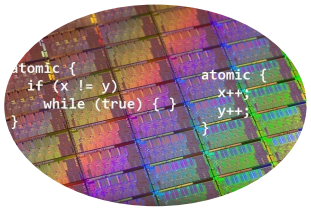
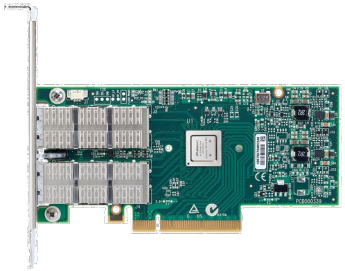





Improving Distributed Systems with New Hardware Features

RONG CHEN

http://ipads.se.sjtu.edu.cn/rong_chen

Institute of Parallel and Distributed Systems
Shanghai Jiao Tong University

Joint work with Haibo, Xinda, Jiaxin, Yanzhe, Youyang@IPADS

Business Demand – High Throughput

Peak transactions per second:

175,000 new orders

120,000 payment

Business Demand – Low Latency

Evolution and Practice: Low-latency Distributed Applications in Finance

The finance industry has unique demands for low-latency distributed systems

- Read input message from network and parse – 5 microseconds
- Look up client profile – 3.2 milliseconds (3,200 microseconds)
- Compute client quote – 15 microseconds
- Log quote – 20 microseconds
- Serialize quote to a response message – 5 microseconds
- Write to network – 5 microseconds

How to Do It? Conventional Approach

TPC-C World Record

504,161 TXs/second
Cost: 30,528,863 USD

172,770 TXs/second
Cost: 14,276,808 USD

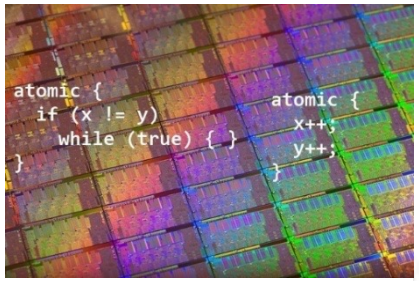
http://www.tpc.org/tpcc/results/tpcc_results.asp?print=false&orderby=tpm&sortby=desc

How to Do It? Today's Approach

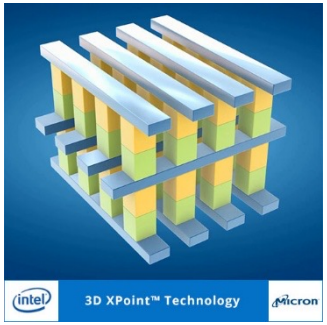
OceanBase **MySQL Cluster**

Hardware Platform

HTM

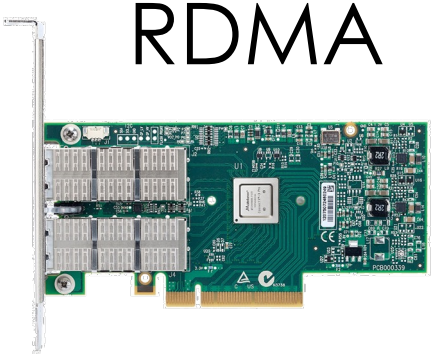


NVM



GPU

RDMA



A few rack-scale machines

Agenda

101 of HTM and RDMA

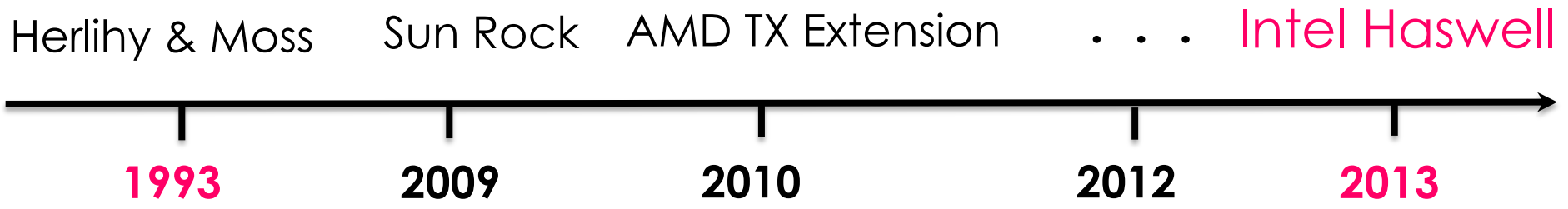
Overall Ideas

RDMA-friendly Distributed Key-value Store

Fast Distributed Transactions using RDMA & HTM

Fast and Concurrency Graph Queries using RDMA

HTM: Hardware Transactional Memory



Massively available

Intel Restricted Transactional Memory

Restricted Transactional Memory (RTM)

- Hardware transactional memory with limitations

Major limitations

- Working set is limited
- System events abort TX

New instruction set

- Xbegin, Xend, Xabort

RTM Usage

```
if _xbegin() == _XBEGIN_STARTED
        do some critical work
    _xend()
else
    fallback routine
```

Handle the abort event

RDMA: Remote Direct Memory Access

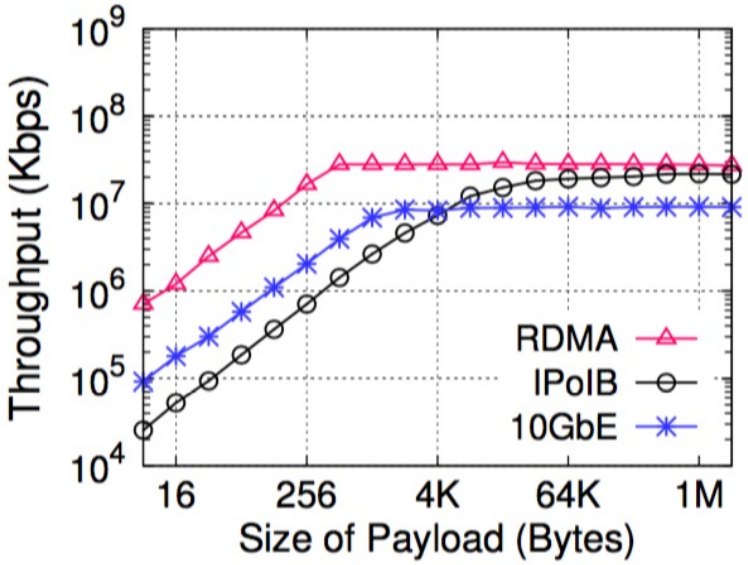
A network feature that allows **direct** access to the memory of a **remote** computer

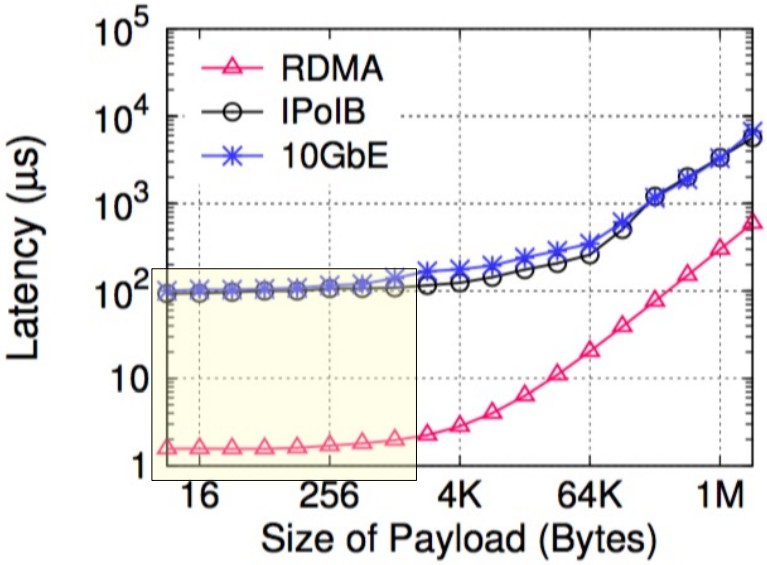
High speed, low latency & low CPU overhead

- Interface: IPoIB, two-sided RDMA (SEND/RECV), and one-sided RDMA (READ/WRITE/CAS)
- Bypasses OS kernels: Zero copy
  Bypasses CPU (one-sided)
- Round-trip time: one-sided/~3μs,
  two-sided/~7μs, IPoIB/~100 μs

One-sided RDMA Performance

Performance of Random Read[1]





Insensitive to payload size:

High/near constant throughput/Low latency when payload is smaller than a threshold

[1] Mellanox ConnectX-3 MCX353A 56Gbps InfiniBand NIC

Overall Idea
Hardware Feature Combination

Opportunities: (not so) New HW Features

HTM: **H**ardware **T**ransaction **M**emory

- Allow a group of load & store instructions to execute in an atomic, consistent and isolated (ACI) way

RDMA: **R**emote **D**irect **M**emory **A**ccess

- Provide cross-machine accesses with high speed, low latency and low CPU overhead

Rethink the design of low-COST scalable in-memory transaction systems

Opportunities with HTM & RDMA

HTM: **H**ardware **T**ransaction **M**emory

a non-transactional code will unconditionally abort a transaction when their accesses conflict

Strong Atomicity

RDMA: **R**emote **D**irect **M**emory **A**ccess

Opportunities with HTM & RDMA

HTM: **H**ardware **T**ransaction **M**emory

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Strong Atomicity

RDMA: **R**emote **D**irect **M**emory **A**ccess

> *one-sided RDMA operations are cache-coherent with local accesses*

Strong Consistency

Opportunities with HTM & RDMA

HTM: **H**ardware **T**ransaction **M**emory

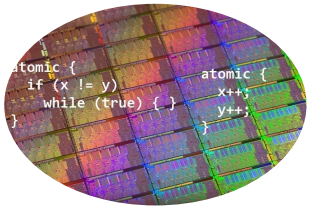
> *a non-transactional code will unconditionally abort a transaction when their accesses conflict*

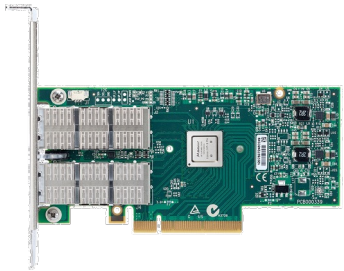
RDMA: **R**emote **D**irect **M**emory **A**ccess

> *one-sided RDMA operations are cache-coherent with local accesses*

HTM Strong Atomicity + **RDMA Strong Consistency** ⇒ **RDMA ops will abort conflicting HTM TX**

RDMA-friendly Distributed Key-value Store





In-memory KV-Stores

Interface: **GET**, **PUT**, etc.

A key pillar for many systems

- Data cache (e.g., Memcached in FB)
- In-memory database (e.g., OLTP, OLAP)
- Graph query processing

Key requirements

- Low latency
- High request rate (Throughput)

Prior systems

Prior systems (e.g. Pilaf[ATC'13] and FaRM[NSDI'14])

- Only leverage one-sided RDMA to read, not write
- Complicated INSERT: hard to leverage HTM
- No RDMA-friendly caching mechanism

Content-based caching (e.g. replication) is hard to perform strong-consistent read and write locally, especially using RDMA

	Pilaf	FaRM
Hashing	Cuckoo	Hopscotch
Race Detection	Checksum	Versioning
Remote Read	One-sided RDMA	
Remote Write	Messaging	
Caching	No	

RDMA & HTM provides a new design space

Prior Systems

	Pilaf	FaRM	HERD	DrTM
Model	Asymmetric	Symmetric	Asymmetric	Symmetric
Hashing	Cuckoo	Hopscotch	Chaining	Chaining
Remote Read	One-sided RDMA		Messaging	One-sided RMDA
Remote Write	Messaging			
Race Detection	Checksum	Versioning	Exclusive Accesses	L: HTM D: Lock
Transaction	No	Yes	No	Yes
Caching	No	No	No	Yes

1. A bias towards RDMA-based remote operations
2. Only leverage one-sided RDMA to read
3. No efficient RDMA-friendly caching scheme
4. Complicated INSERT: hard to leverage HTM

DrTM-KV's Design

- ✓ Simple hash structure to fully leverage HTM
- ✓ Decouple race detection from memory store
  - Use HTM to detect races
  - Use one-sided RDMA ops for remote read & write
- ✓ Location-based and fully transparent cache

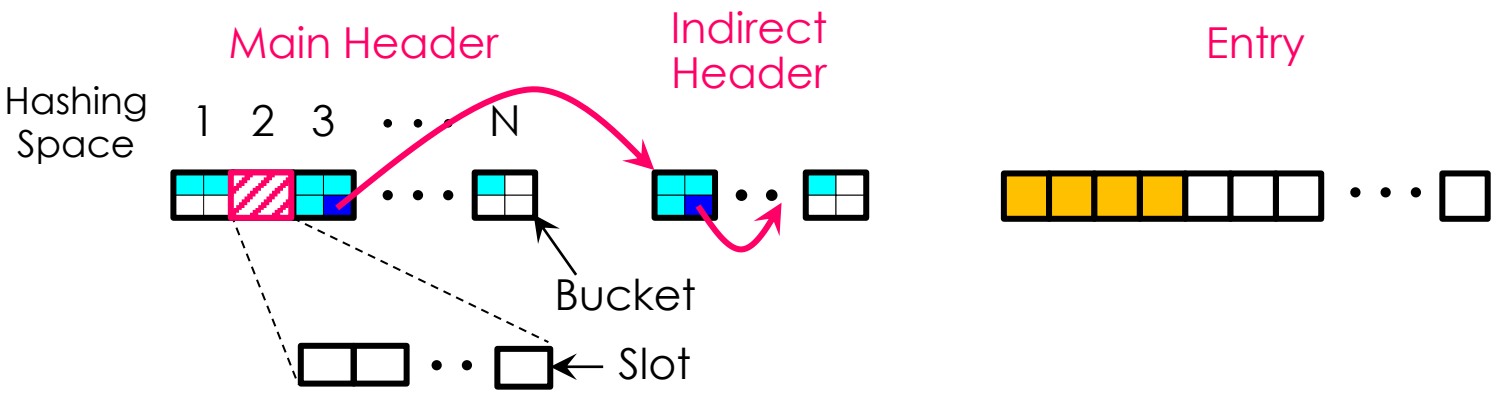
	Pilaf	FaRM	DrTM-kV
Hashing	Cuckoo	Hopscotch	Chaining
Race Detection	Checksum	Versioning	HTM
Remote Read	One-sided RDMA		One-sided RMDA
Remote Write	Messaging		
Caching	No		Yes

→ Simple

→ Efficient

RDMA-friendly Cluster Chaining

- ✓ Similar to traditional chaining HT with associativity
- ✓ Decoupled memory region: index & data
- ✓ Shared indirect headers: high space efficiency



RDMA-friendly Cluster Chaining

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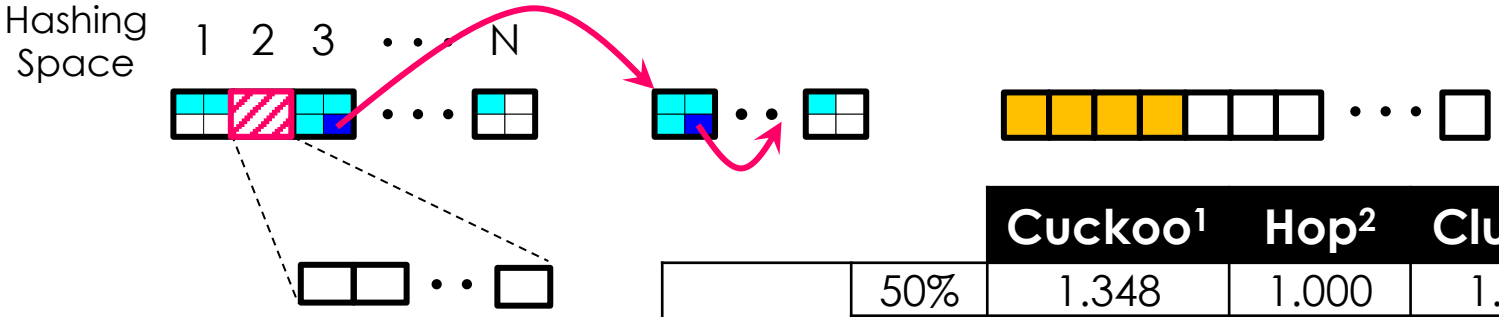


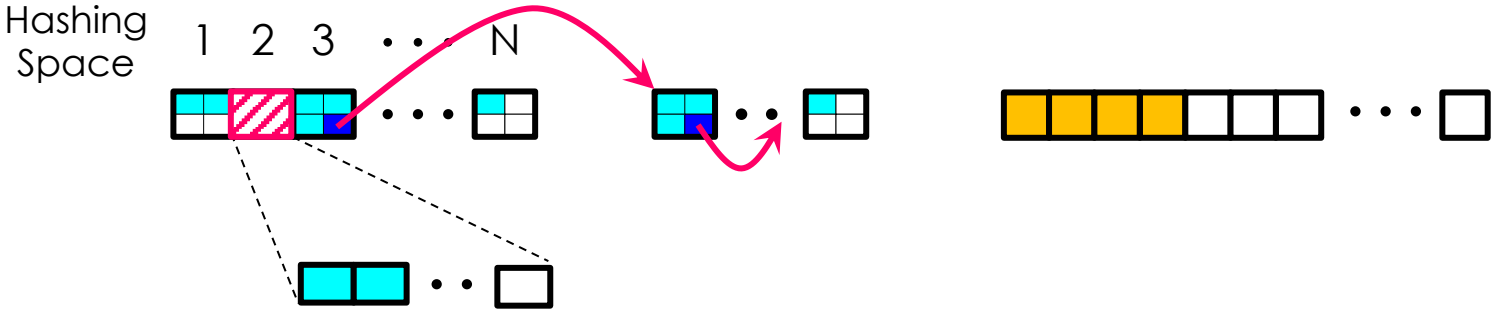
The average number of RDMA READs for lookups at different occupancies

		Cuckoo[1]	Hop[2]	Cluster[3]
Uniform	50%	1.348	1.000	1.008
	75%	1.652	1.011	1.052
	90%	1.956	1.044	1.100
Zipf θ=0.99	50%	1.304	1.000	1.004
	75%	1.712	1.020	1.039
	90%	1.924	1.040	1.091

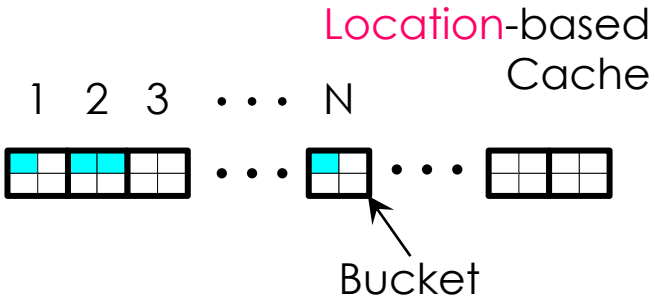
[1] Hopscotch hashing in FaRM configures the neighborhood with 8 (H=8).
[2] Cuckoo hashing in Pilaf uses 3 orthogonal hash functions and each bucket contains 1 slot.
[3] Cluster hashing in DrTM configures the associativity with 8.

Location-based Caching

✓ RDMA-friendly: focus on minimizing the lookup cost

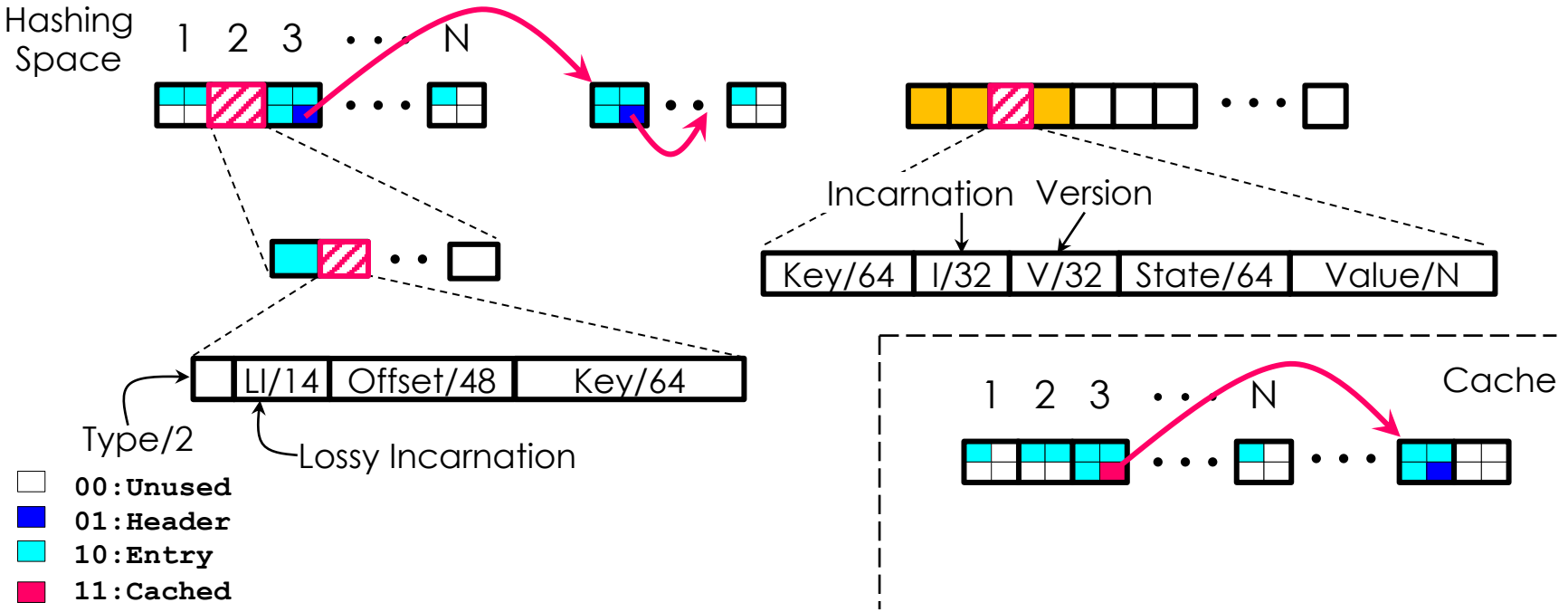


Treat cache as a partially stale snapshot of headers



Location-based Caching

- ✓ RDMA-friendly: focus on minimizing the lookup cost
- ✓ Retain the full transparency to the host
  - All metadata used by other concurrency control mechanisms is encoded in the key-value entry



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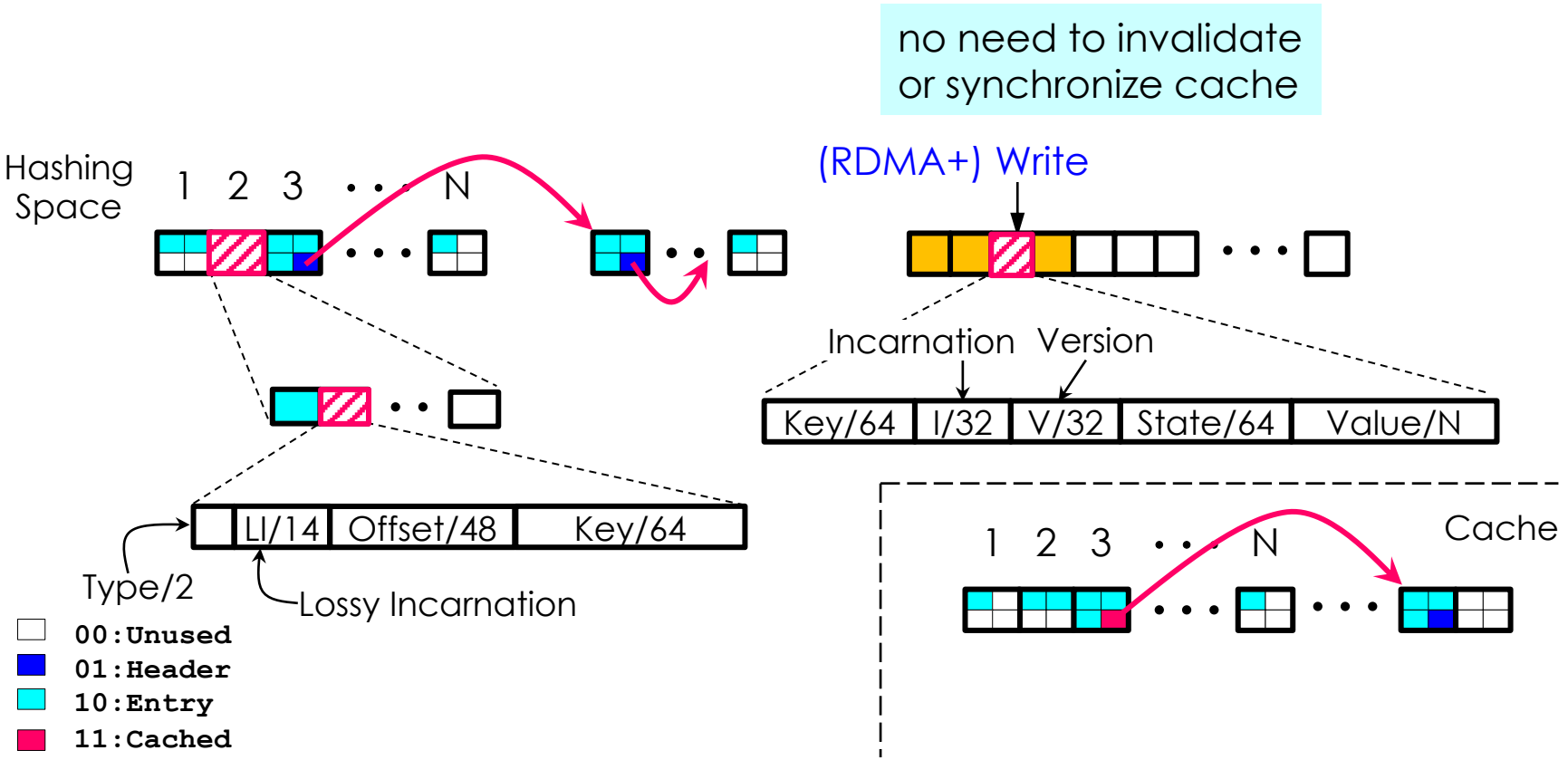

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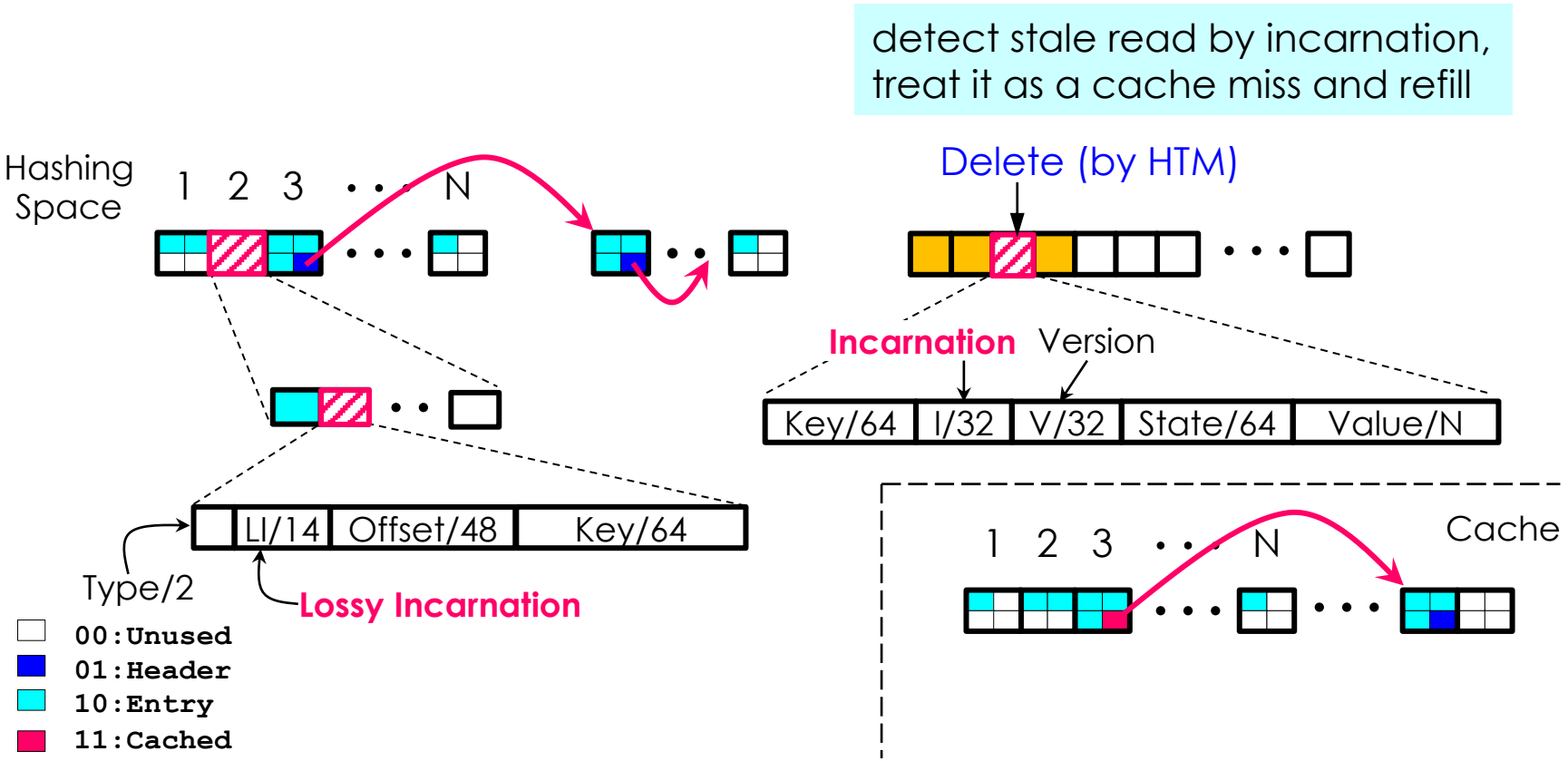
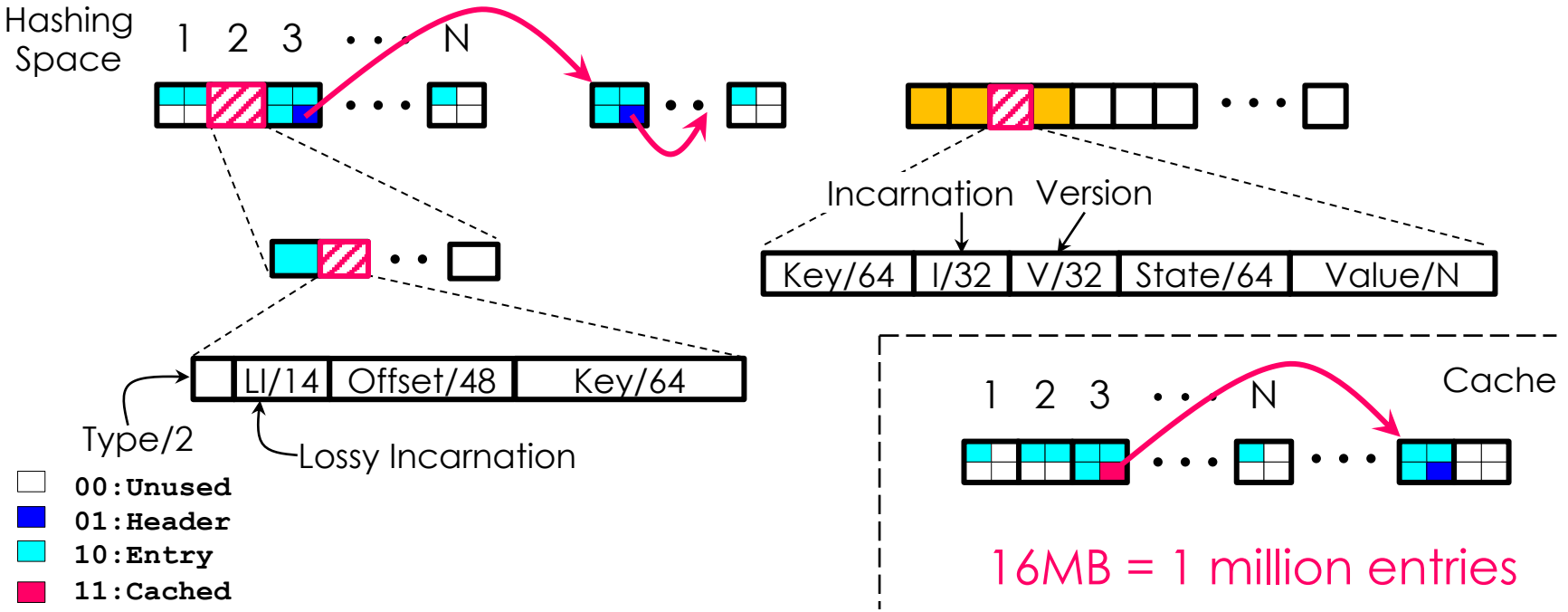


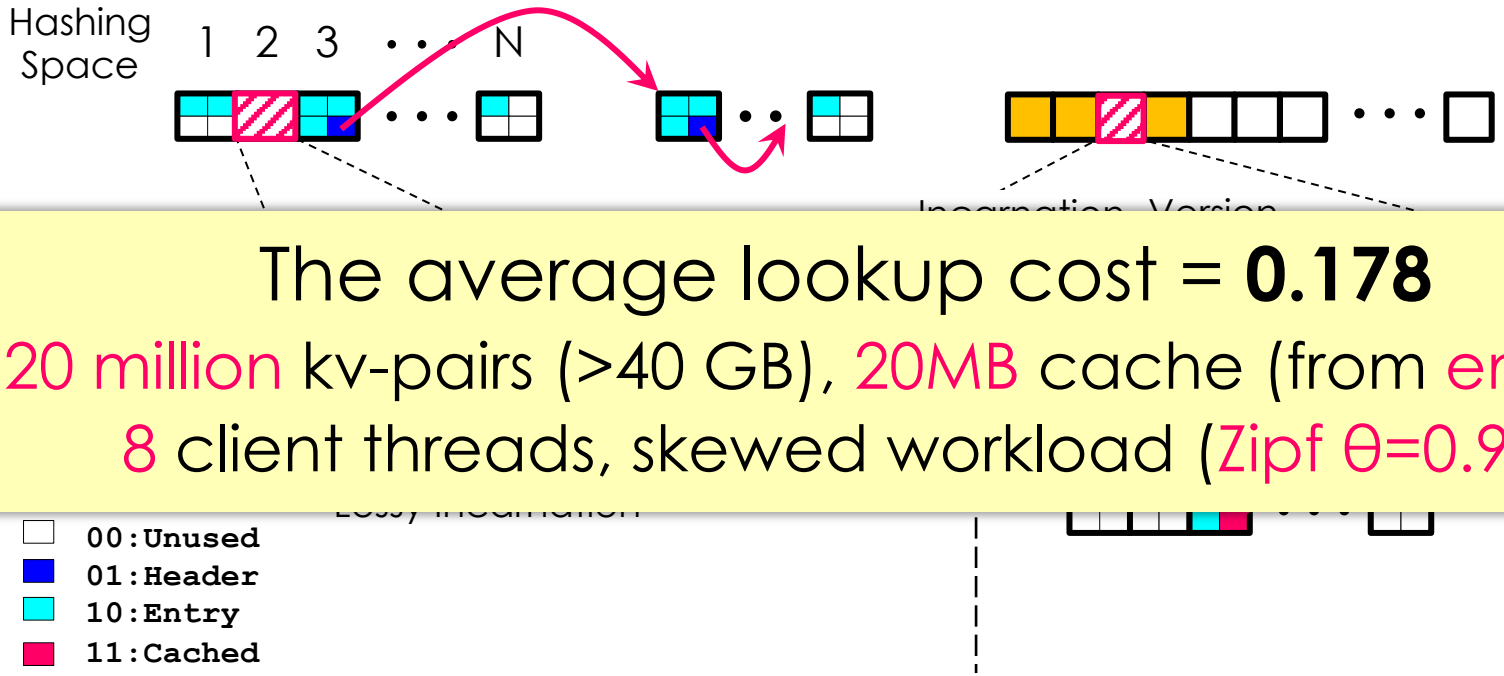
Location-based Caching

- ✓ RDMA-friendly: focus on minimizing the lookup cost
- ✓ Retain the full transparency to the host
- ✓ The size of cache for location is small



Location-based Caching

- ✓ RDMA-friendly: focus on minimizing the lookup cost
- ✓ Retain the full transparency to the host
- ✓ The size of cache for location is small
- ✓ All client threads can directly share the cache

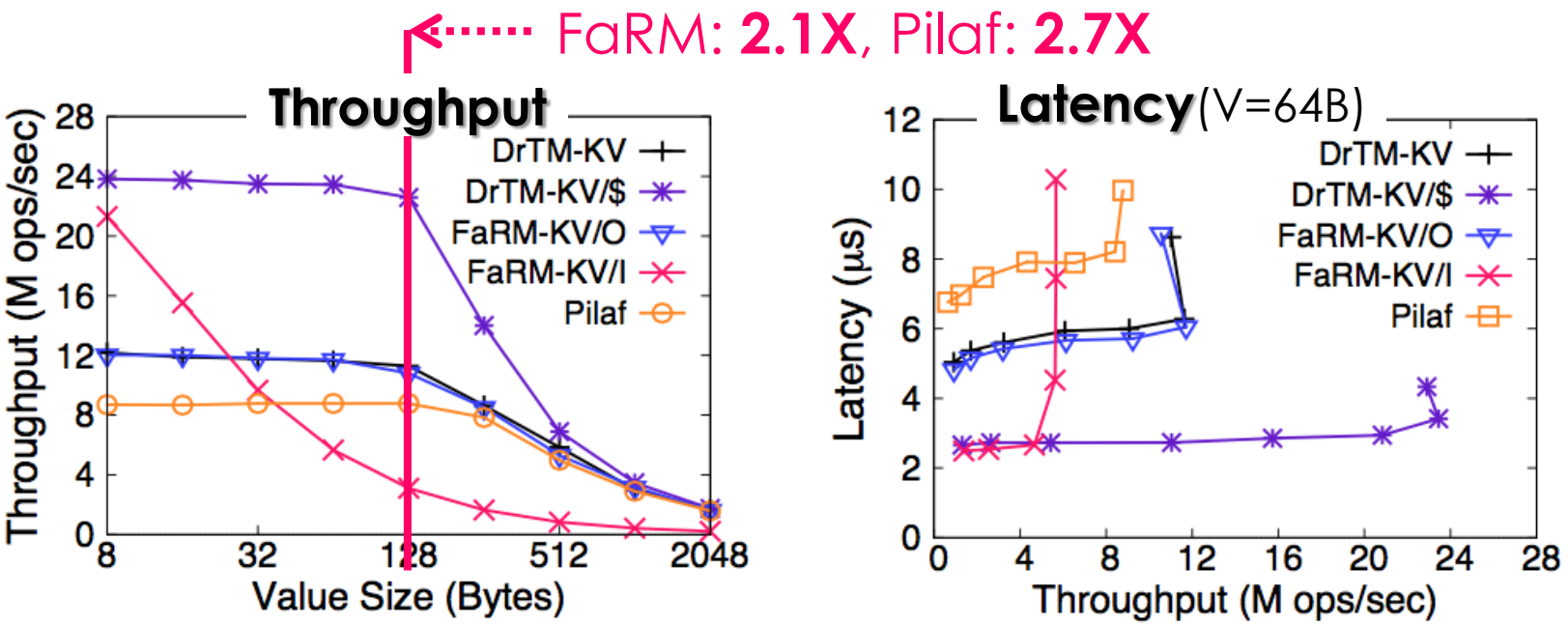


The average lookup cost = **0.178**

20 million kv-pairs (>40 GB), 20MB cache (from empty), 8 client threads, skewed workload (Zipf θ=0.99)

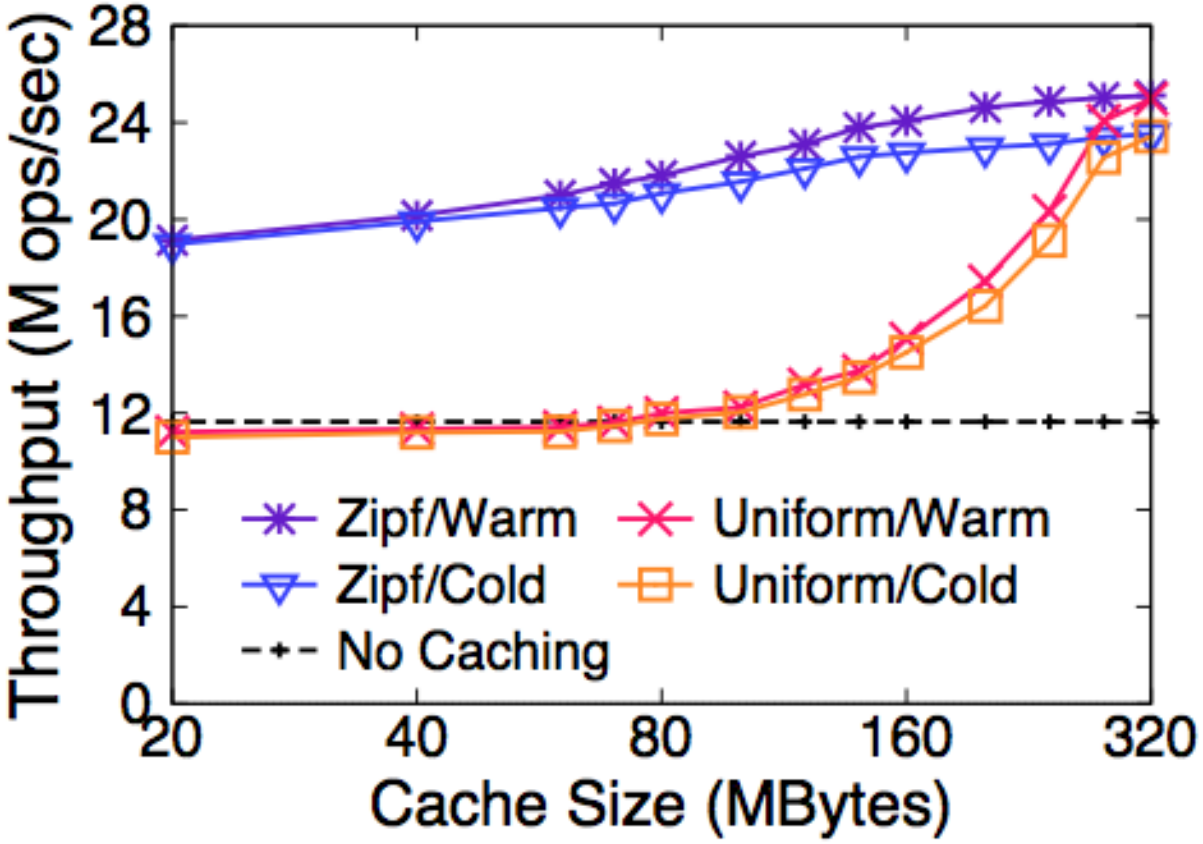
Performance of DrTM-KV

- ✓ DrTM-KV w/o caching provides a comparable performance
- ✓ DrTM-KV w/ caching (DrTM-KV/$) can achieve both lowest latency (3.4 µs) and highest throughput (23.4 Mops/sec)

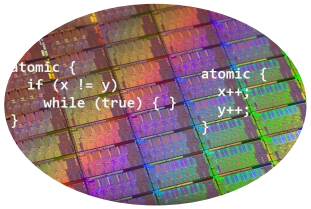


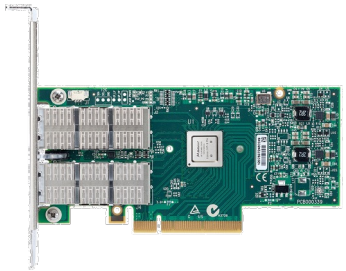
Setting: 1 server and 5 clients (up to 8 threads), 20 million k/v pairs
peak throughput of random RDMA READ ≈ 26 Mops/sec

Performance of Caching



Fast Distributed Transactions using RDMA & HTM





High COST for Distributed TX

Many scalable systems have low performance

- Usually 10s~100s of thousands of TX/second
- High COST[1] (config. that outperform single thread)
- e.g., HStore, Calvin[SIGMOD'12]

Emerging speedy TX systems not scale-out

- Achieve over 100s of thousands TX/second
- e.g., Silo[SOSP'13], DBX[EuroSys'14]

Dilemma:

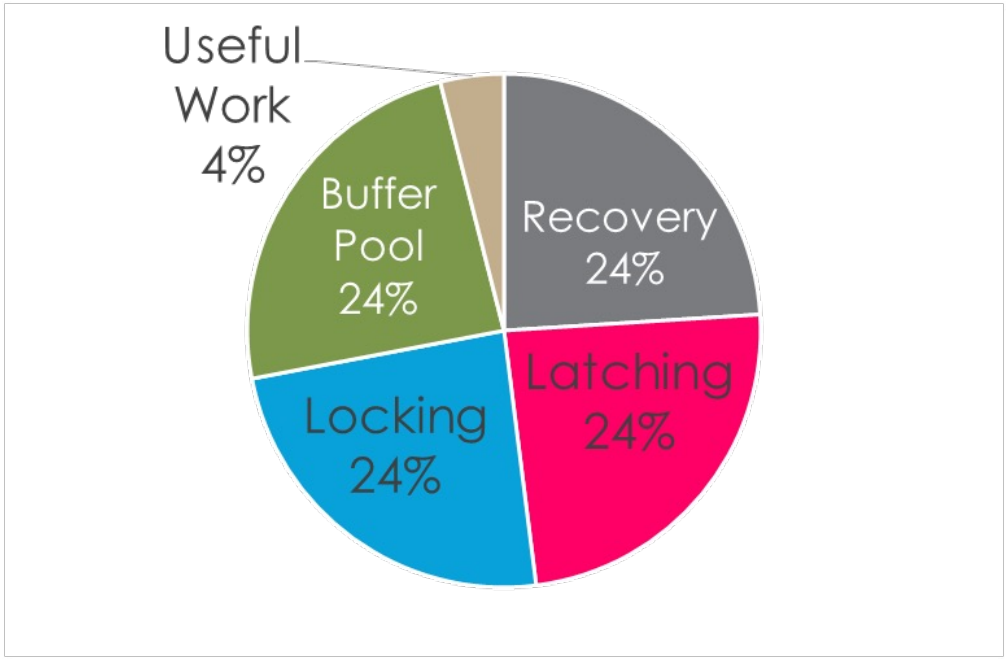
single-node perf. *vs.* **scale-out**

[1] Salability! But at what Cost? HotOS 2015

Why (Distributed) TXs are Slow?

Only **4% of wall-clock time** spent on useful data processing, while the rest is occupied with **buffer pools**, **locking**, **latching**, **recovery**.[1]

-- Michael *Stonebraker*



[1] "The Traditional RDBMS Wisdom is All Wrong"

Opportunities with HTM & RDMA

HTM: **H**ardware **T**ransaction **M**emory

> *a non-transactional code will unconditionally abort a transaction when their accesses conflict*

RDMA: **R**emote **D**irect **M**emory **A**ccess

> *one-sided RDMA operations are cache-coherent with local accesses*

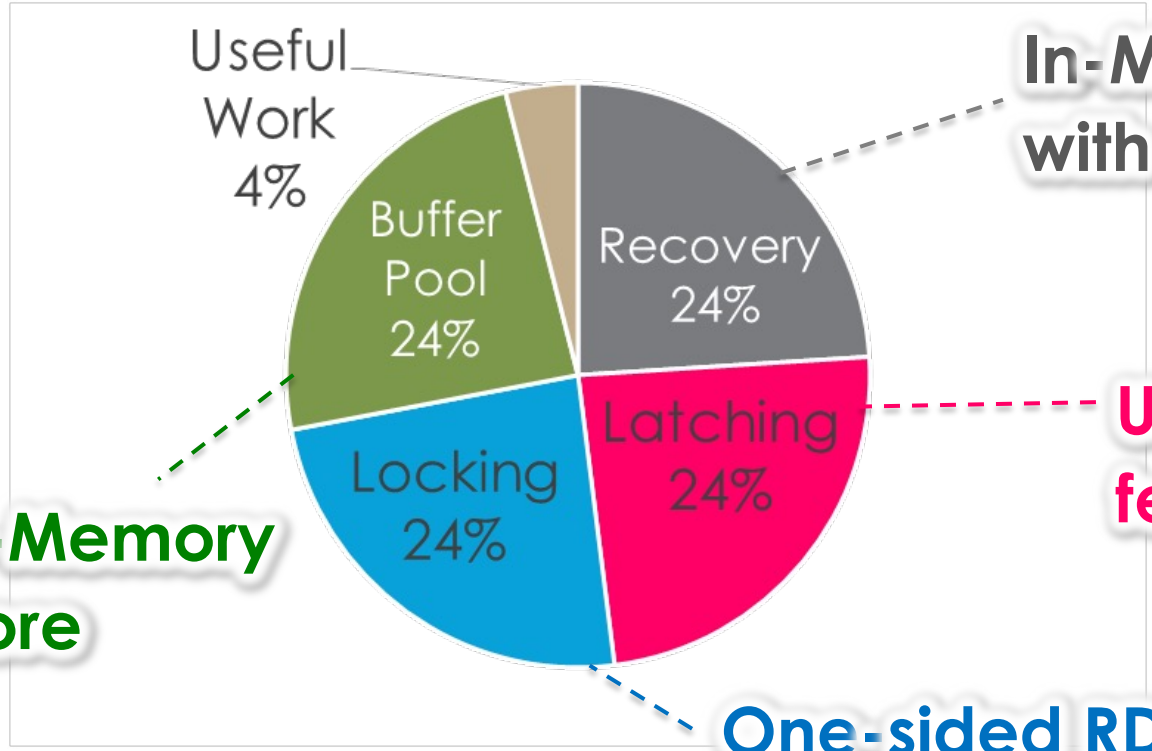
HTM Strong Atomicity + **RDMA Strong Consistency** ⇒ **RDMA ops will abort conflicting HTM TX**

Basis for Distributed TM

DrTM: Fast In-memory Transaction Processing using RDMA and HTM

Use HTM's ACI properties for local TX execution

Use one-sided RDMA to glue multiple HTM TXs



In-Memory Logging with NVM

Use HTM's ACI features

In-Memory Store

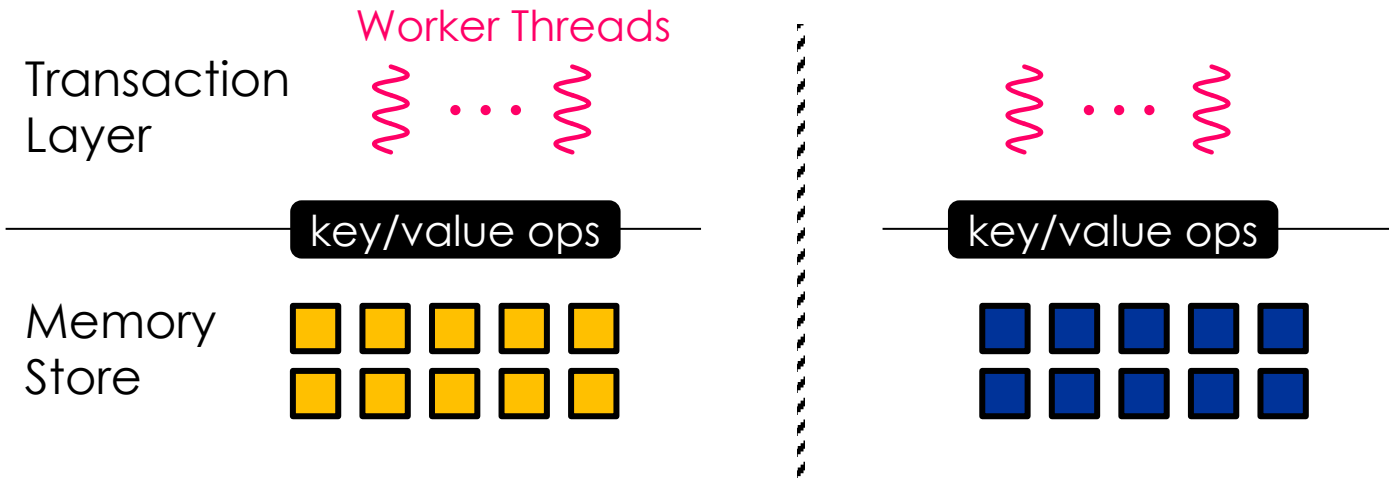
One-sided RDMA Ops

System Overview

DrTM : Distributed TX with HTM & RDMA

- Target: OLTP workloads over large volume of data
- Two independent components using HTM&RDMA

  Transaction layer & **memory store**
- Low COST distributed TX
  - Achieve over 5.52 million TXs/sec for TPC-C on 6 nodes



Challenge#1: Restriction of HTM

HTM is only a compelling hardware feature for single machine platform

- Distributed TX cannot directly benefit from it

Some instructions & system events (e.g. network I/O) will unconditionally abort **HTM** transactions

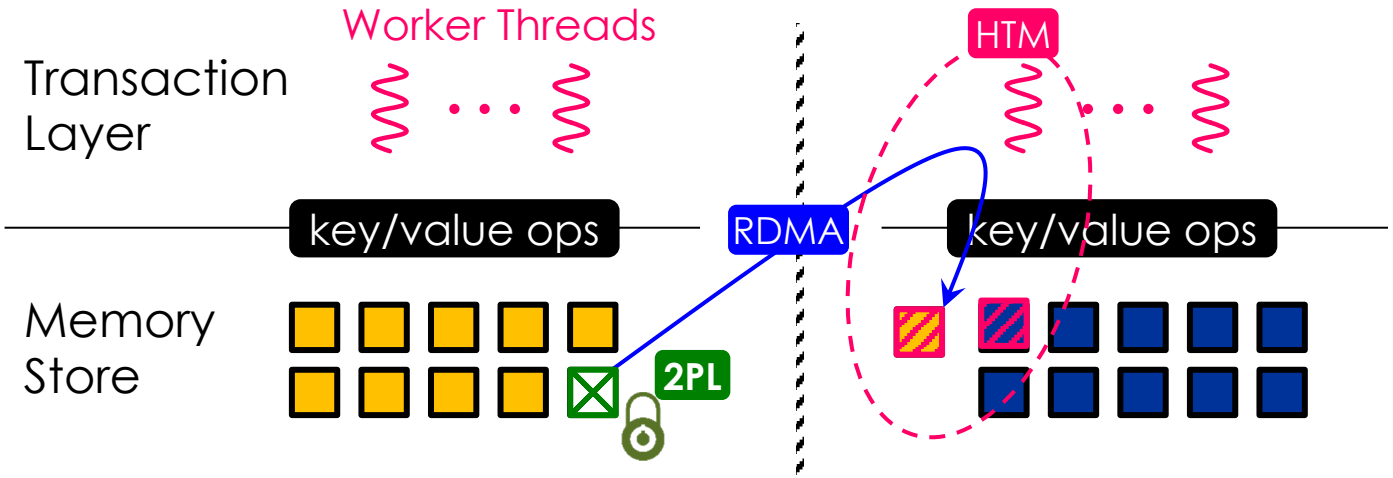
- Like any RDMA ops: READ/WRITE, CAS, SEND/RECV

How to glue multiple HTM transactions together by RDMA while preserving serializability?

Combining HTM with 2PL

Using **2PL** to accumulate all remote records prior to accesses in an HTM transaction

- Transform a distributed TX to a local one
- Limitation: require advanced knowledge of read/write sets of transactions[1]



[1] This is similar with prior work (e.g. Sinfonia & Calvin) and the case for typical OLTP workloads

DrTM's Concurrency Control

Local TX vs. Local TX: HTM

Distributed TX vs. Distributed TX: 2PL

Local TX vs. Distributed TX: abort local TX

DrTM's Concurrency Control

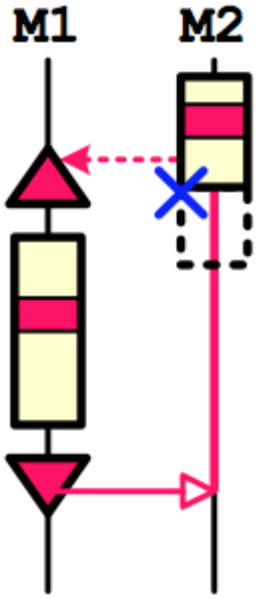
Local TX vs. Local TX: HTM

Distributed TX vs. Distributed TX: 2PL

Local TX vs. Distributed TX: abort local TX

Local TX prior to
Distributed TX

→ RDMA (strong consistency)
+ HTM (strong atomicity)



DrTM's Concurrency Control

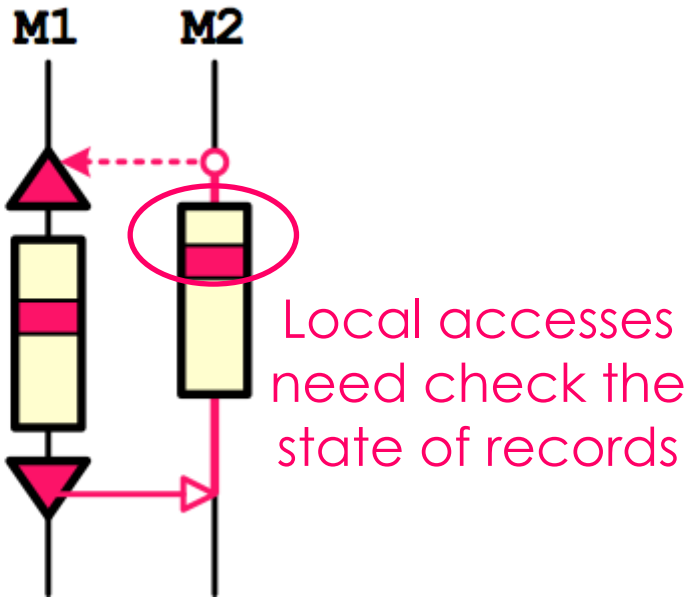
Local TX vs. Local TX: HTM

Distributed TX vs. Distributed TX: 2PL

Local TX vs. Distributed TX: abort local TX

Distributed TX
prior to Local TX

→ Local TX checks (but not locks) the records



Challenge#2: Limit of RDMA Semantics

RDMA provides three communication options

- IPoIB, SEND/RECV and one-sided RDMA ops

Good performance (e.g. latency)
and without involving the host CPU

One-sided RDMA has much limited interfaces

- READ, WRITE, CAS and XADD

How to support exclusive and shared accesses
in 2PL protocol using one-sided RDMA ops

DrTM's Lock

RDMA CAS: atomic compare-and-swap

- Similar to the semantic of normal CAS (i.e. local CAS)

1. DrTM's **exclusive** lock
   - Spinlock: use RDMA CAS to acquire & release
2. DrTM's **shared** lock
   - Lease-based protocol

Shared (Read) Lock

Lease-based protocol

- Grant read right to the lock holder in a time period
- No need to explicit release or invalidate the lock

exclusive & shared lock

Lease's **end-time** machine-ID[1] **exclusive**-bit

$000...000_2$ unlocked

$000...yy1_2$ exclusive locked

$xxx...000_2$ shared locked

State is atomically compare and swap using RDMA CAS

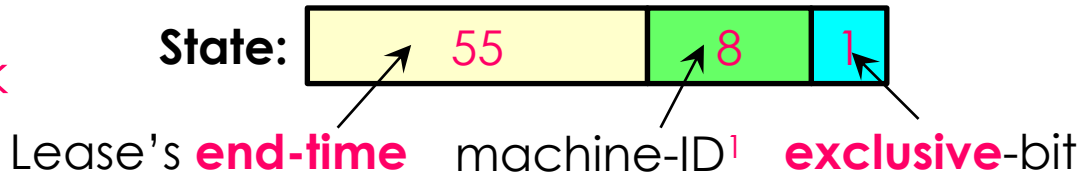
[1] Machine ID is only used by recovery

Shared (Read) Lock

Lease-based protocol

- Grant read right to the lock holder in a time period
- No need to explicit release or invalidate the lock
- Synchronized time is provided by PTP[2]

exclusive & shared lock



$000...000_2$ **unlocked**

$000...yy1_2$ **exclusive locked**

$xxx..000_2$ **shared locked**

EXPIRED: if now > end-time + DELTA

INVALID: if now < end-time - DELTA

DELTA is used to tolerate the time bias among machines

[1] Machine ID is only used by recovery
[2] PTP: precision time protocol, http://sourceforge.net/p/ptpd/wiki/Home/

Challenge#3: Durability

All machines can immediately observe the local updates after the commitment of HTM transaction

- Database transaction enclosing this HTM txn must be eventually committed, even if machine failed

One-sided RDMA can directly accesses remote records without the involvement of host machine

- A single machine can no longer solely log all accesses to its records

How to provide durability with HTM and RDMA

Durability

Failure model

- Similar to WSP[ASPLOS'12] and DTX[SOSP'15]
- Assume flush-on-failure policy

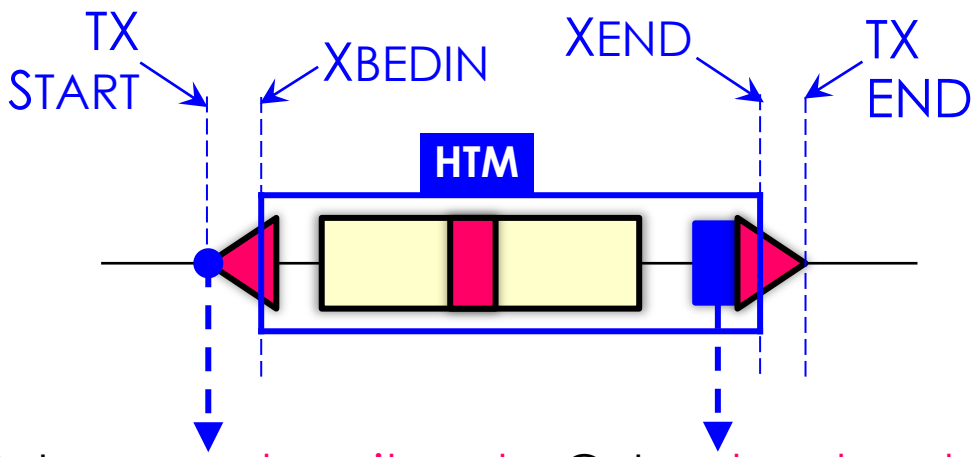
> Flush any transient state in registers and cache lines to non-volatile DRAM (NVRAM) and finally to a persistent storage (SSD) upon a failure by the power from UPS

- Fail-stop crash instead of arbitrary failures (e.g., BFT)
- Zookeeper
  - Detect machine failures by a heartbeat mechanism
  - Notify surviving machines to assist the recovery of crashed machines

Cooperative Logging & Recovery

Logging

1. Log local updates within an HTM transaction
2. Log remote updates through RDMA operations
   e.g., locking (RDMA CAS) & update (RDMA WRITE)



① Log remote write set
(*Lock-ahead log*)

② Log local and
remote updates
(*Write-ahead log*)

if **only** ①,
then UNCOMMITTED

→ Unlock remote records

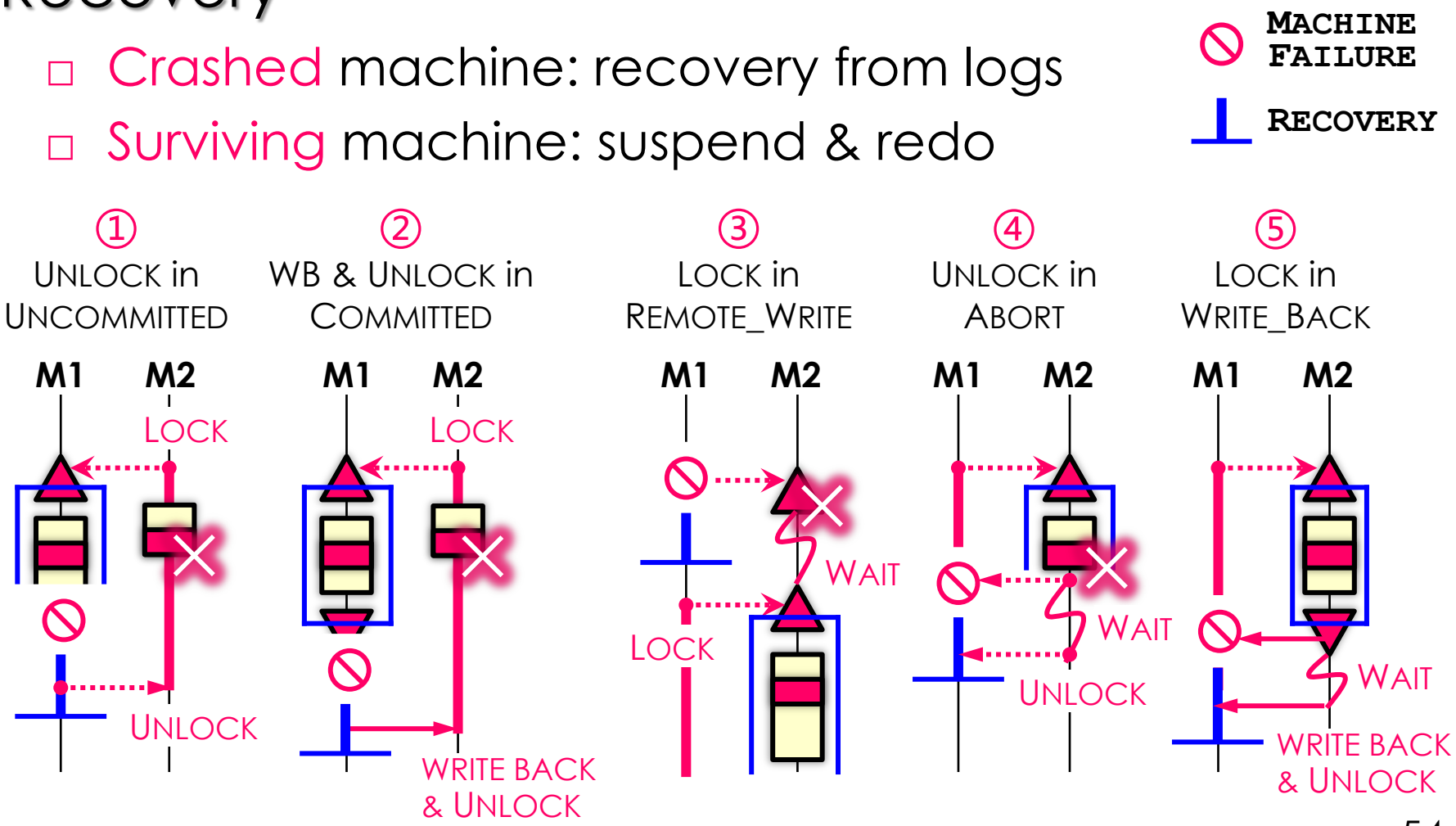
if **both** ① **and** ②,
then COMMITTED

→ Eventually write back
& unlock records

Cooperative Logging & Recovery

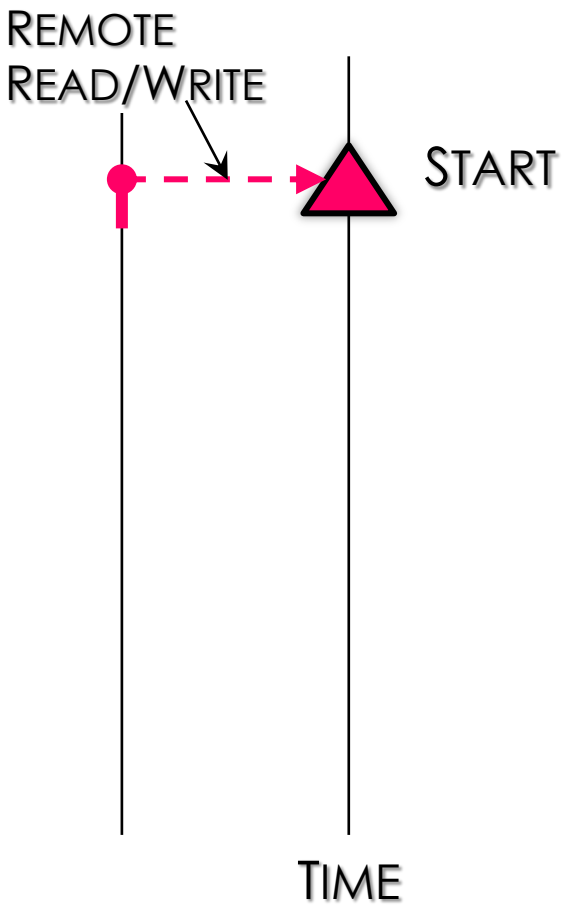
Recovery

- Crashed machine: recovery from logs
- Surviving machine: suspend & redo



Transaction Execution Flow

DrTM's Transaction: **START** + **LOCALTX** + **COMMIT**

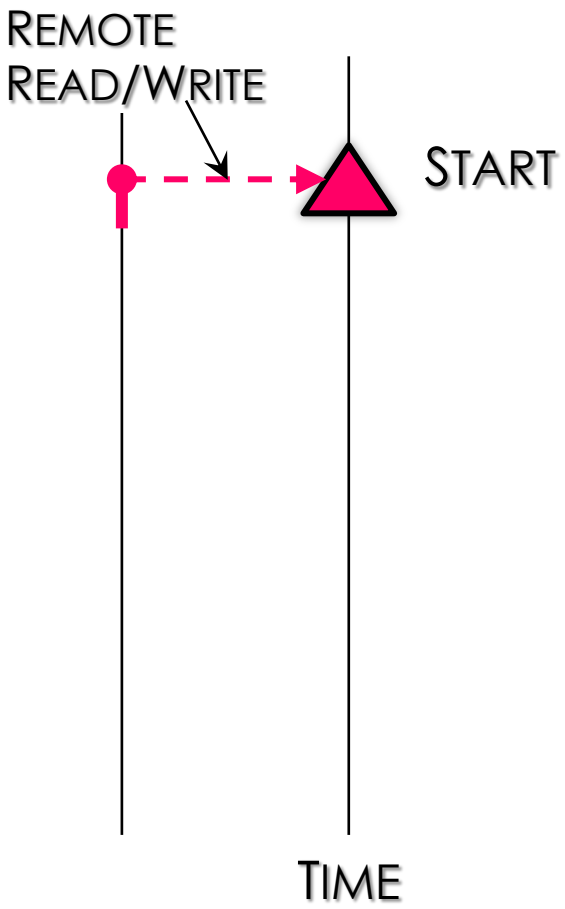



```
START (remote_writeset,remote_readset)
  foreach key in remote_writeset
    value = Exclusive_lock_fetch(key)
    cache[key] = value
  foreach key in remote_readset
    value = Shared_lease_fetch(key)
    cache[key] = value

  XBEGIN()
```

Transaction Execution Flow

DrTM's Transaction: **START** + **LOCALTX** + **COMMIT**

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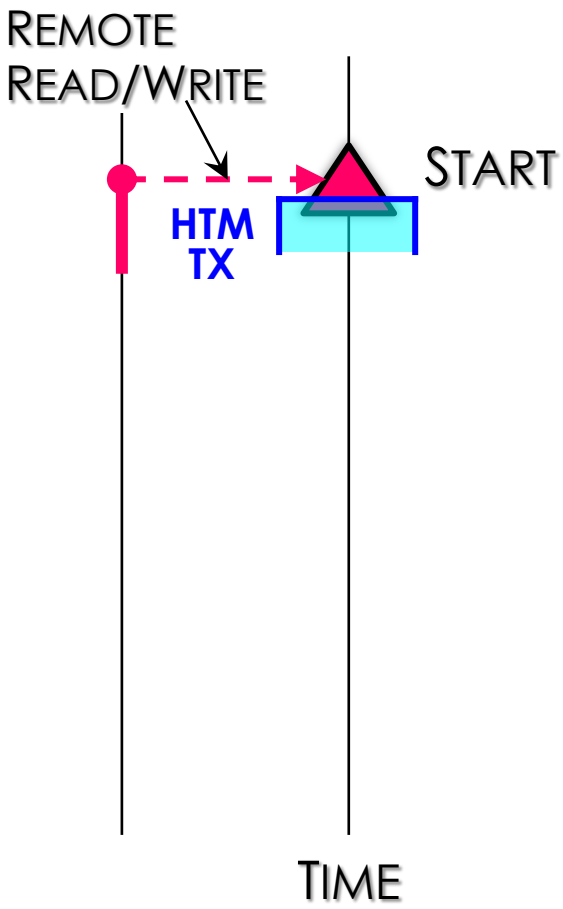


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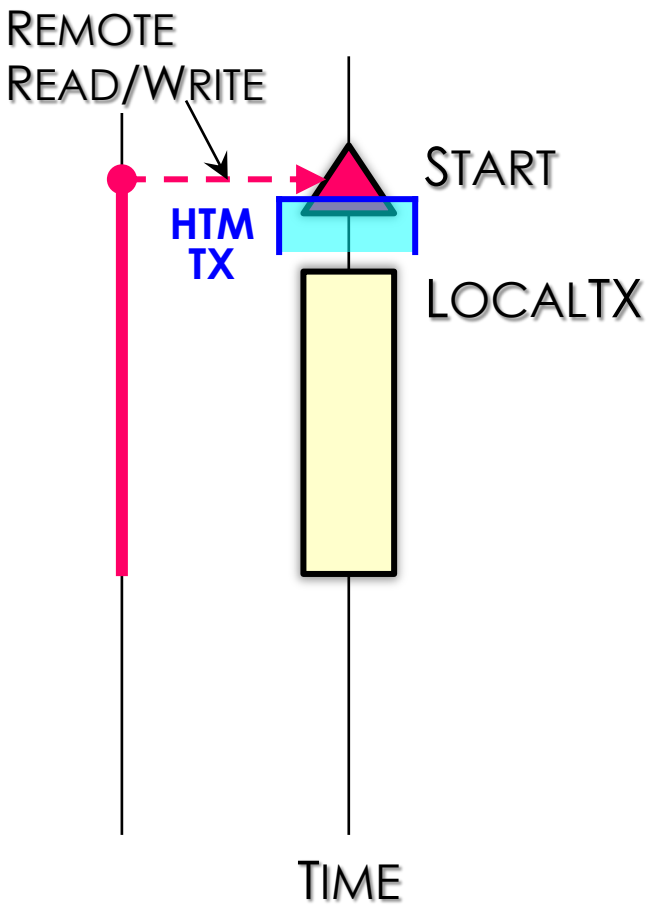
Transactional Read & Write

DrTM's Transaction: START + LOCALTX + COMMIT

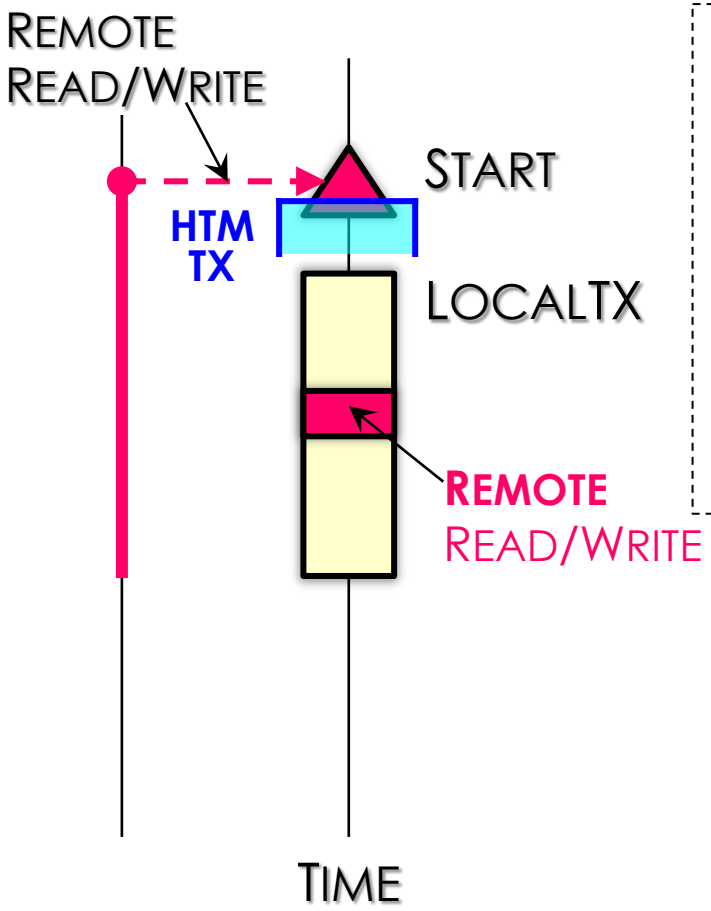



```
READ(key)
  if key.is_remote() == true
    return cache[key]
  else return LOCAL_READ(key)

WRITE(key, value)
  if key.is_remote() == true
    cache[key] = value
  else LOCAL_WRITE(key, value)
```

Transactional Read & Write

DrTM's Transaction: **START** + **LOCALTX** + **COMMIT**

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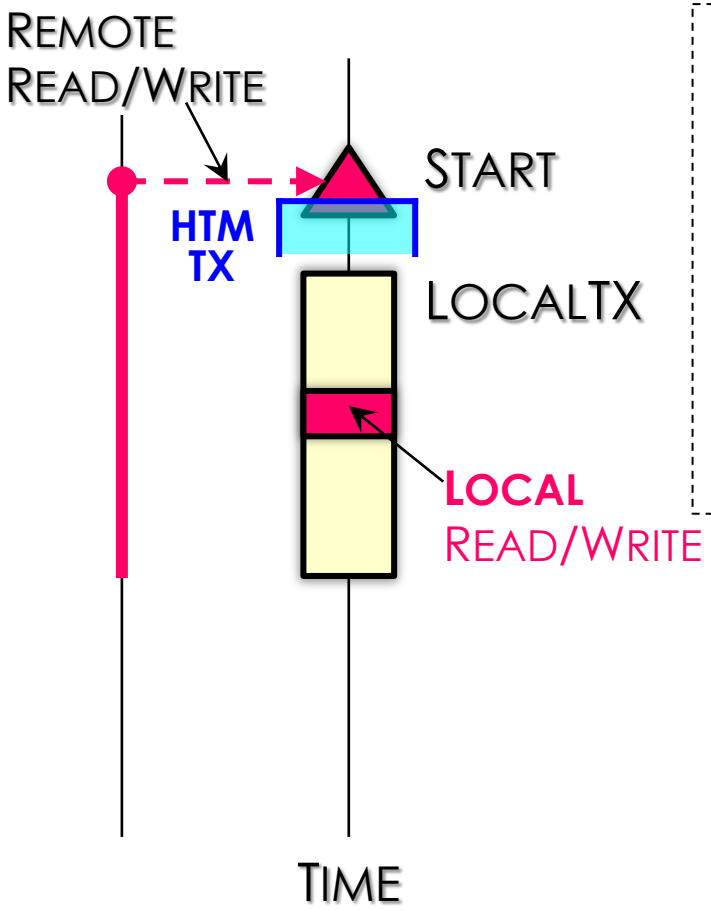
Transactional Read & Write

DrTM's Transaction: START + LOCALTX + COMMIT

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Transactional Read & Write

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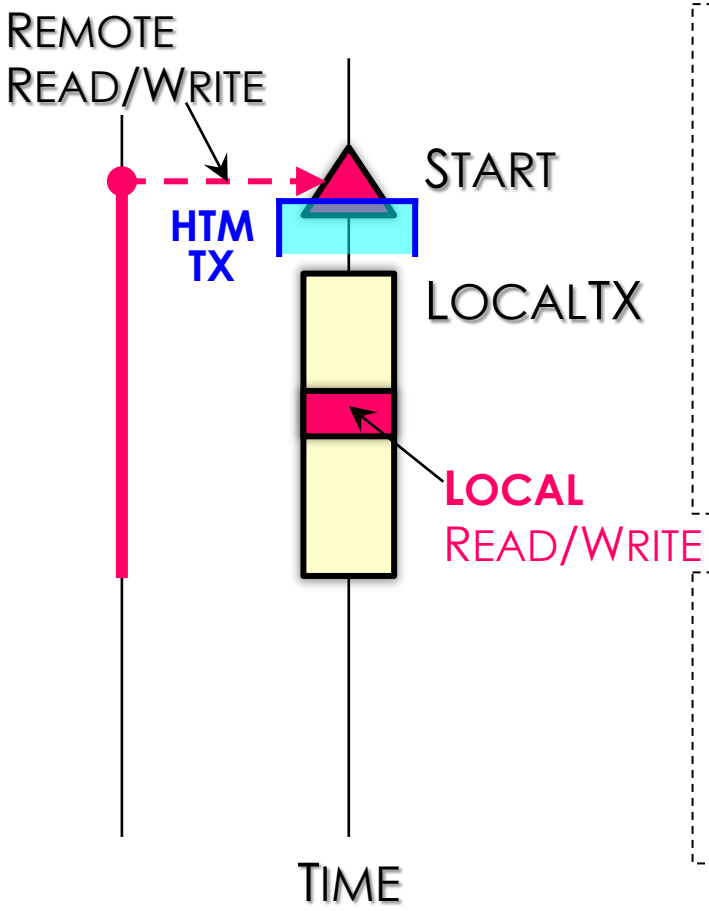


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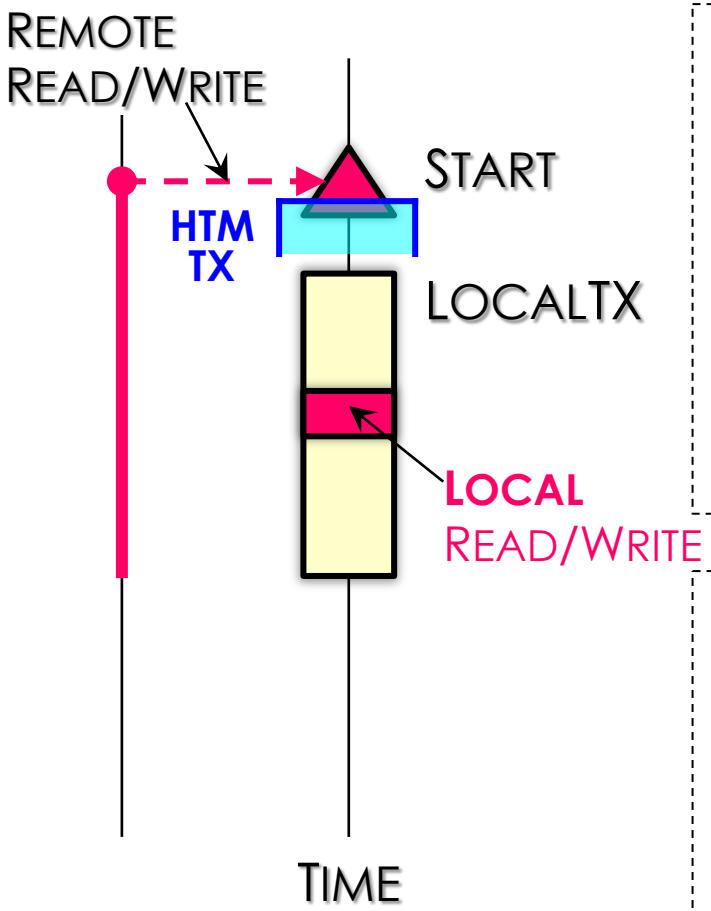
  if key.is_remote() == true
    cache[key] = value
  else LOCAL_WRITE(key, value)
```

```
LOCAL_READ(key)
  if states[key].w_lock == W_LOCKED
    ABORT()
  else
    return values[key]
```

Transactional Read & Write

DrTM's Transaction: START + LOCALTX + COMMIT

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WRITE(key, value)
  if key.is_remote() == true
    cache[key] = value
  else LOCAL_WRITE(key, value)
```
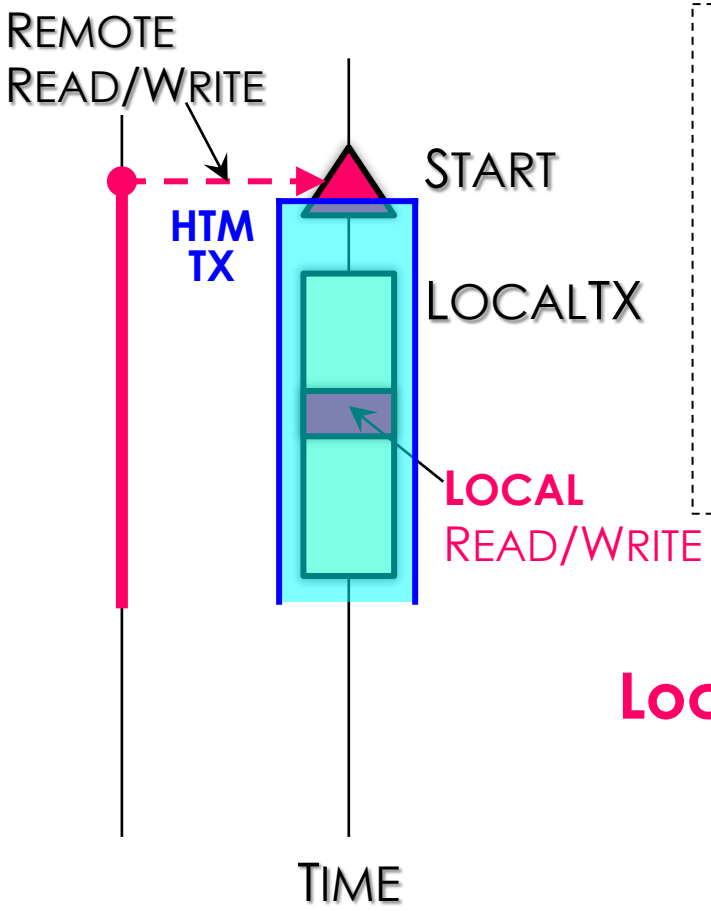

```
LOCAL_WRITE(key, value)
  if states[key].w_lock == W_LOCKED
    ABORT()
   else if EXPIRED(END_TIME(states[key]))
    values[key] = value
  else ABORT()
```

Transactional Read & Write

DrTM's Transaction: START + LOCALTX + COMMIT

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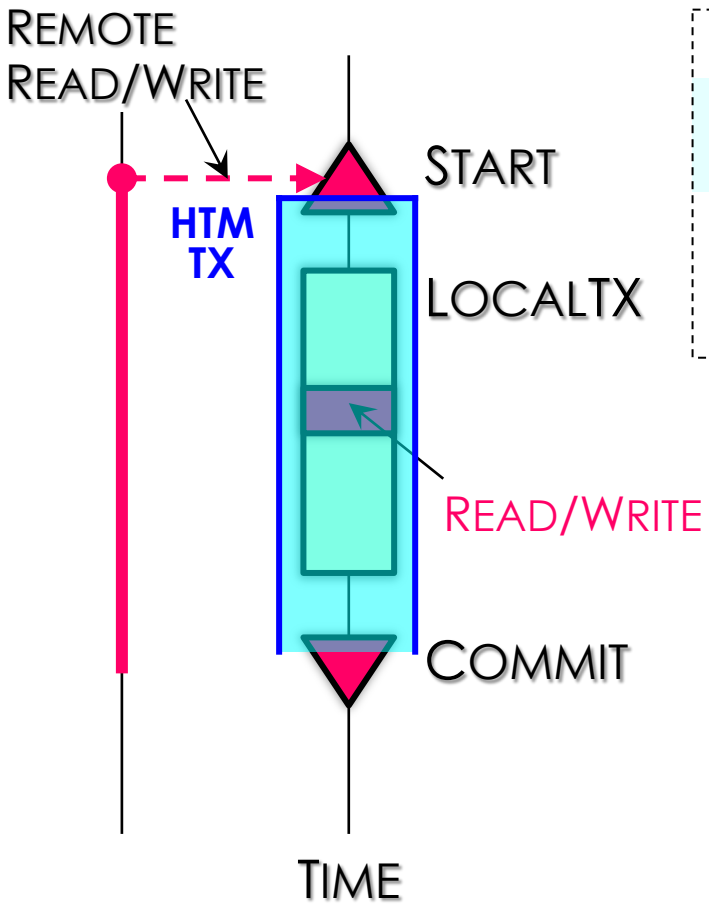
WRITE(key, value)
  if key.is_remote() == true
    cache[key] = value
  else LOCAL_WRITE(key, value)
```

Local conflicts are detected by **HTM**

Transaction Execution Flow

DrTM's Transaction: **START** + **LOCALTX** + **COMMIT**



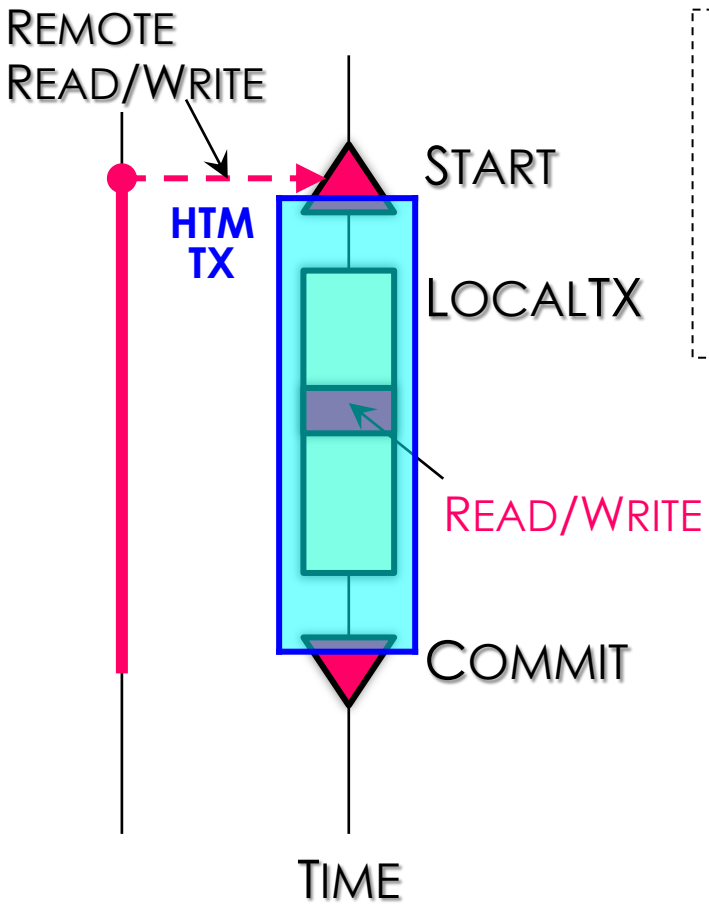

```
COMMIT(remote_writeset,remote_readset)
  if !VALID(end_time)
    ABORT()
  XEND()
  foreach key in remote_writeset
    RELEASE_WRITE_BACK(key,cache[key])
```

2PL: all **shared locks** must be released in shrinking phase

- Insert validation to all leases just before HTM commit

Transaction Execution Flow

DrTM's Transaction: **START** + **LOCALTX** + **COMMIT**

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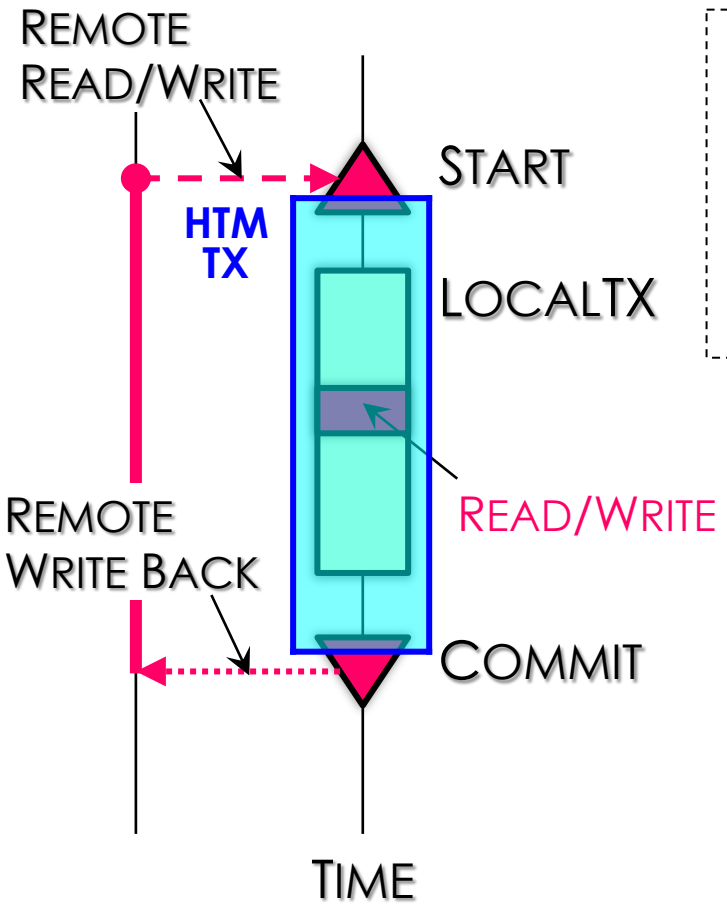
Commit **local** updates by **HTM**

Transaction Execution Flow

DrTM's Transaction: **START** + **LOCALTX** + **COMMIT**

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  if !VALID(end_time)
    ABORT()
  XEND()
  foreach key in remote_writeset
    RELEASE_WRITE_BACK(key,cache[key])
```
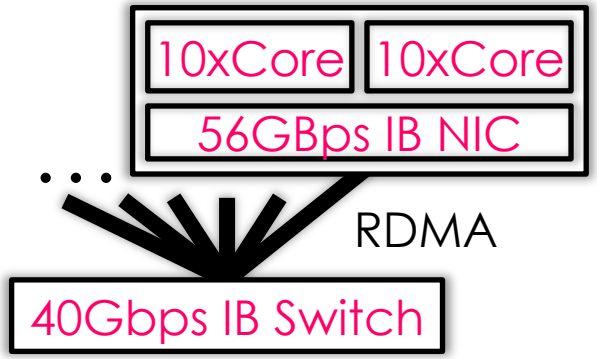

2PL & HTM → Serializability

Commit **local** updates by **HTM**

Commit **remote** updates by **RDMA**

Evaluation



Baseline: Latest *Calvin* (Mar. 2015)

Platforms: A small-scale 6-machine cluster

- Each: two 10-cores, RTM-enabled Intel Xeon E5-2650 (disabled HT), 64GB DRAM, Mellanox ConnectX-3 MCX353A 56Gbps InfiniBand NIC w/ RDMA[1]

Benchmark[2]

- TPC-C

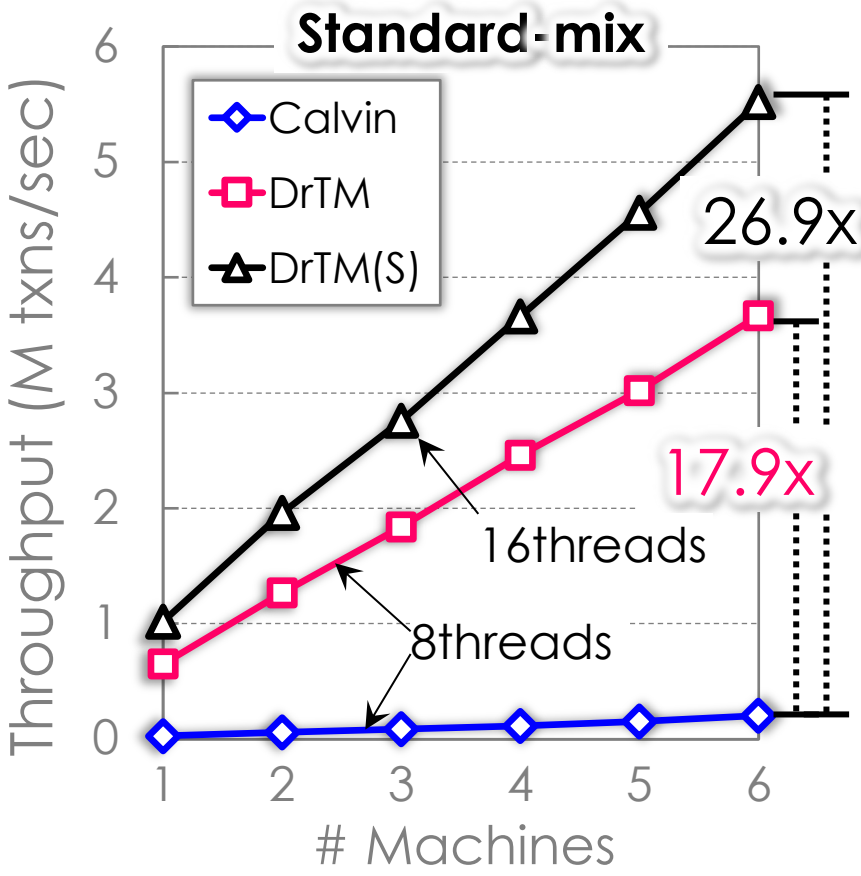
TPC-C	NEW	PAY	DLY	OS	SL
Ratio	45%	43%	4%	4%	4%
Type	d+rw	d+rw	l+rw	l+ro	l+ro

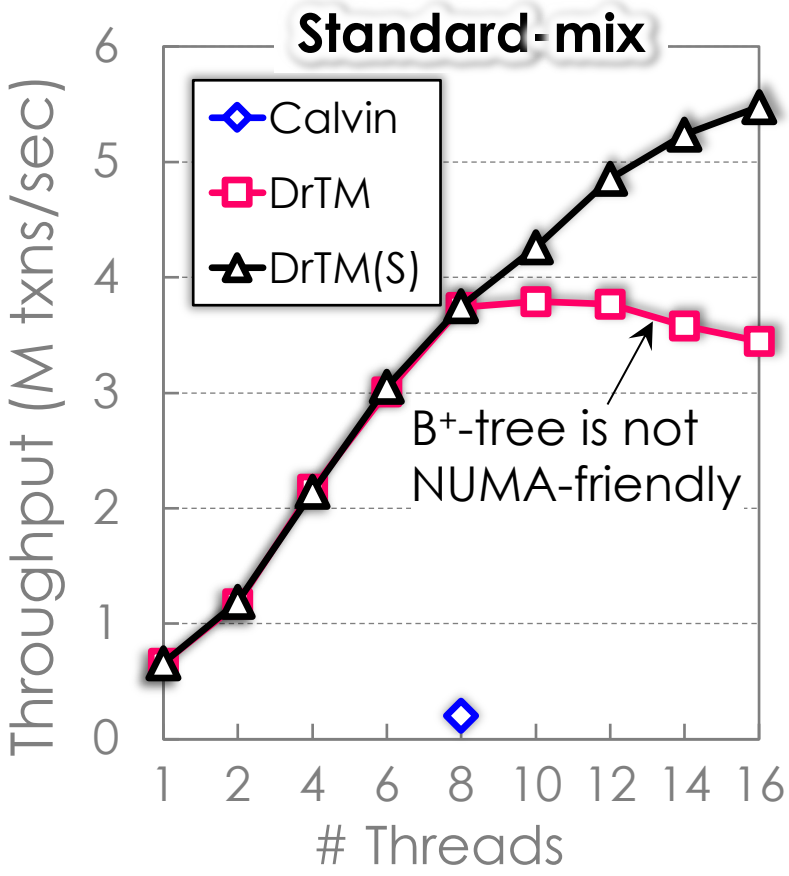
[1] All machines run Ubuntu 14.04 with Mellanox OFED v3.0-2.0.1 stack.
[2] **d** and **l** stand for distributed and local. **rw** and **ro** stand for read-write and read-only.

Performance on TPC-C

New-order TX
≈ Standard-mix x45%

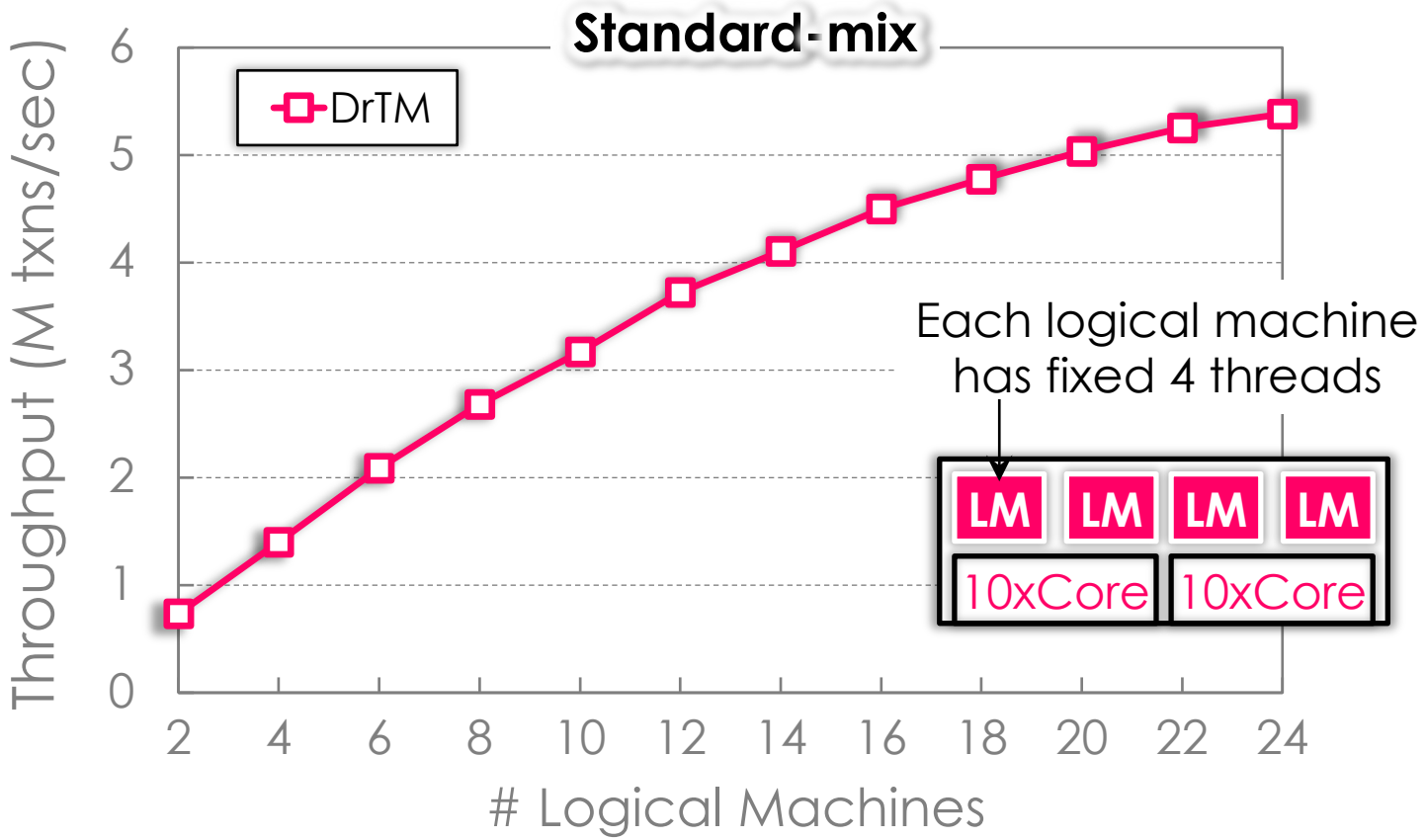
DrTM(S): run a separate logical node on each socket





Scalability on TPC-C

New-order TX
≈ Standard-mix x45%



NOTE: the interaction btw. two logical nodes sharing the same machine still uses our RDMA-friendly 2PL protocol

Summary

In-memory computing demands high throughput and low latency

RDMA: helps bridge the gap from incommensurate scaling for in-memory computing

- Distributed key/value store
- In-memory transactions

Achieving orders-of-magnitude lower latency & higher throughput than prior state-of-the-art centralized and distributed systems

Next Lecture

Topic: Distributed File Systems

Paper

Sanjay Ghemawat et al, "***Google File System***". International Symposium on Operating Systems Principles (SOSP), **2003**