely limit performance

Can we do better?



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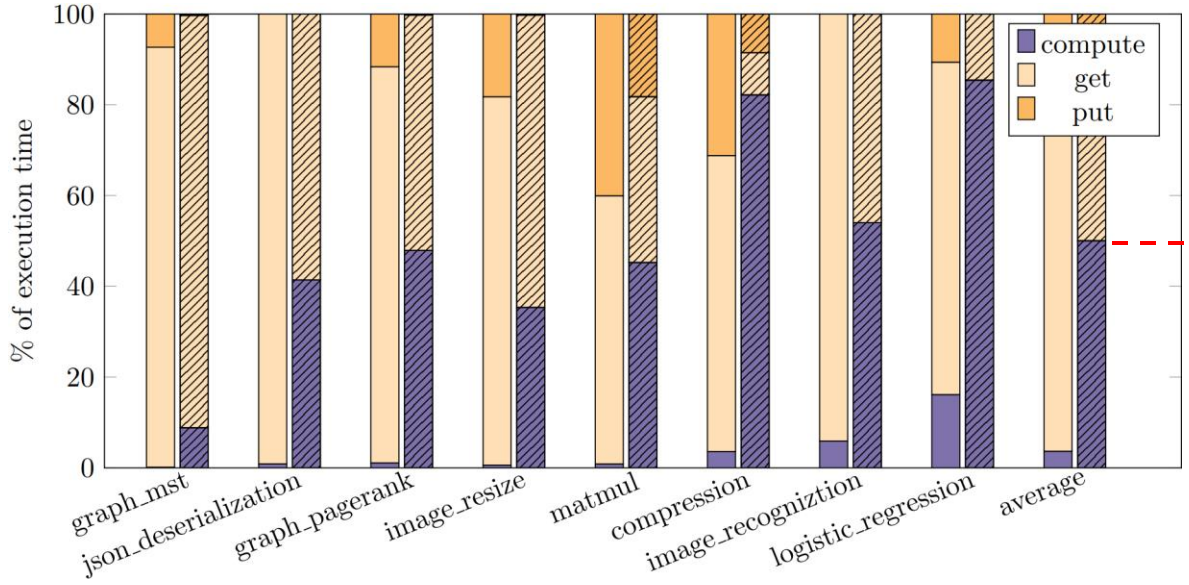
Can we do better?

- High-performance in-memory object store
- One-sided RDMA verbs to read/write objects
- Infiniband network (Mellanox ConnectX-3 NIC on PCIe-gen3 x16)



51% of execution time is spent in retrieving data from object store

The problem: Communication overheads

"The two most expensive operations in terms of cost were the orchestration workflow and when data passed between distributed components."

Āpta architecture

Object-granular CXL disaggregated memory

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Object-granular CXL disaggregated memory

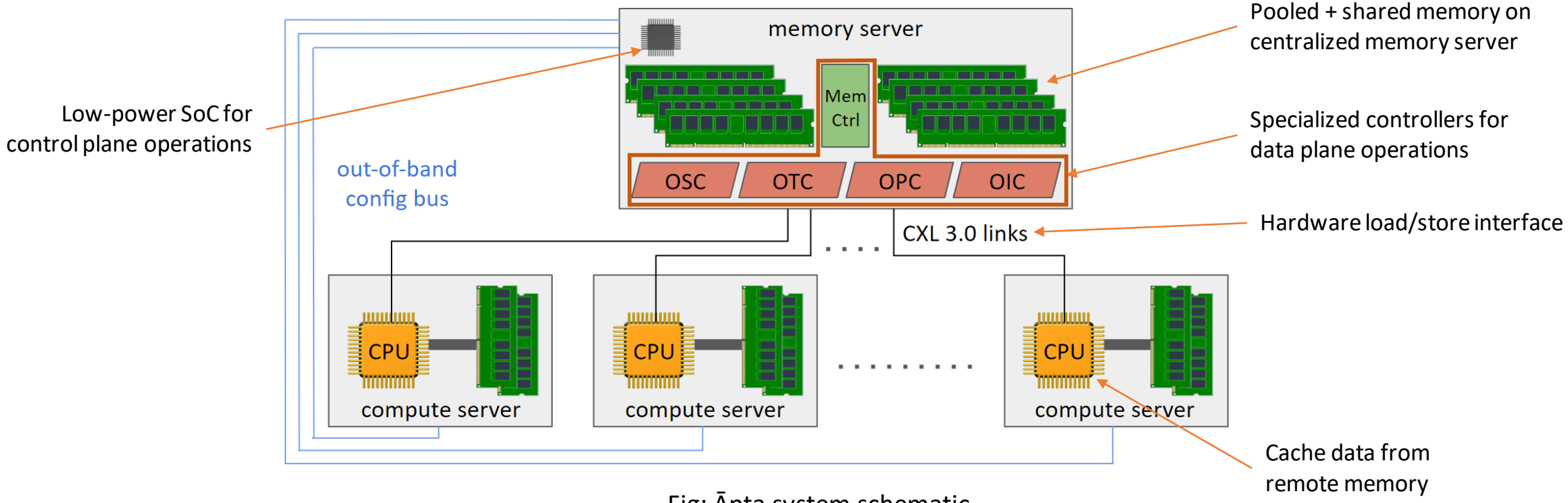
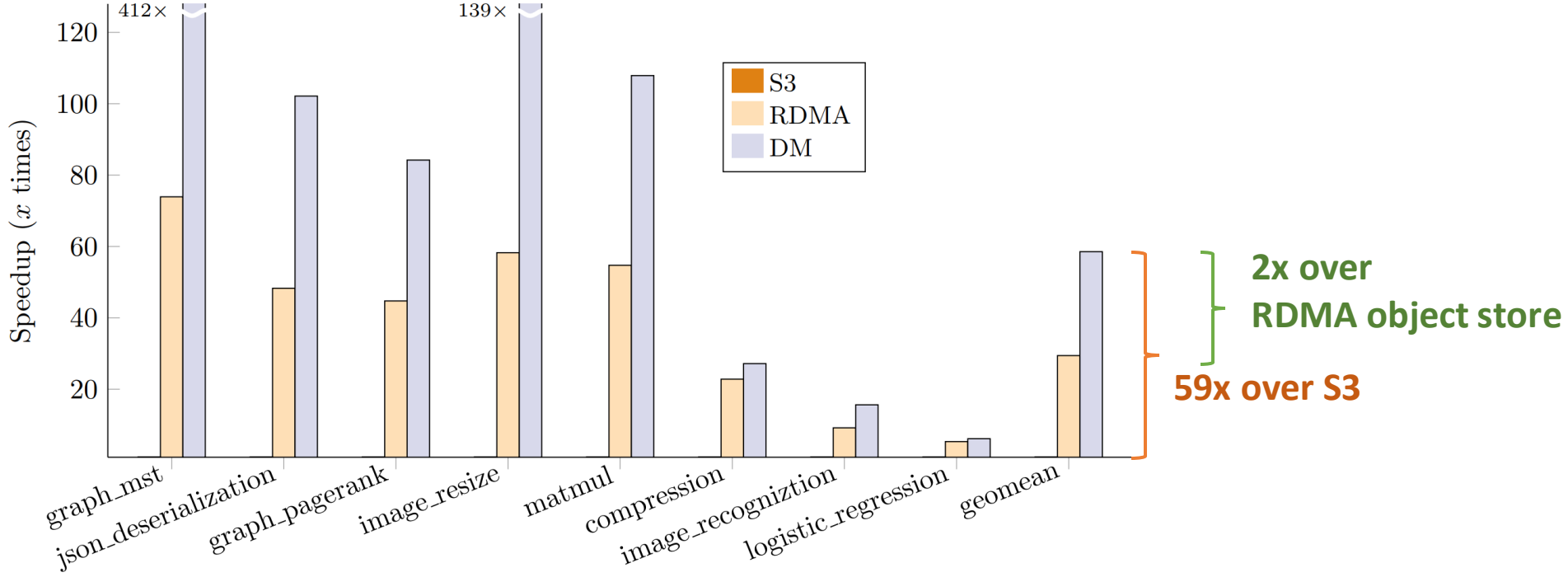


Fig: Āpta system schematic

Performance potential of Āpta

With disaggregated memory - OpenCAPI-like access latency / bandwidth†

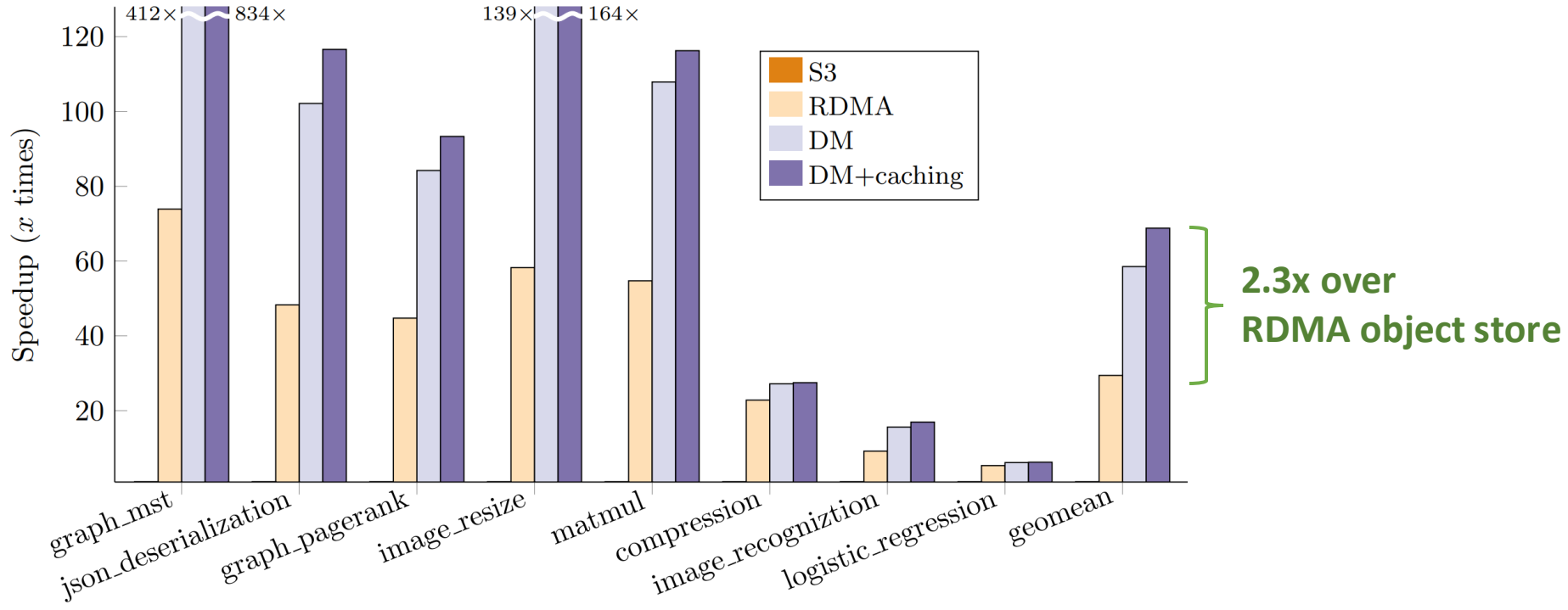


13% communication overheads (Recall 51% for RDMA-based object store)

† ThymesisFlow [MICRO 20]

Performance potential of Āpta

With object caching at compute server



2.3x over RDMA object store

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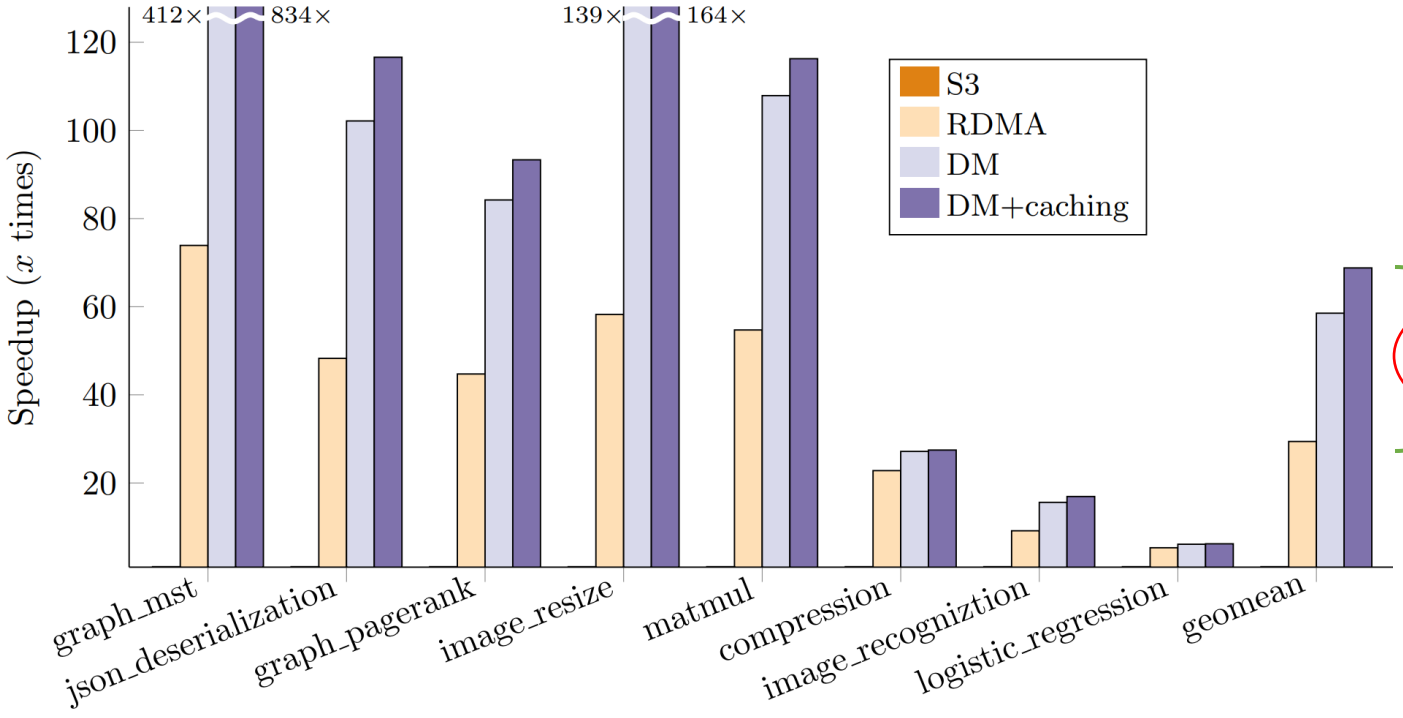

2.3x over RDMA object store

Our target!

The CXL.mem coherence

- Enforcing strong consistency in presence of caching

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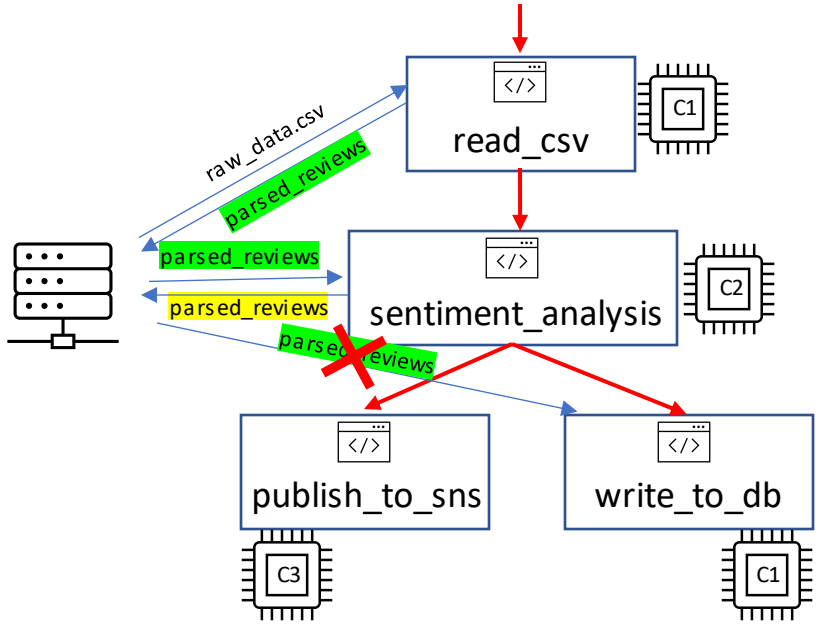

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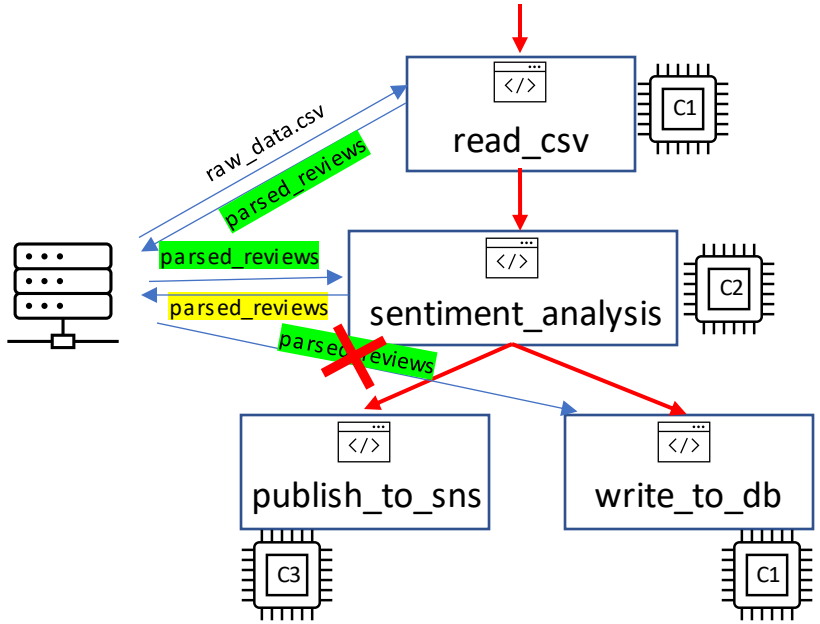
The CXL.mem coherence

- Enforcing strong consistency in presence of caching
  - CXL 3.0 inter-node coherence protocol
  - Enforces SWMR invariant



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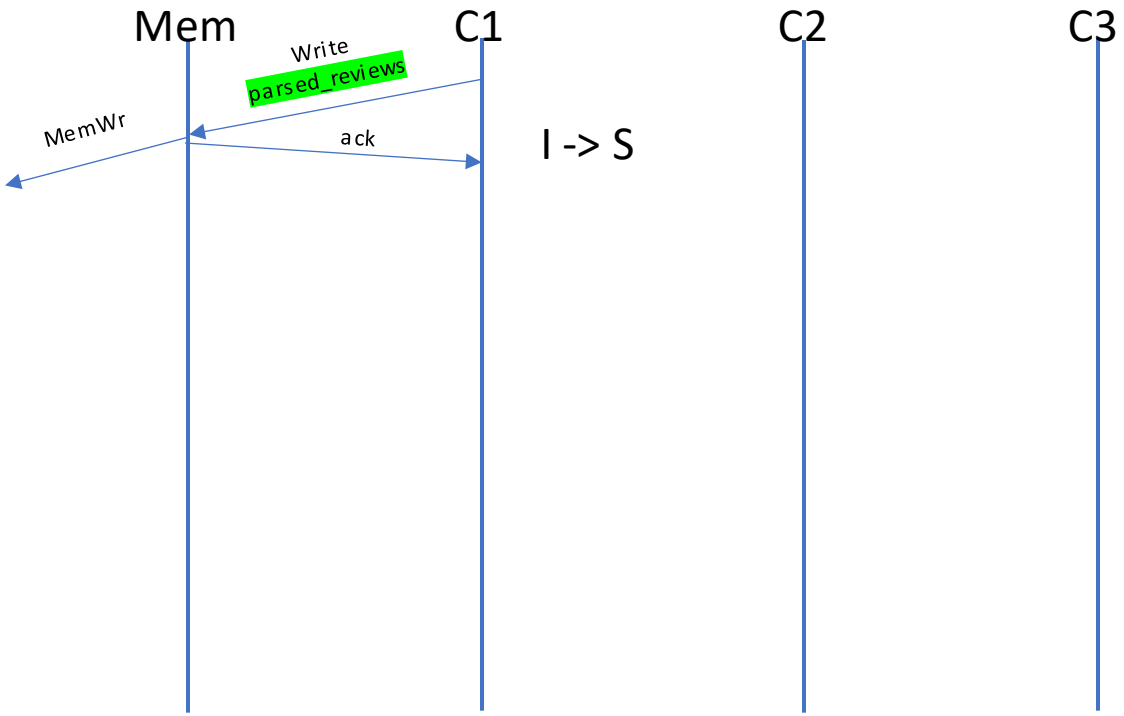

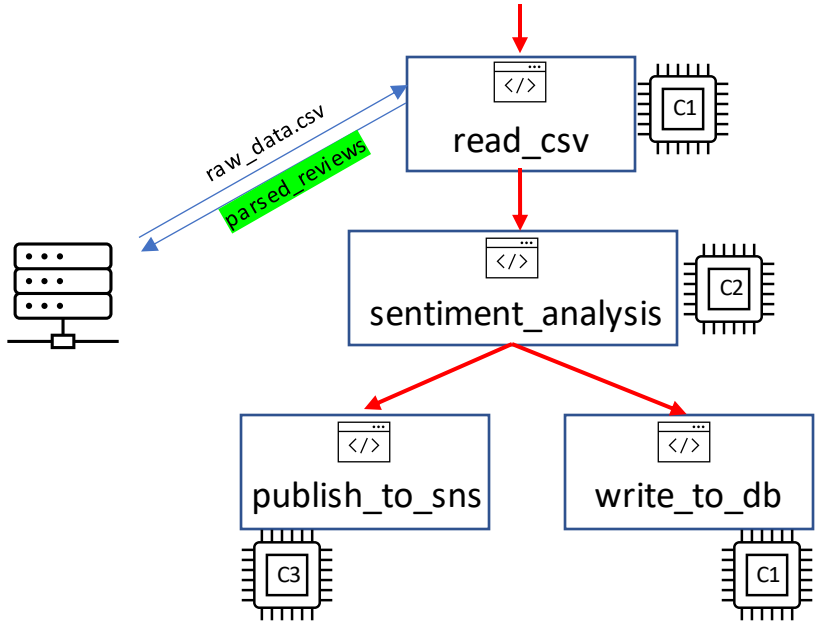

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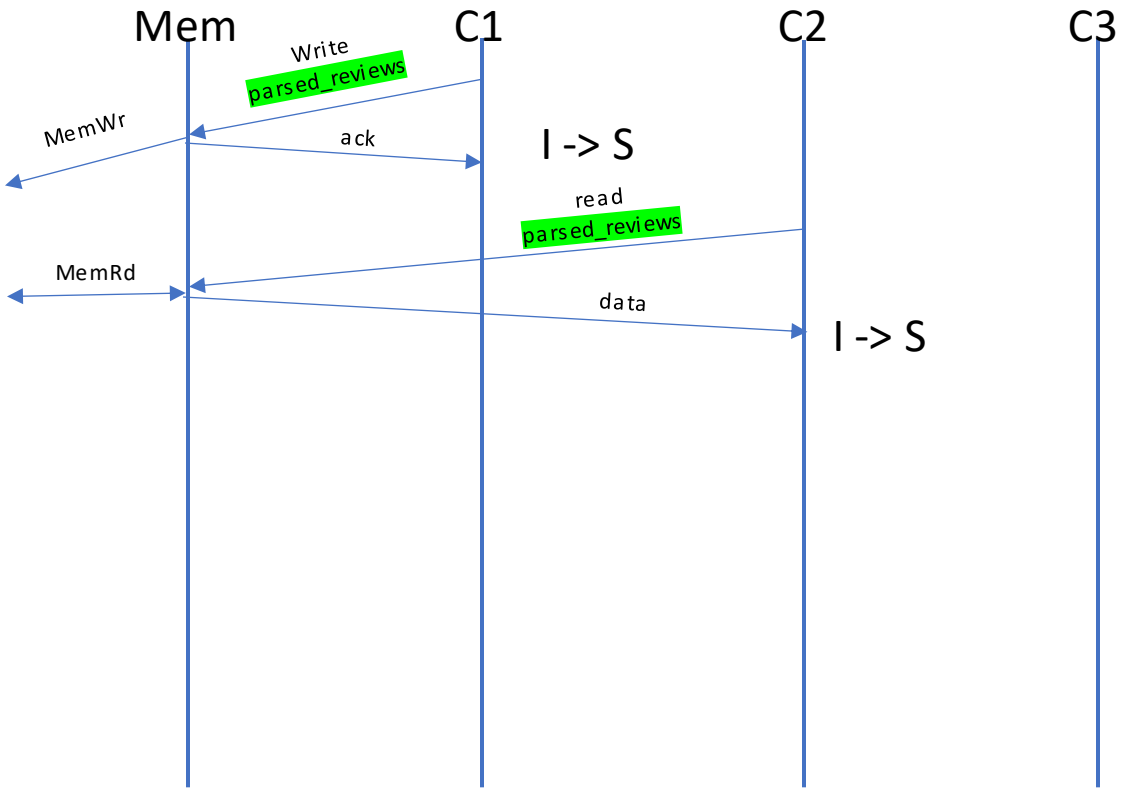

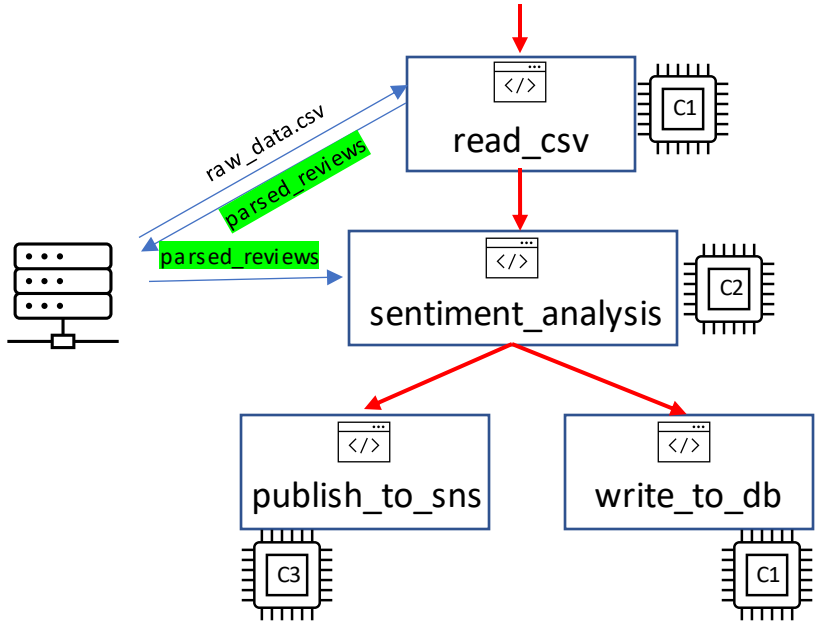

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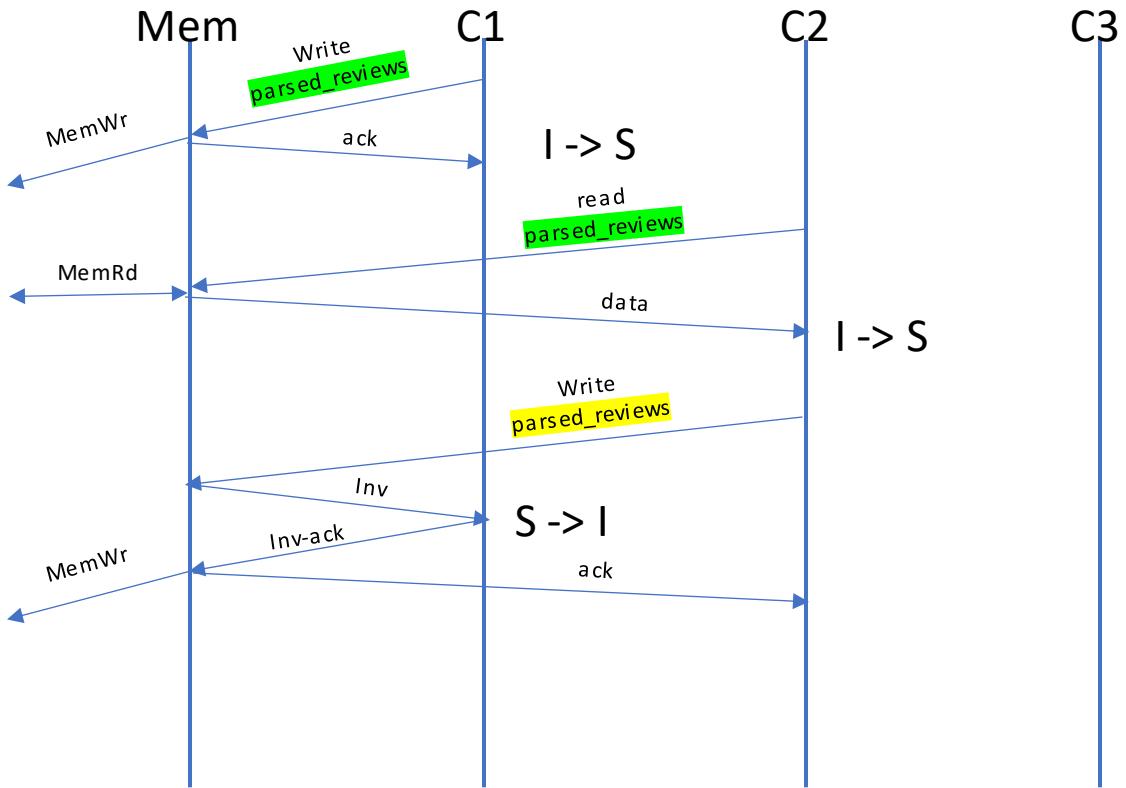

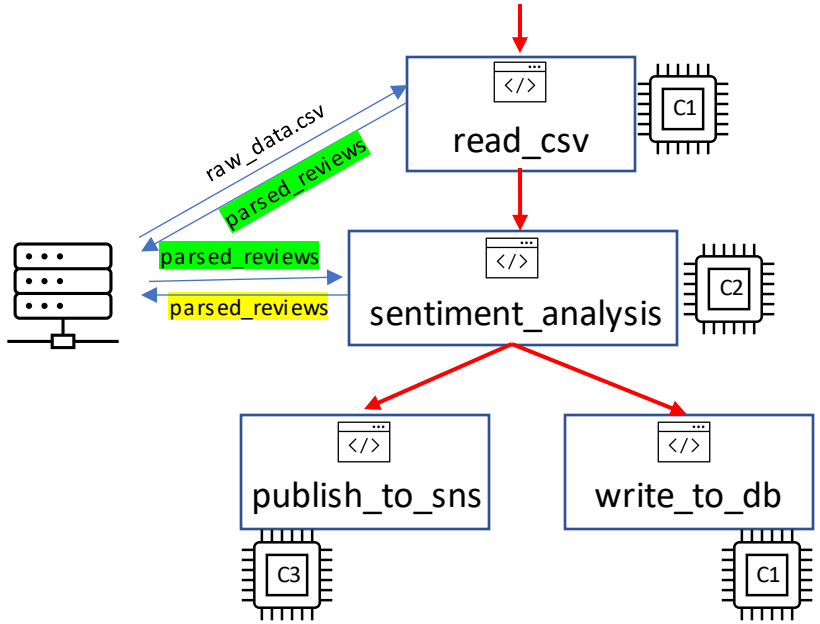

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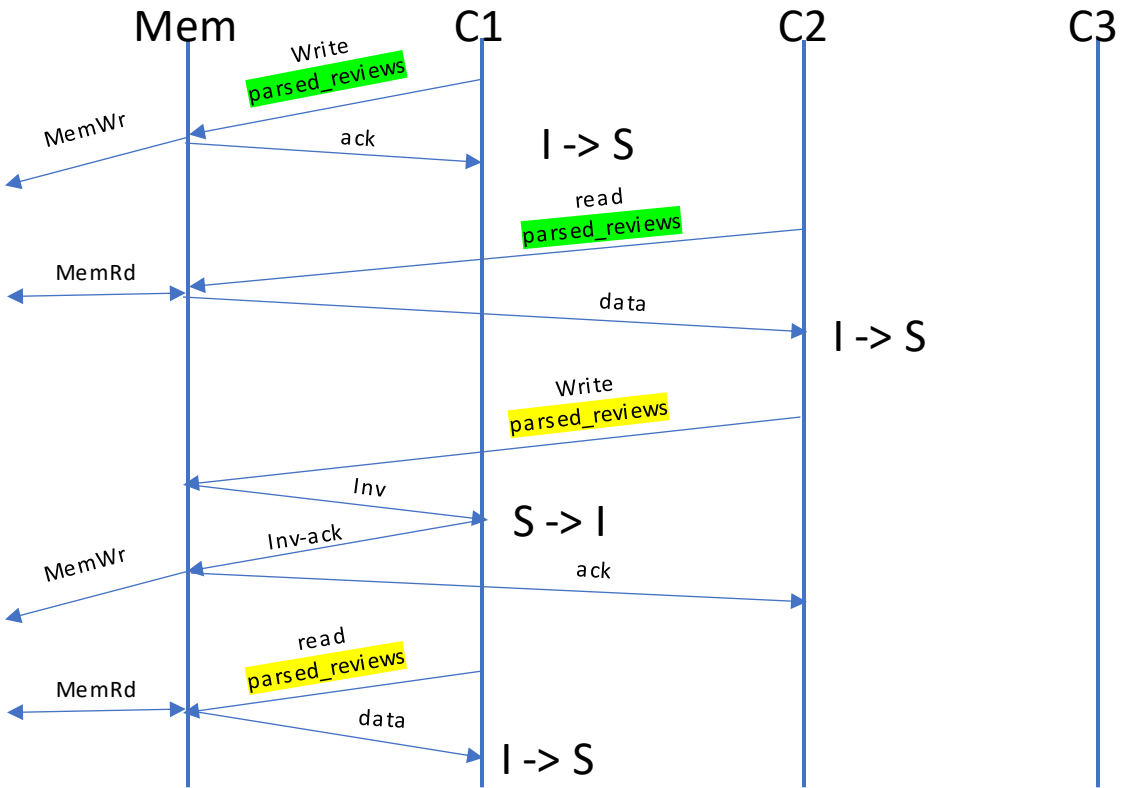

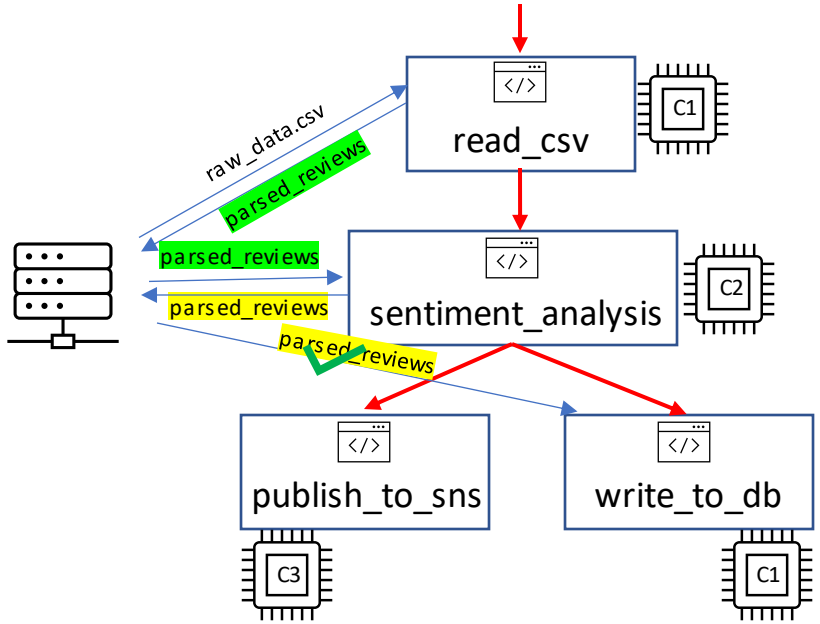

The need for fault-tolerant coherence

- The fault tolerance problem

  Compute server failures

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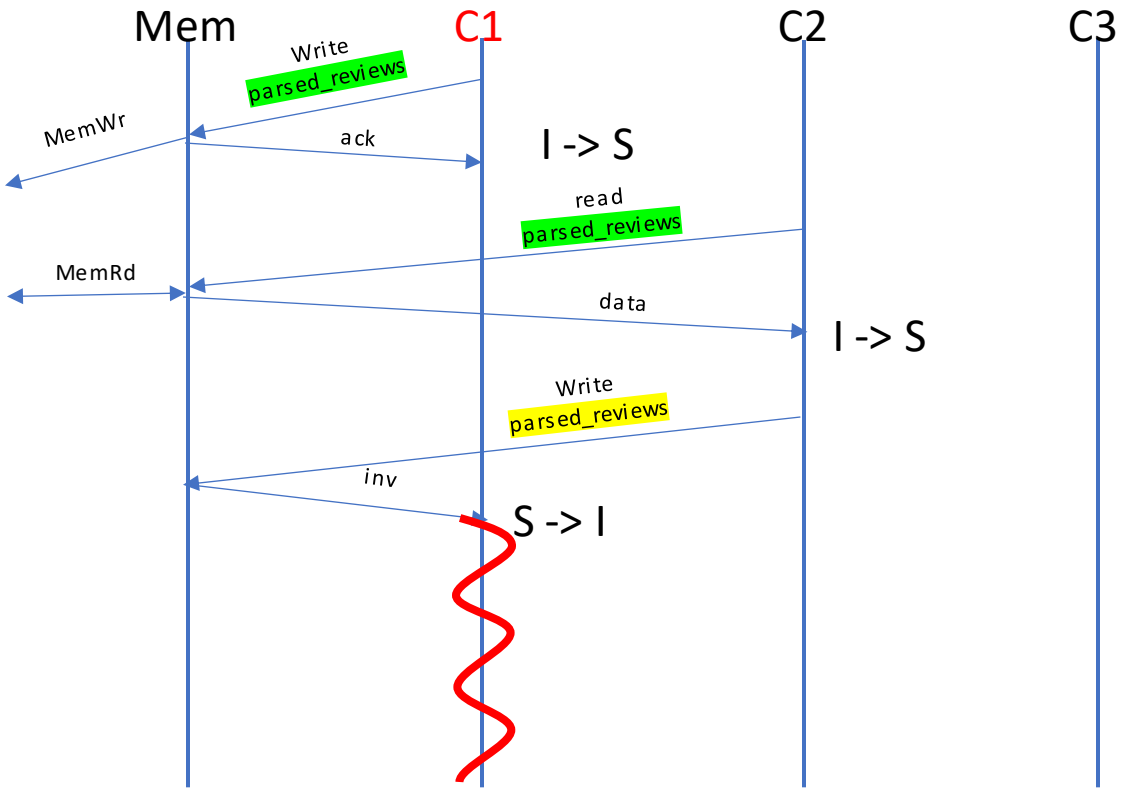
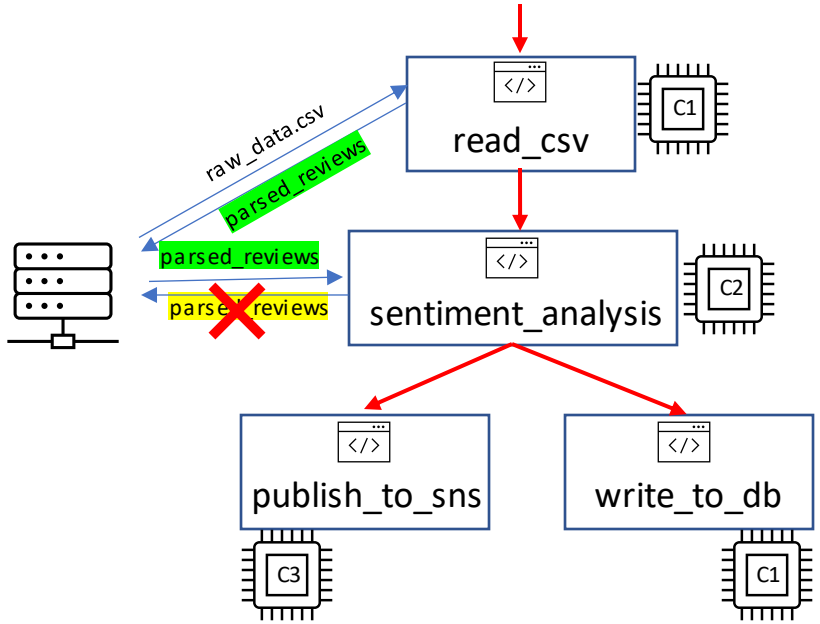
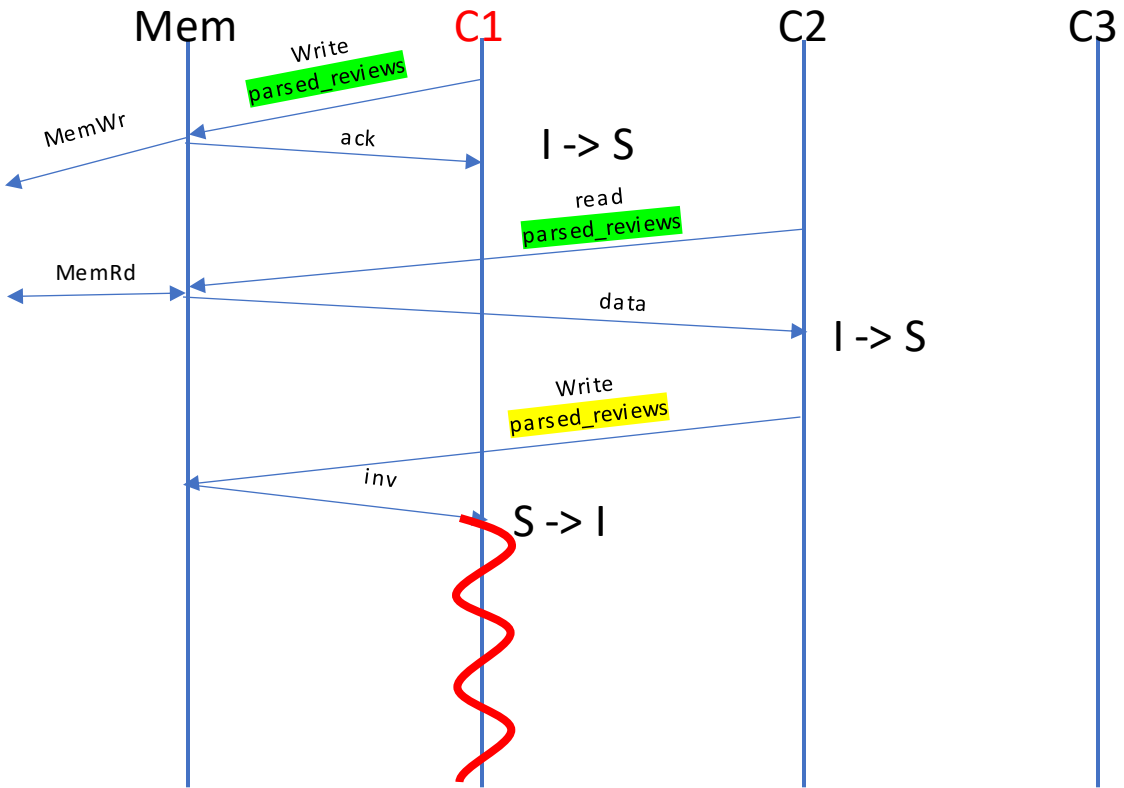


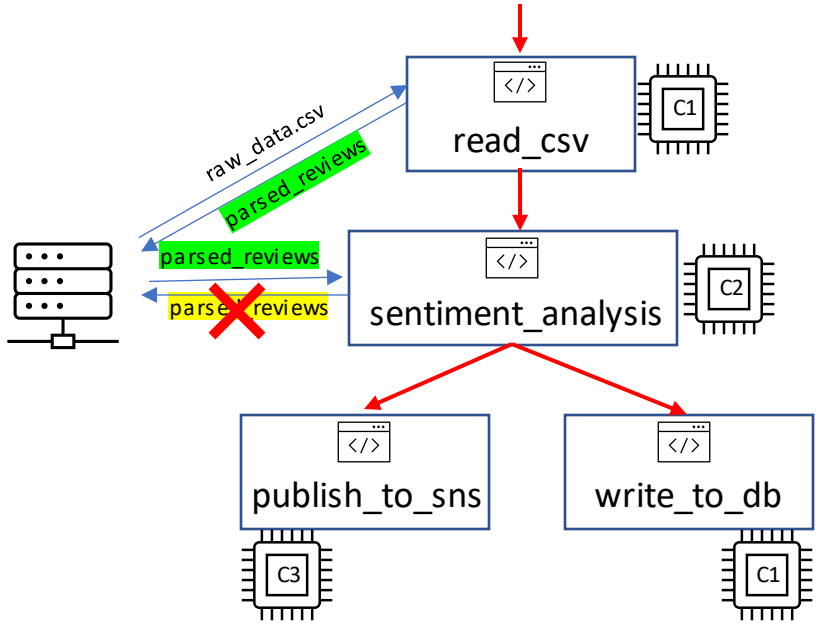


The need for fault-tolerant coherence

- The fault tolerance problem

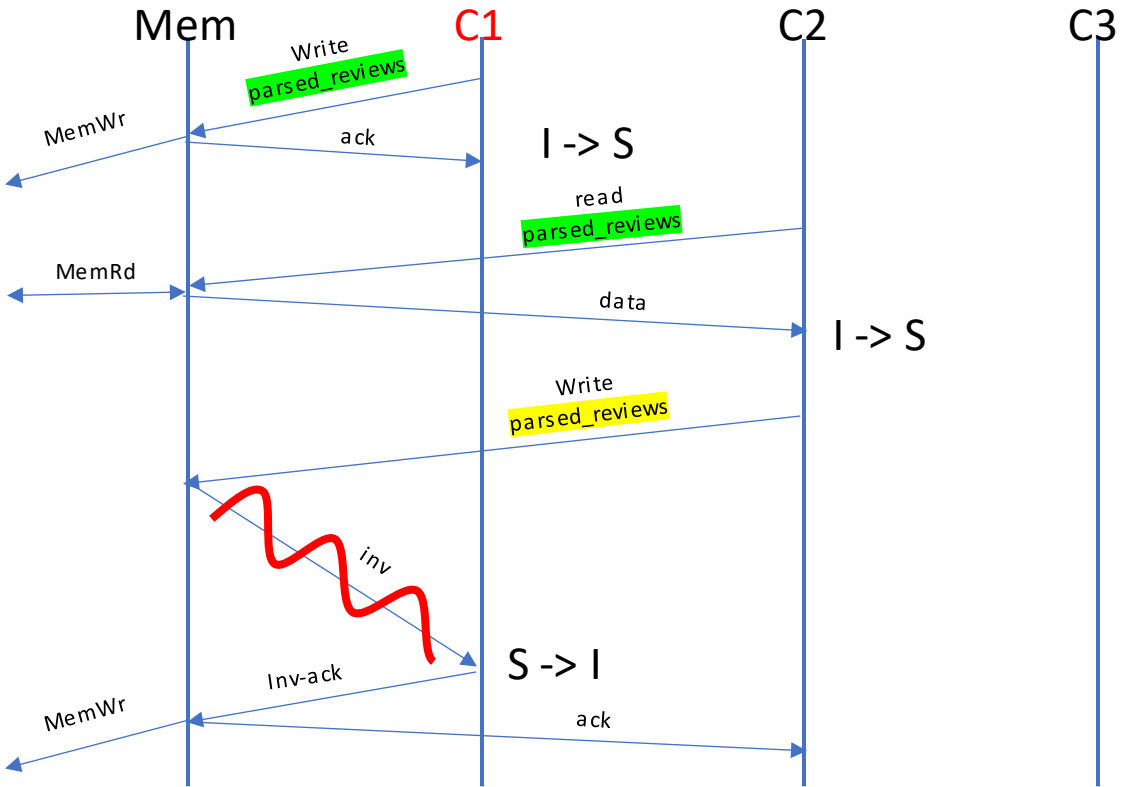
  Compute server failures – blocking

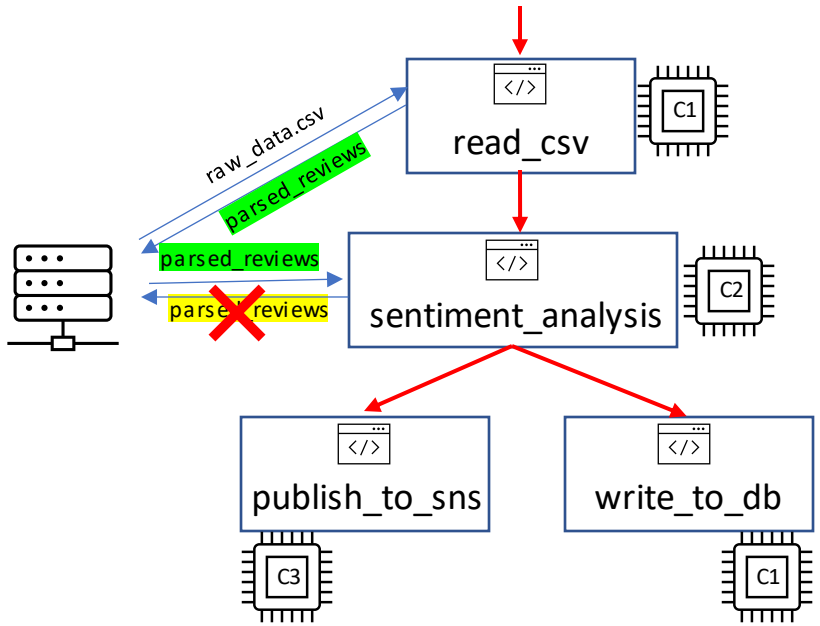




The need for fault-tolerant coherence

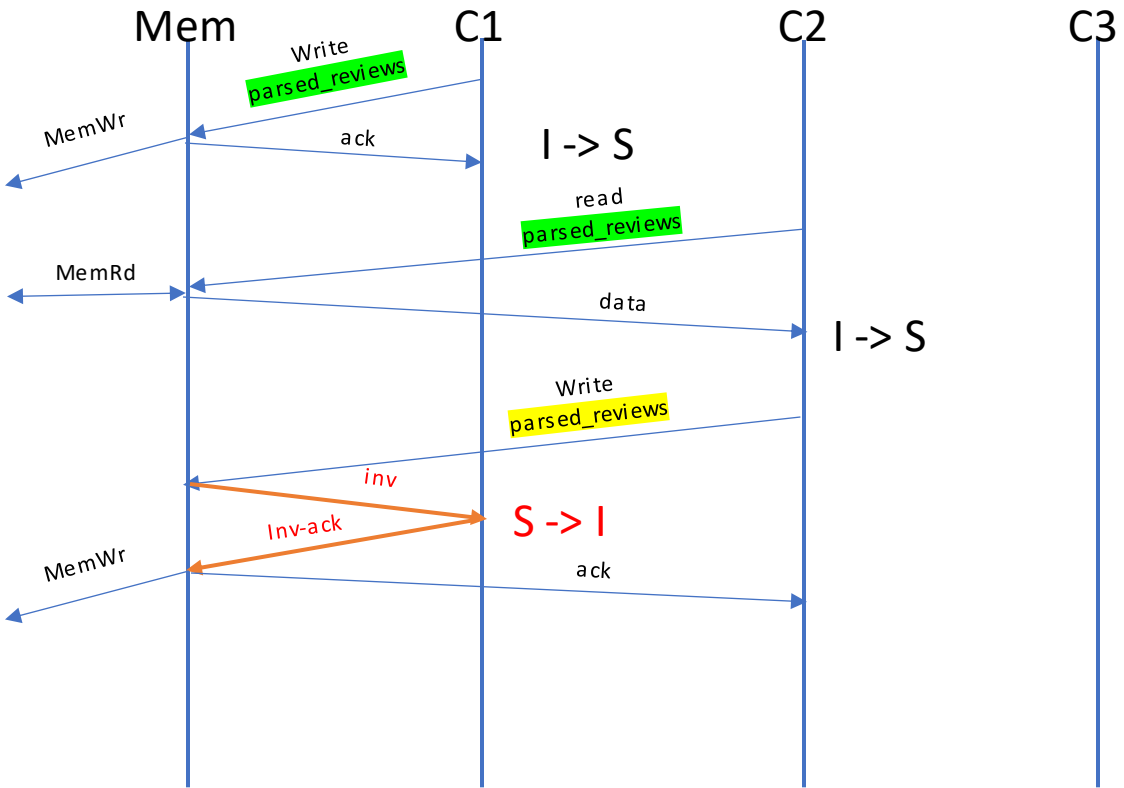
- The fault tolerance problem
  - Compute server failures – blocking
  - Network congestions – high tail latency

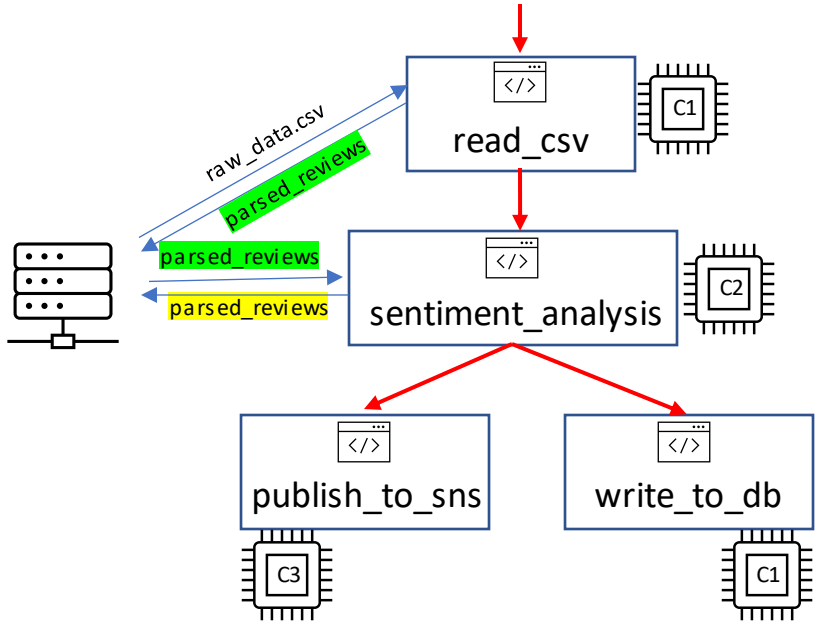




Key Problem – CXL not fault-tolerant!

- Invalidation in critical path of write => Writes block when compute servers fail





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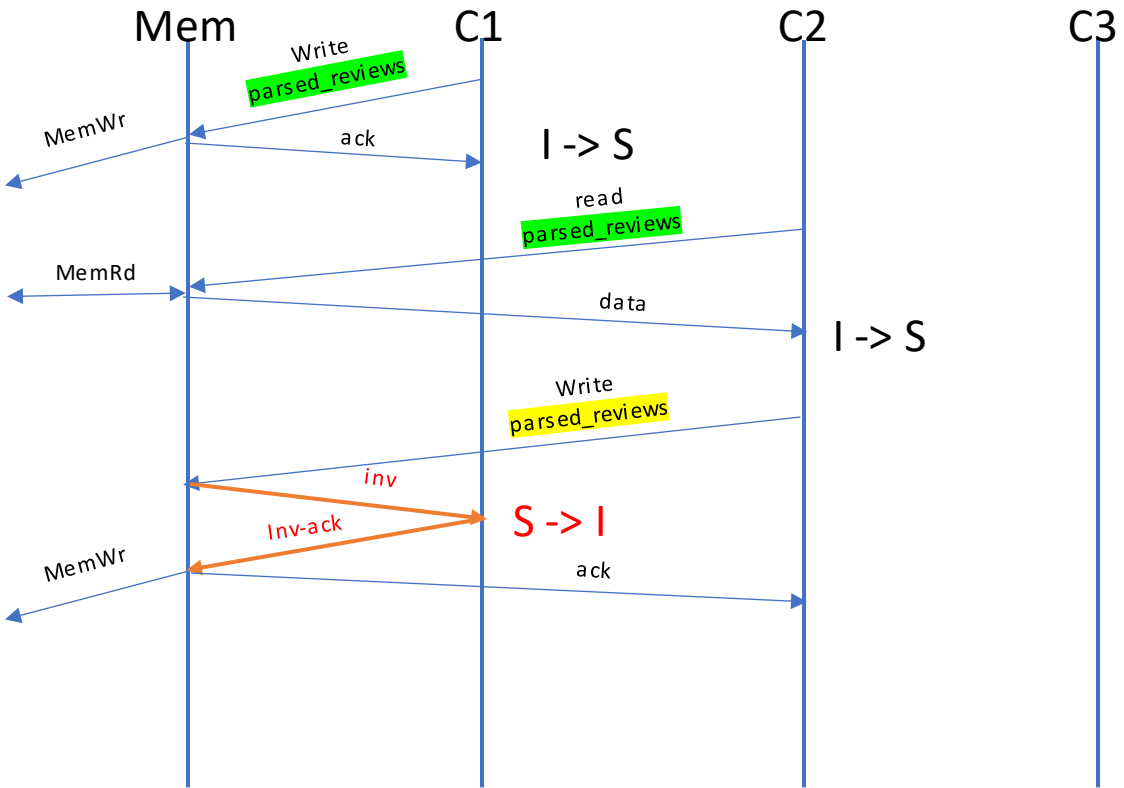
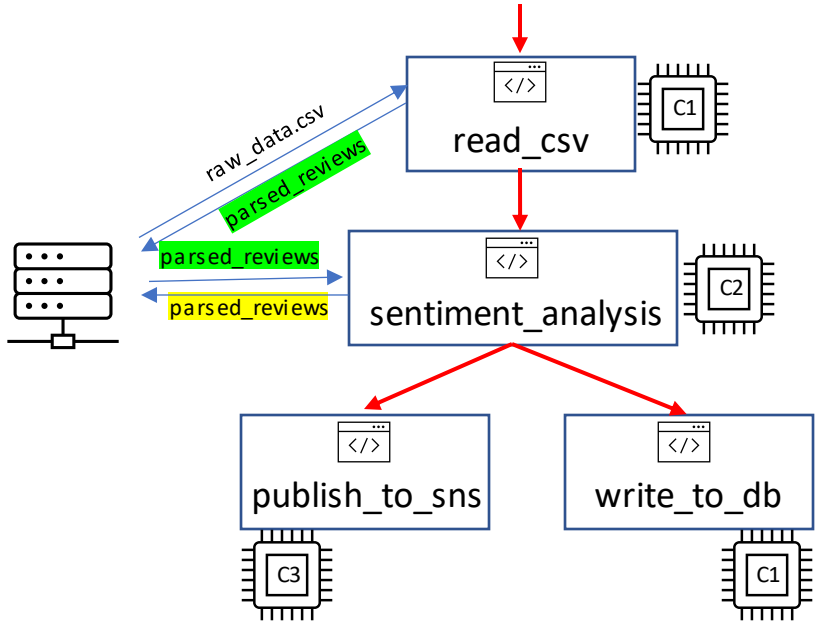
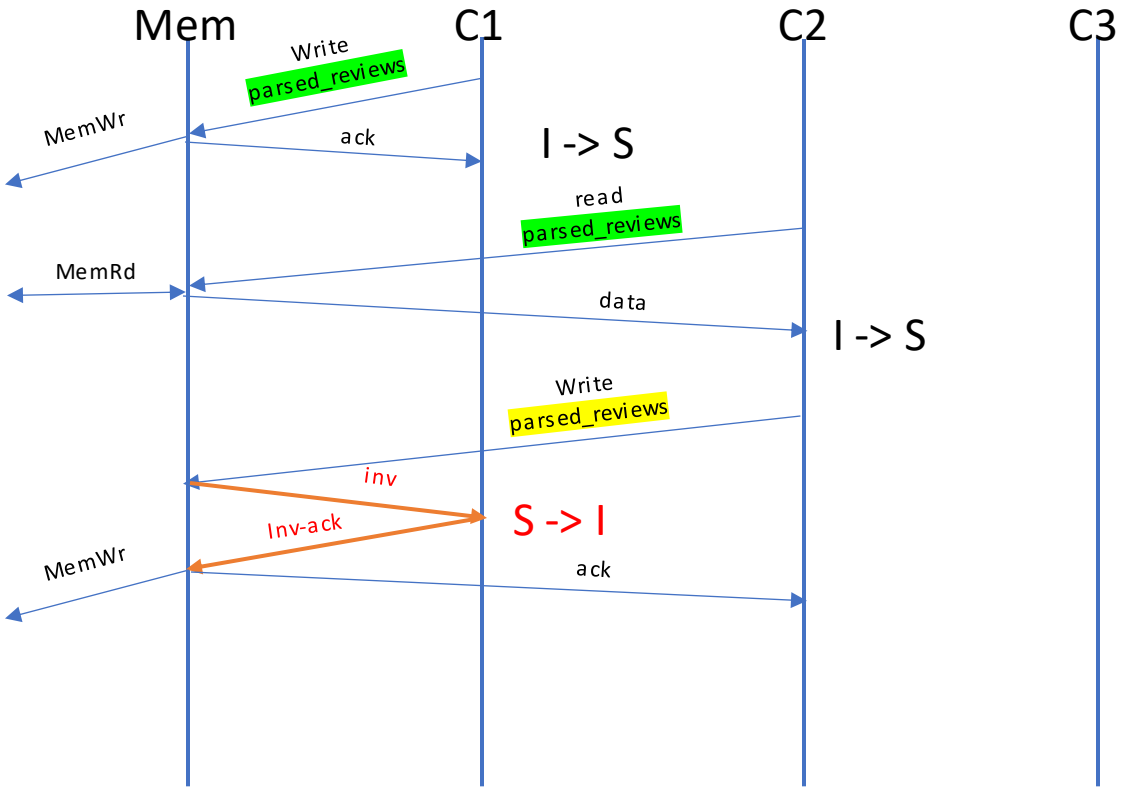
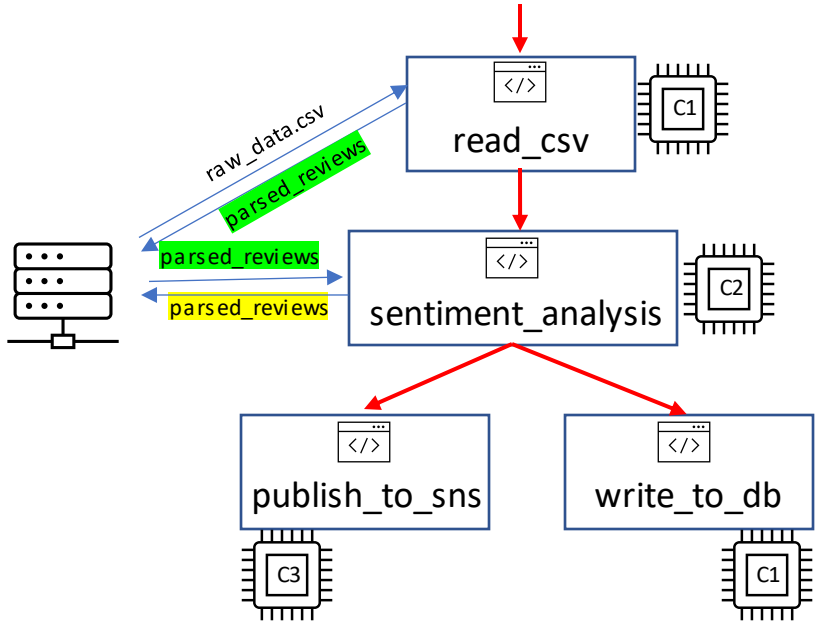




Key Problem – CXL not fault-tolerant!

- Invalidation in critical path of write => Writes block when compute servers fail
- Insufficient RAS capabilities in CXL specification
- FaaS embraces fault-tolerance => CXL must likewise





Āpta: Fault-tolerant Coherence Protocol

i. Lazy invalidation policy

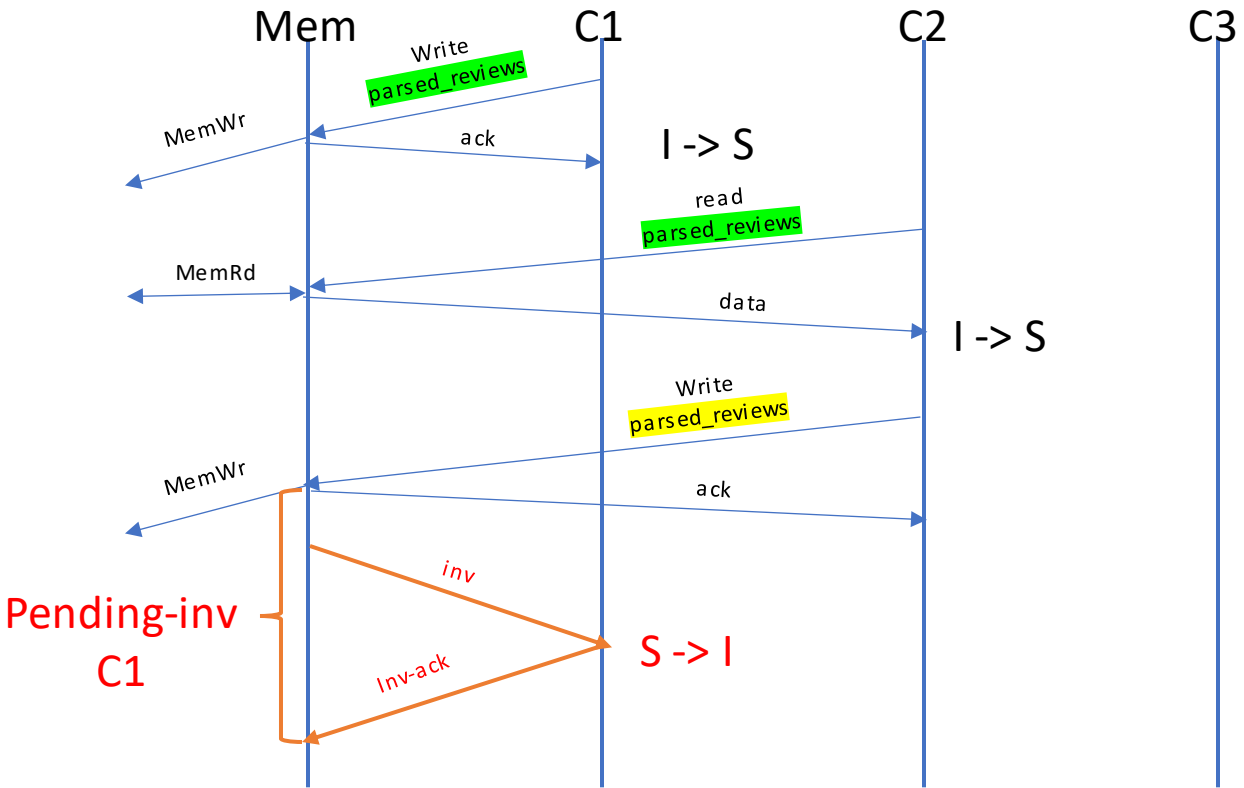
ii. Coherence-aware function scheduling

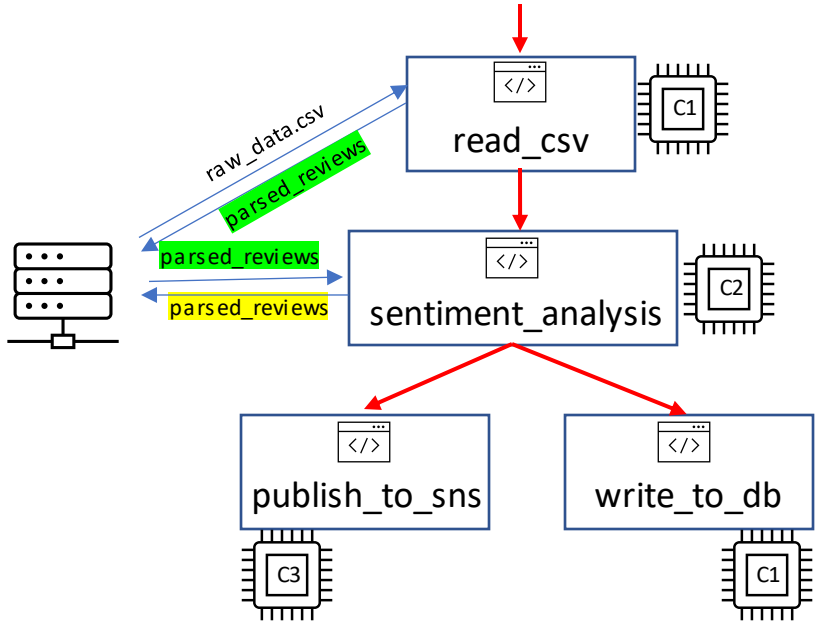
Āpta: Fault-tolerant Coherence Protocol

i. Lazy invalidation policy

Write is acknowledged immediately

Invalidation messages are sent asynchronously and tracked

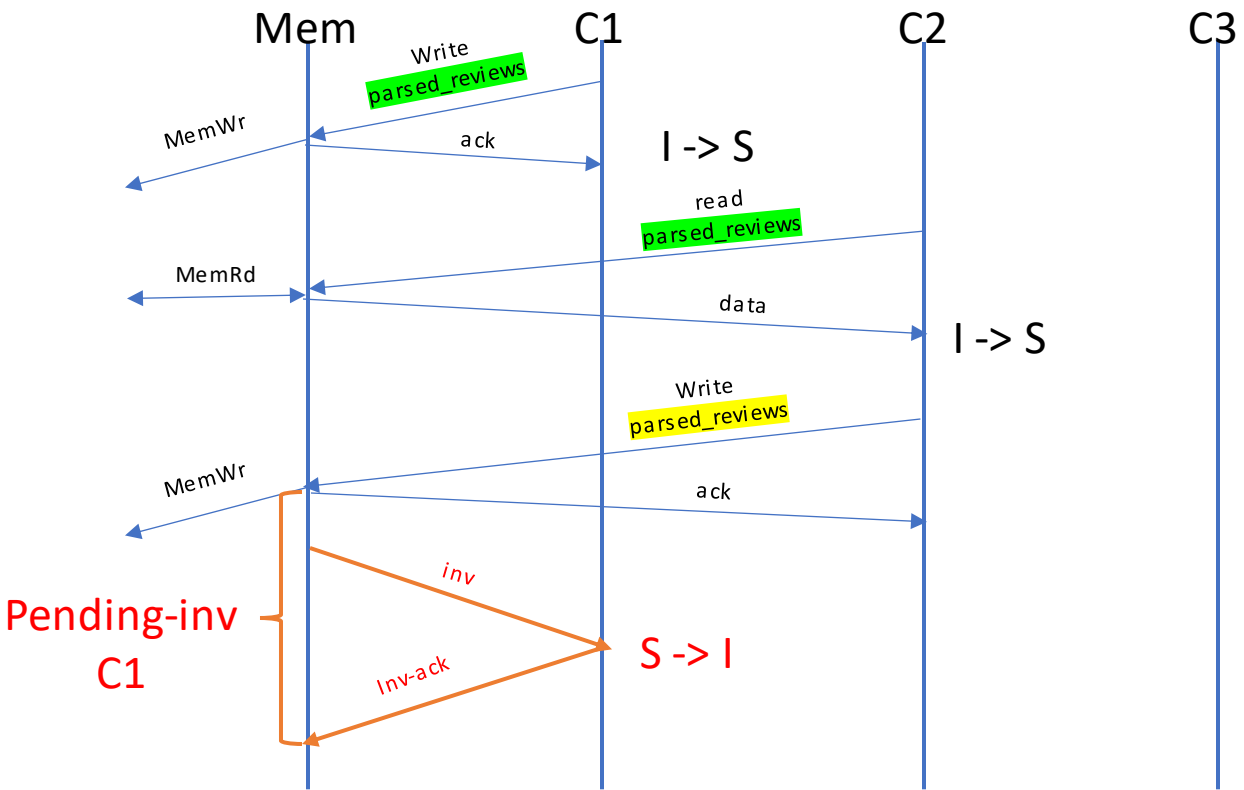


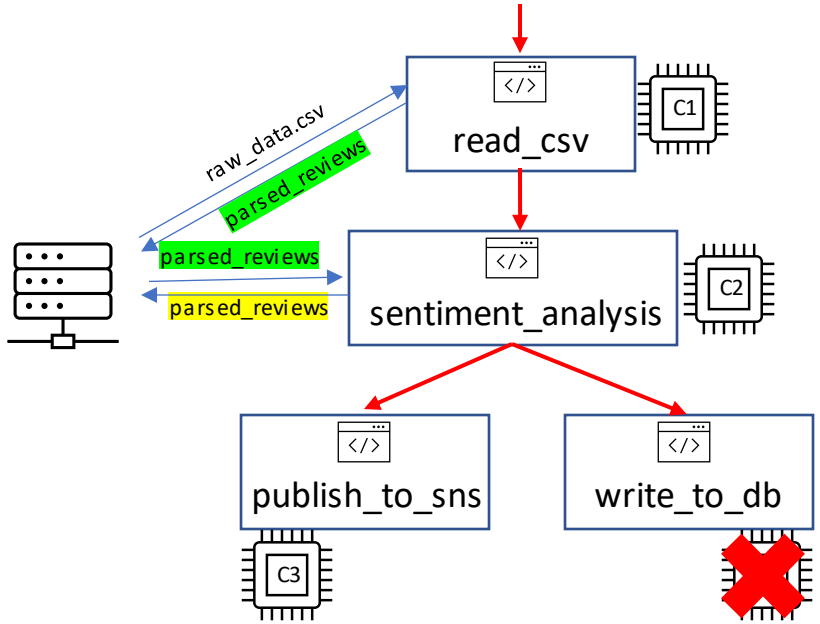


Āpta: Fault-tolerant Coherence Protocol

ii. Coherence-aware function scheduling

Never schedules function invocations on servers with pending invalidation-acknowlegements

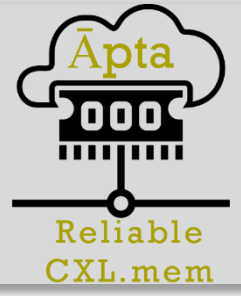




Āpta: Fault-tolerant Coherence Protocol

Strong consistency + Availability

- ✓ Lazy linearizability
  - Lazy invalidation protocol + Coherence-aware scheduling
- ✓ Fault-tolerant operation
  - Resilient to failure of compute server
- ✓ Provides line-rate coherence
  - Enables deployment on DPUs / SmartNIC / ToR switches



Āpta's design

a) CXL disaggregated memory-based object store
   - Extended shmem IPC
   - Defines a caching policy
   - Locality-aware scheduling

b) Fault-tolerant coherence protocol
   - Tailored coherence protocol
   - Lazy Invalidation of sharers and coherence-aware scheduling

This talk

c) Object-granular disaggregated memory
   - Bulk cache-line loads
   - Transactional atomic durability

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Realizing Āpta's design

Object-granular CXL disaggregated memory

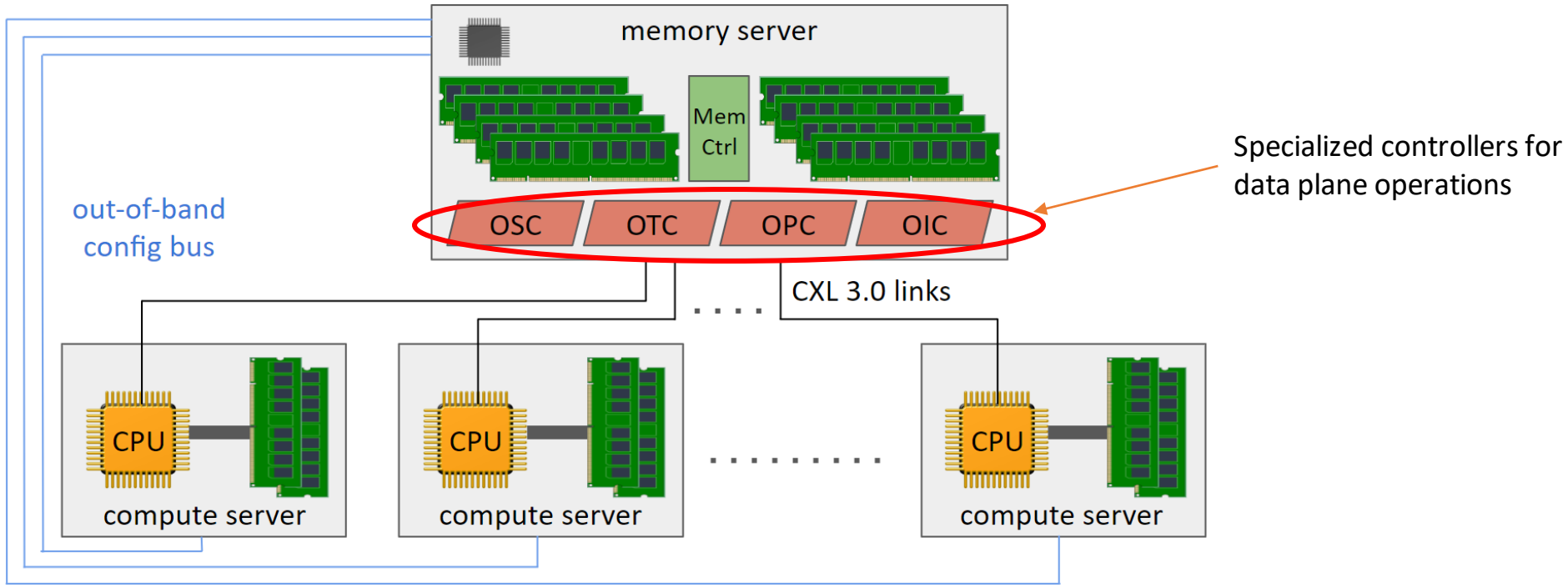
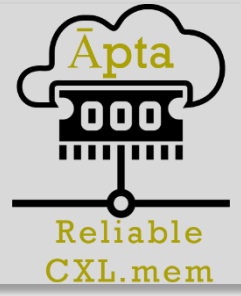


Fig: Āpta system schematic



Realizing Āpta's design

(b) Fault-tolerant coherence

OTC

Object Tracking Controller

Directory for the coherence protocol

OIC

Object Invalidation Controller

Reverse address translation + tracks invalidation-acks

(c) Object-granular disaggregated mem

OSC

Object Serving Controller

Address translation + bulk cache line response

OPC

Object Persistence Controller

Persists entire object atomically using one-phase commit

Performance Evaluation

Custom trace-driven gem5 simulation

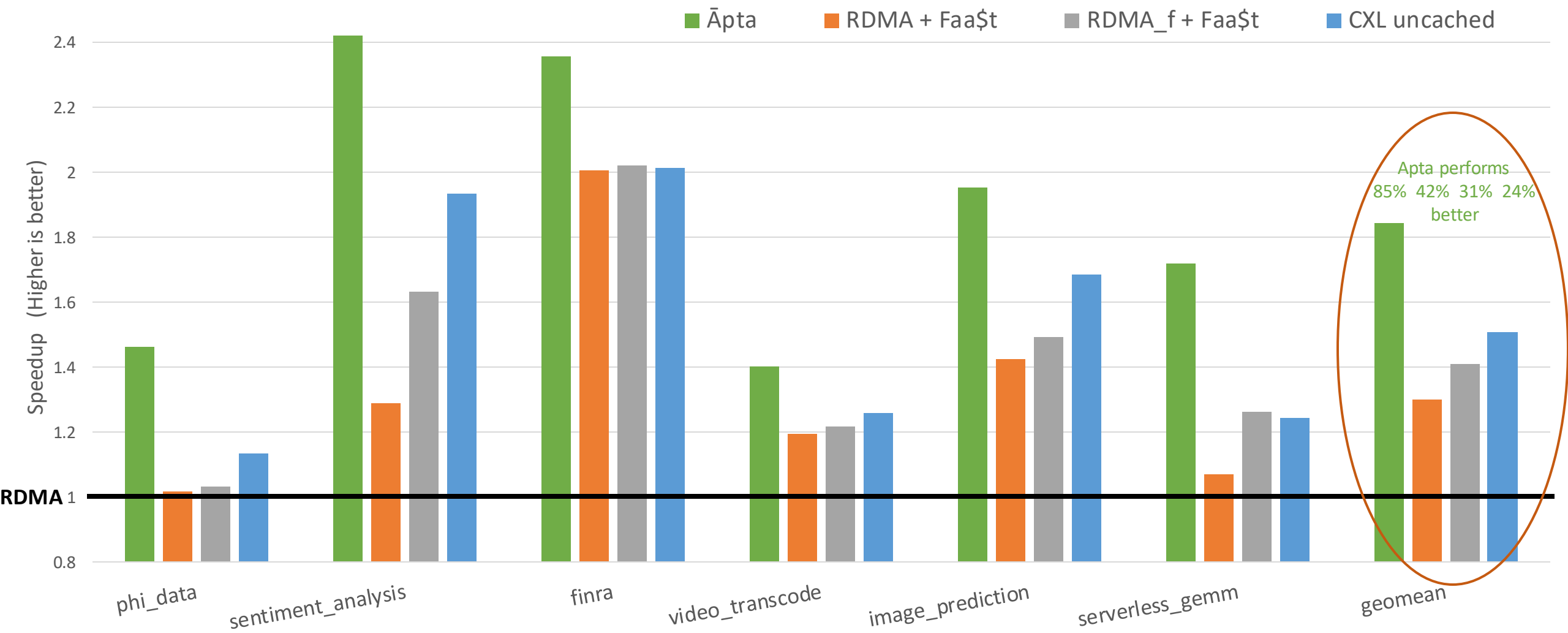
- **Prism traces** [†] annotated with phase of execution
- 3 compute servers, 1 disaggregated memory server
- Compute server: single socket 3GHz, per-core L1, shared L2, 2 x 8GB DDR4
- Memory server: 2 x 8GB DDR4, modelled controllers (OTC, OIC, OPC, OSC)
- Coherence Protocol: MOESI (intra-server), Āpta (inter-server)
- Interconnect: point-to-point (500ns, 80bps), full-duplex

Benchmarks

- **Full FaaS applications** - 6 workflows, 27 functions
- Different domains, communication patterns, realistic scheduling decisions
- Applications from AWS use cases and serverless frameworks (numpywren, THIS)
  PHI data, Sentiment analysis, FINRA, Video transcode, Image prediction, Serverless GEMM

[†] SynchroTrace, ISPASS ‘15

Performance Evaluation



Āpta Summary

Accelerating function-as-a-service

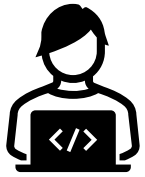
40% – 142% over RDMA
21% – 90% over RDMA + caching
15% – 42% over un-cached CXL

Fault-tolerant coherence protocol

Protocol verified in Murφ model checker
32% lower standard deviation of exec time

Object-granular Disaggregated Memory

Shared memory IPC
Bulk cache-line loads
Transaction atomic durability



Artifacts available

https://github.com/adarshpatil/apta
https://adar.sh/apta

#OpenToWork @adarshpatil