# FAST In-memory Transaction Processing using New Hardware Features

*—— A Perspective from Systems Software ——*

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# Transaction: Key Pillar for Many Systems

amazon.com

426 items/second

Amazon sold 426 items per second during its 'best ever' holiday season

Alibaba.com

$9.3 billion/day

Alibaba's 'Singles Day' rings up $9.3 billion in new record

**Demand Speedy Distributed Transaction Over Large Data Volumes**

12306

9.56 million tickets/day

re than 9.56 million . Dec 19, a new high daily sales, as people rushed to book tickets home before the Spring Festival.

PayPal

11. 6 million payments/day

million payments for our customers per day.

# 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

# Conventional Approach [Before 2015]

TPC-C World Record

**SPARC SuperCluster***

Perf: **504 K TXs/s**

Cost: **30 Million USD**

Cost / Perf: **60.6** **[2010]**


**IBM Power 780 Server+**

Perf: **173 K TXs/s**

Cost: **14 Million USD**

Cost / Perf: **82.6** **[2010]**


* http://tpc.org/tpcc/results/tpcc_result_detail5.asp?id=110120201
+ http://tpc.org/tpcc/results/tpcc_result_detail5.asp?id=110081702

# Conventional Approach [Now]

TPC-C World Record

**Alibaba Cloud / OceanBase*** **[2020]**

Perf: **11.8 M TXs/s**, Cost: **2,815 Million CNY**, Cost / Perf: **238.7**

* http://tpc.org/tpcc/results/tpcc_result_detail5.asp?id=120051701

# High **COST** for Distributed TX

Many **scalable** systems have **LOW perf.**

- Usually 10s~100s of thousands of TX/second
- High COST* (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**

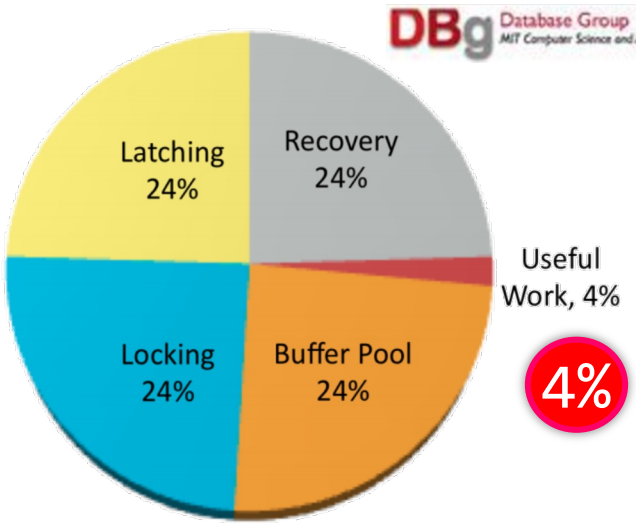
**high perf.** *vs.* **scale-out**

* 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**.*

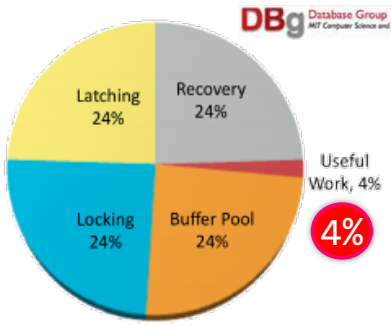
— Michael *Stonebraker*




*Michael Stonebraker*
2014 Turing Award

* "The Traditional RDBMS Wisdom is All Wrong"

# Why **distributed** TXs are Slow?




*Michael Stonebraker*
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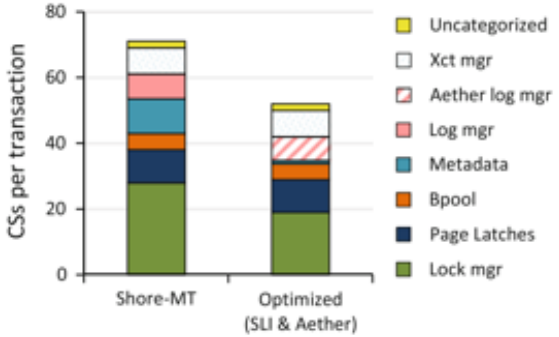
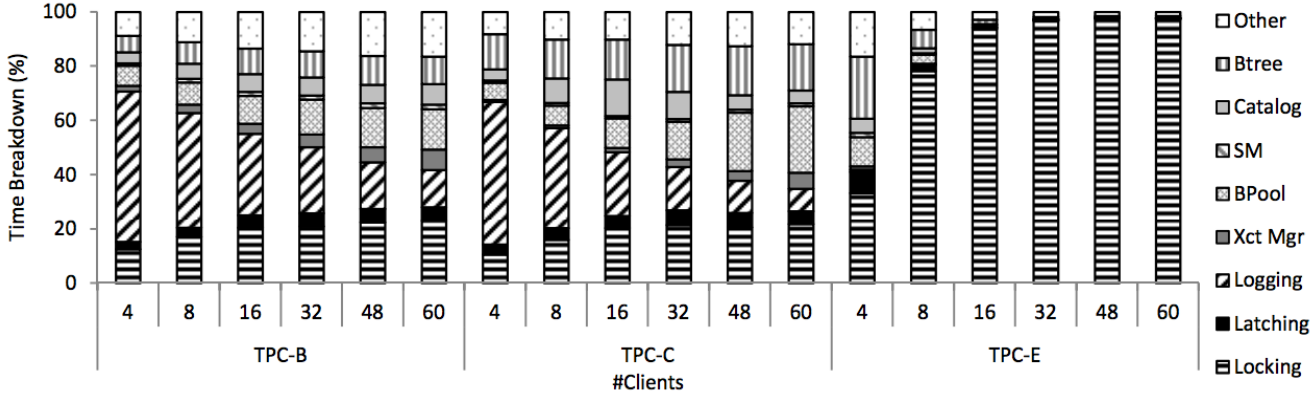



*Eliminating unscalable communication in transaction processing,* VLDBJ 2014



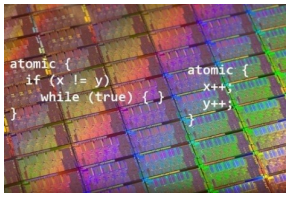

*From A to E: Analyzing TPC's OLTP Benchmarks,* EDBT/ICDT'13

# **Our Approach**: New Hardware

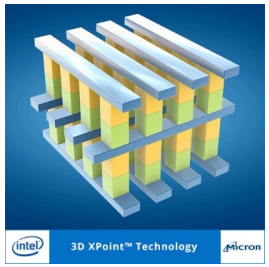
**DrTM / DELL Cluster (16 nodes)**

Perf: > 6 M TXs/s, Cost: < 1 Million CNY, Cost / Perf: < 0.17

**HTM**

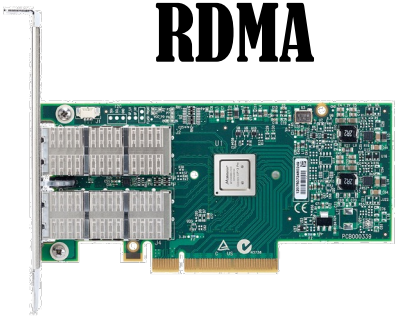



**NVM**

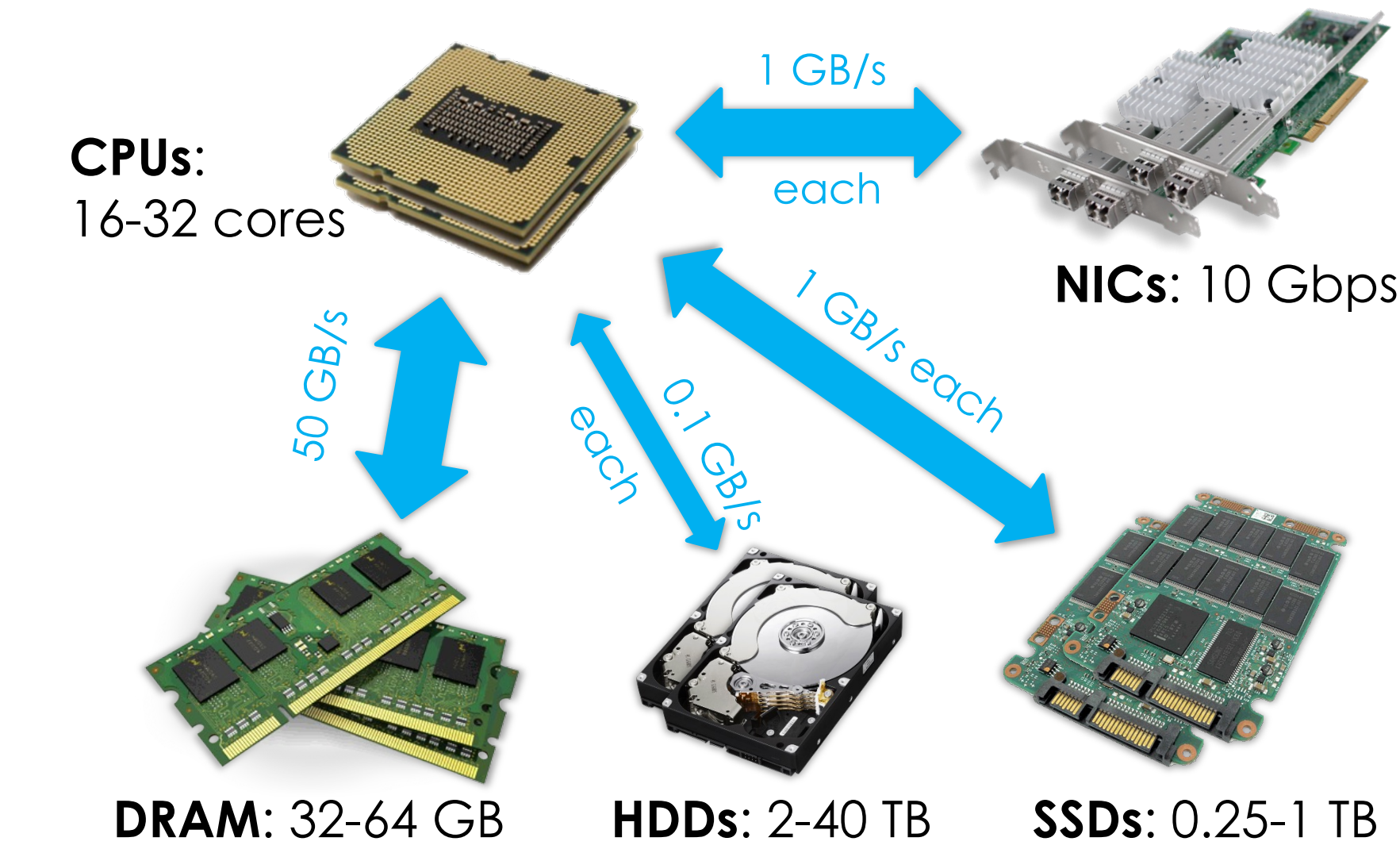



A few *rack-scale machines*

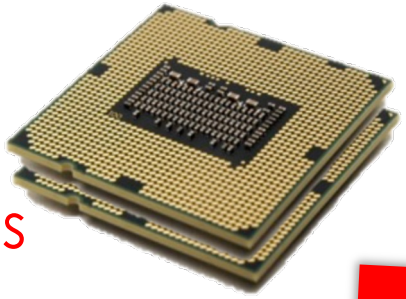
**RDMA**



# Traditional Server @DC

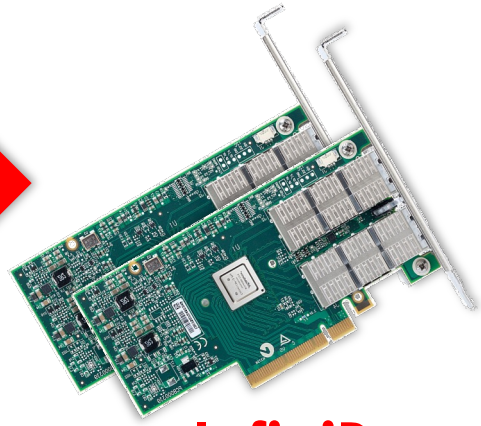


# "Not So New" Hardware Features



**CPUs**:
16-32 cores
w/ **HTM**

10 GB/s each



**InfiniBand NICs**:
100-200 Gbps
w/ **RDMA**

50 GB/s

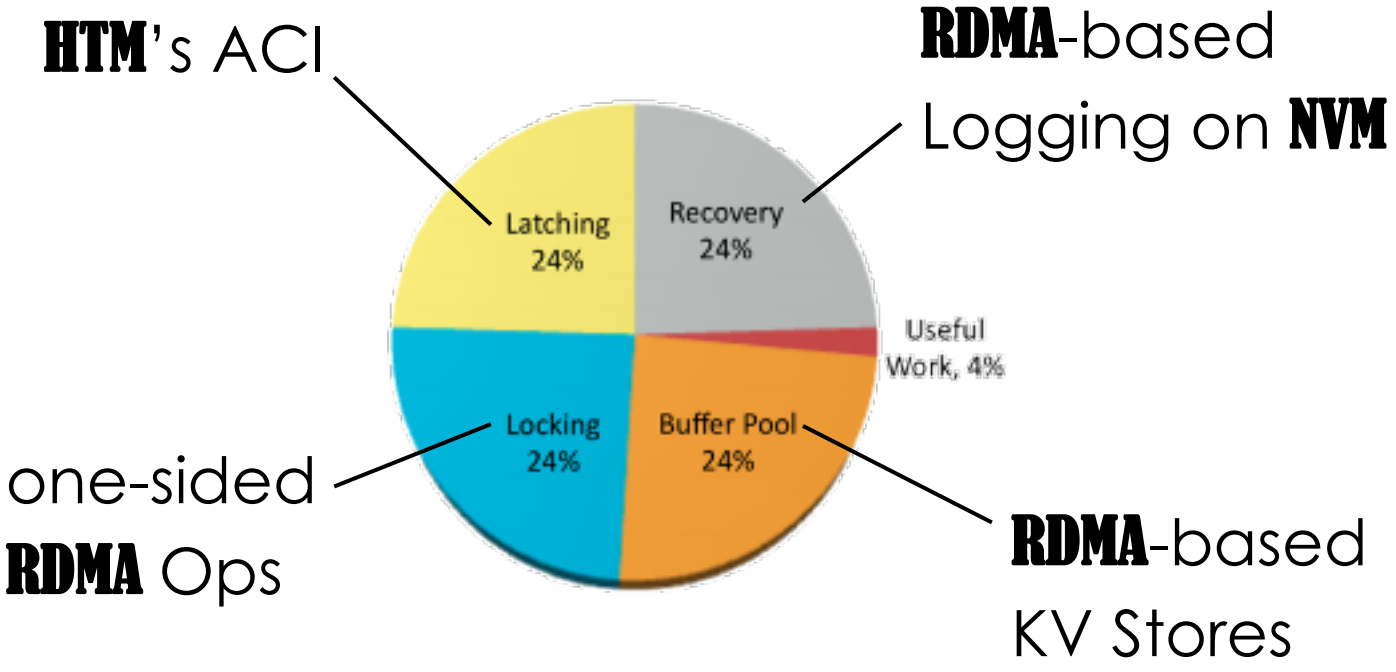
10-50 GB/s

**NVM**: 256-512 GB
w/ **Persistency**

**DRAM**: 128-256 GB

# General Idea

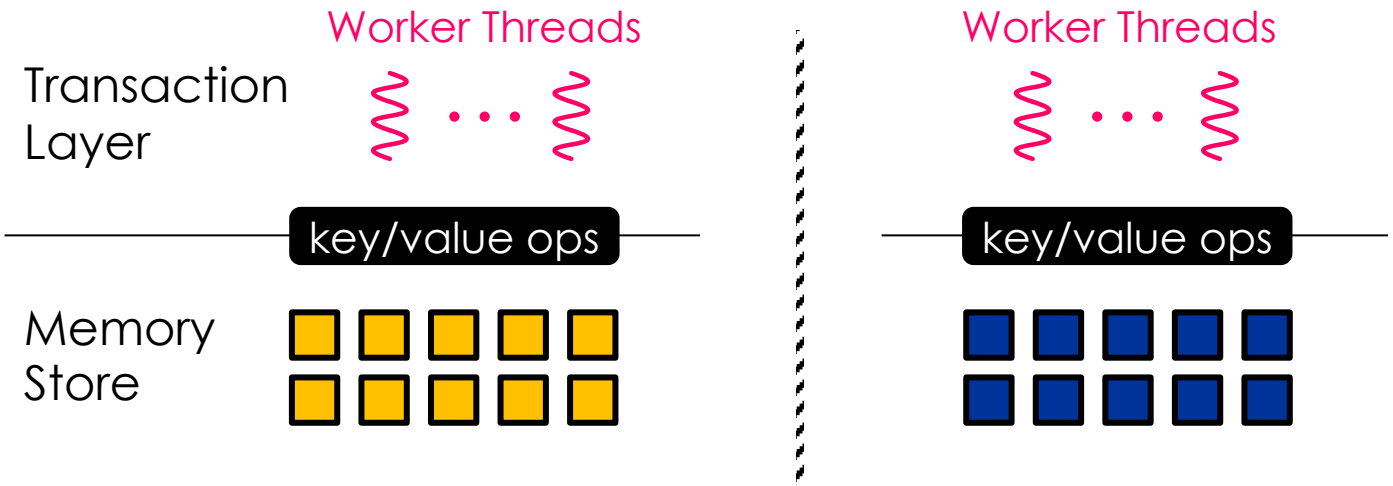
Leveraging new hardware features to accelerate distributed transaction processing



# System Architecture

Distributed transaction processing

- **Target**: OLTP workloads over large volume of data
- Two independent components on each node
  - ► Transaction layer & memory store
- Low COST distributed TX



# This Course

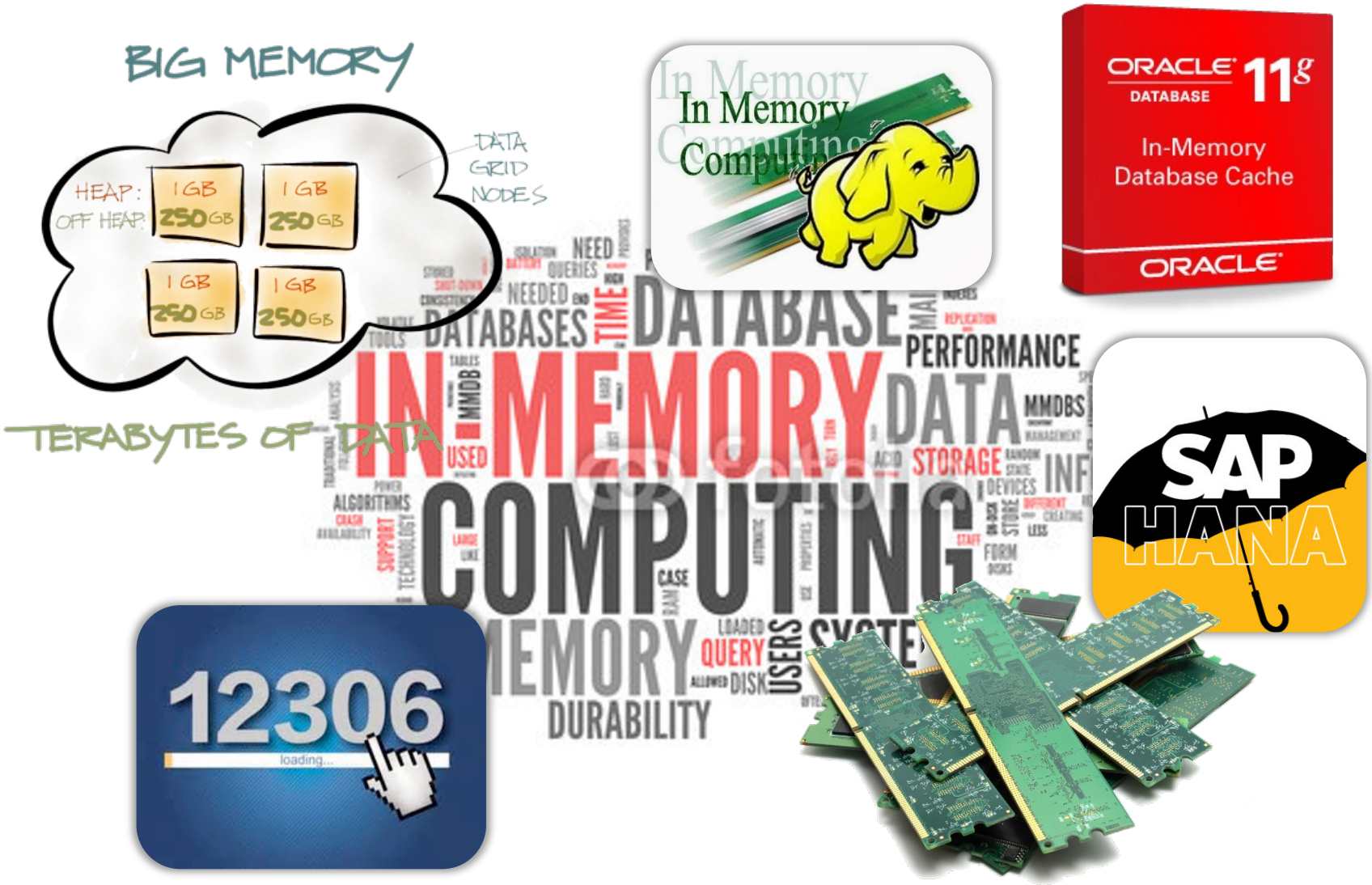
101 of New Hardware Features


Distributed Transaction Protocol

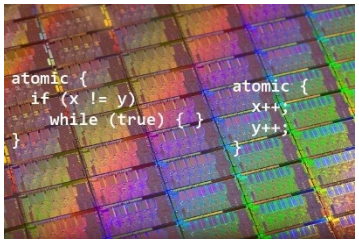

In-memory Key-Value Store


High Availability with Replication

# **In-Memory** Computing



# HTM: Hardware Transactional Memory




Herlihy & Moss — 1993

Sun Rock — 2009

AMD TX Extension — 2010

. . . — 2012

Intel Haswell — 2013

Massively available

# Intel RTM

*Restricted* Transactional Memory (**RTM**)

- Commercial hardware TM with limitations

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New Instructions:

`Xbegin, Xend, Xabort`

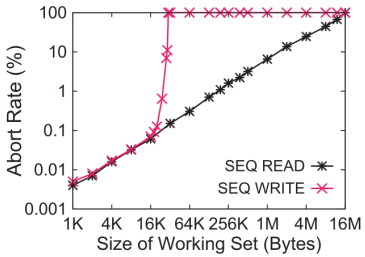
RTM Usage

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

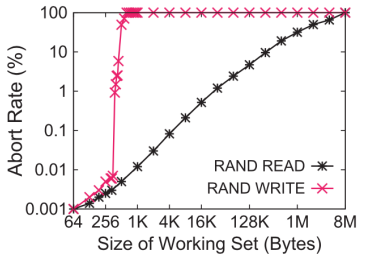
Handle the abort event

Major Limitations

1. Working set is limited
2. System events abort TX




SEQ Access




RAND Access

# Deconstructing **RTM**

**RTM** prefers read than write

- Asymmetric Read/Write Limits

**RTM** prefers read before write

- Eviction of cache lines in write set will abort TX

The execution time affects TX abort

- Timer interrupt unconditionally abort a TX (e.g., 4ms on 250HZ kernel)

# RDMA: Remote Direct Memory Access

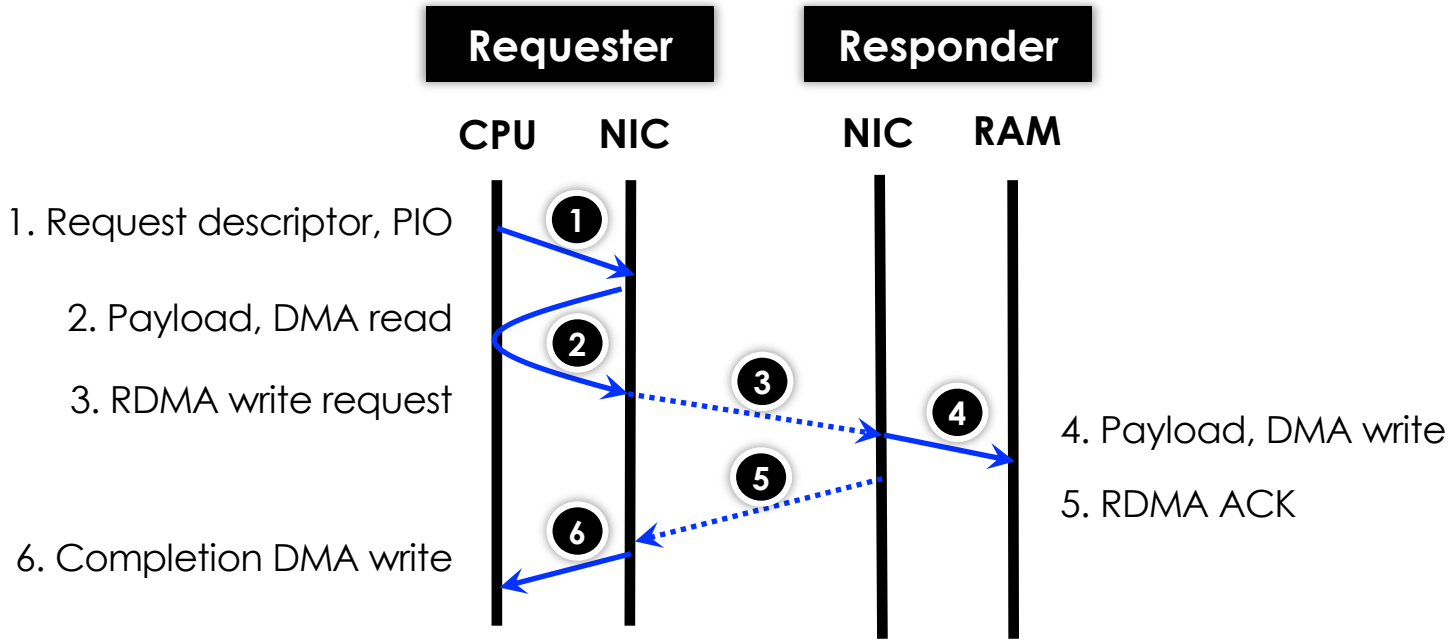
A network feature that allows **direct** access to the memory of a **remote** computer

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 Primitives

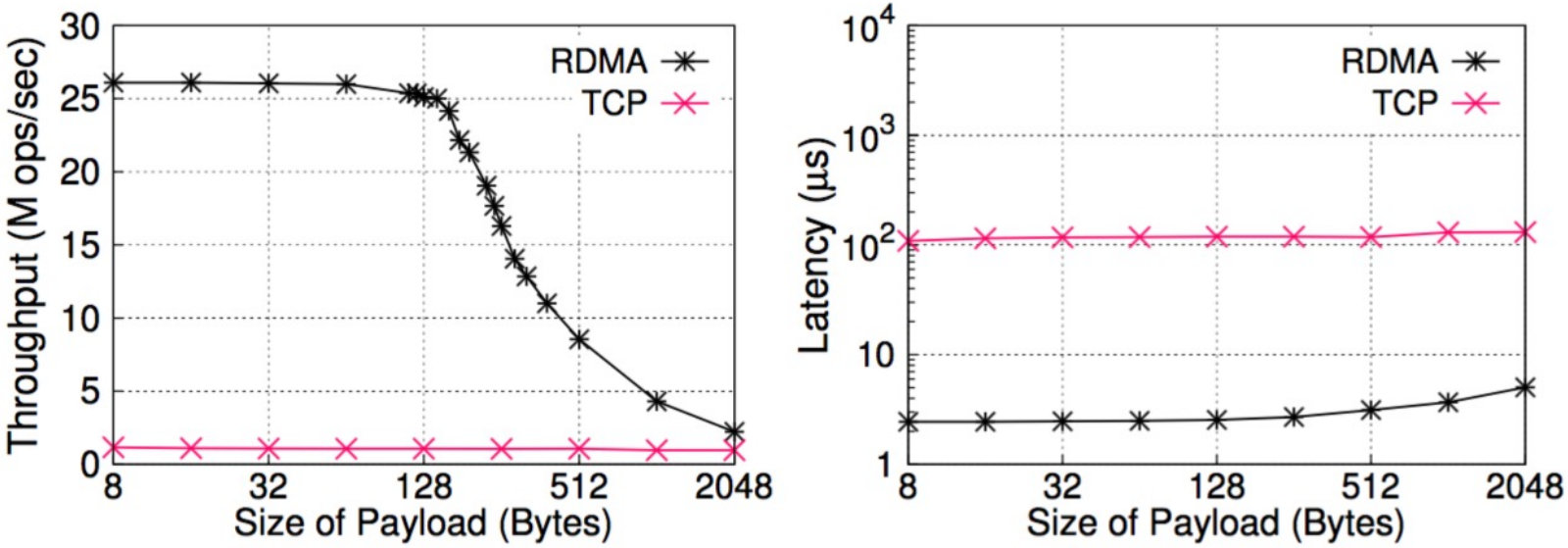
For example: life-cycle of an RDMA WRITE




Credit: Anuj Kalia's SIGCOMM talk

# RDMA READ Performance

## Performance of Random Read*




Insensitive to payload size: high/near constant throughput and low latency when payload is smaller than a threshold

* Mellanox ConnectX-3 MCX353A 56Gbps InfiniBand NIC

# This Course

101 of New Hardware Features


Distributed Transaction Protocol


In-memory Key-Value Store


High Availability with Replication

# Opportunity of **HTM** and **RDMA**

**HTM**: Hardware Transaction Memory

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

**Strong Atomicity**

**RDMA**: Remote Direct Memory Access

# Opportunity of **HTM** and **RDMA**

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

**Strong Atomicity**

**RDMA**: Remote Direct Memory Access

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

**Strong Consistency**

# Opportunity of **HTM** and **RDMA**

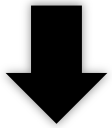
**HTM**: Hardware Transaction Memory

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

**RDMA**: Remote Direct Memory Access

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

**RDMA** ops will abort conflicting **HTM** TX



Basis for **Distributed HTM**

# Challenge#1: Restriction of HTM

**HTM** is only a compelling hardware feature for single machine platform

- Distributed TXs cannot directly benefit from it

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

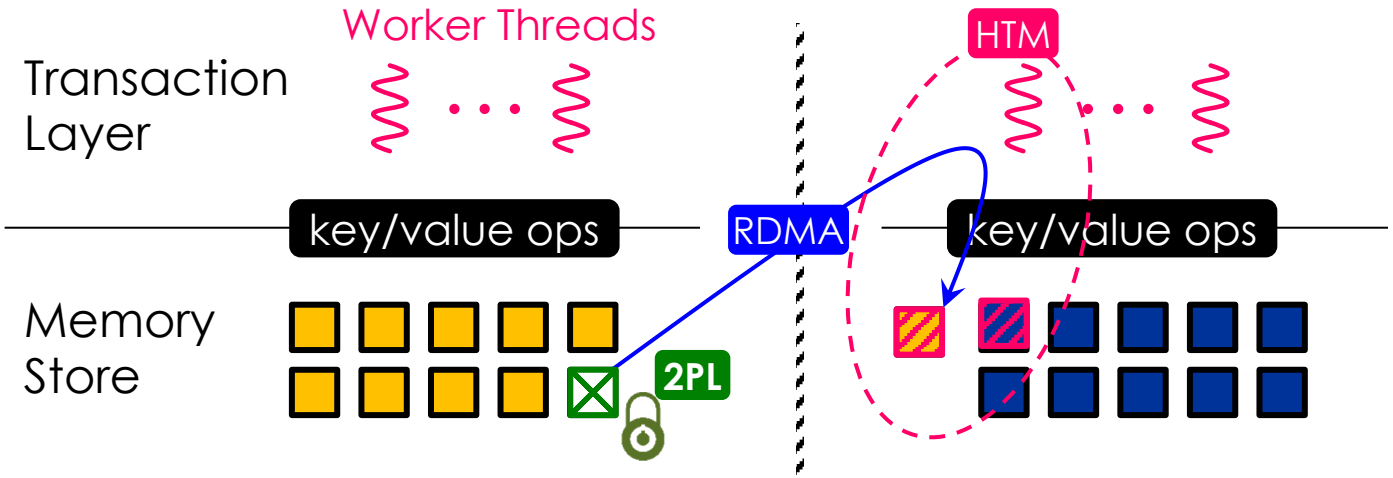
- Like any **RDMA** ops: READ/WRITE, CAS, . . .

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*




* similar to prior work (e.g. Sinfonia & Calvin) and the case for typical OLTP workloads

# Concurrency Control Protocol

Local TX vs. Local TX: **HTM**

Distributed TX vs. Distributed TX: 2PL

Local TX vs. Distributed TX: abort local TX

# Concurrency Control Protocol

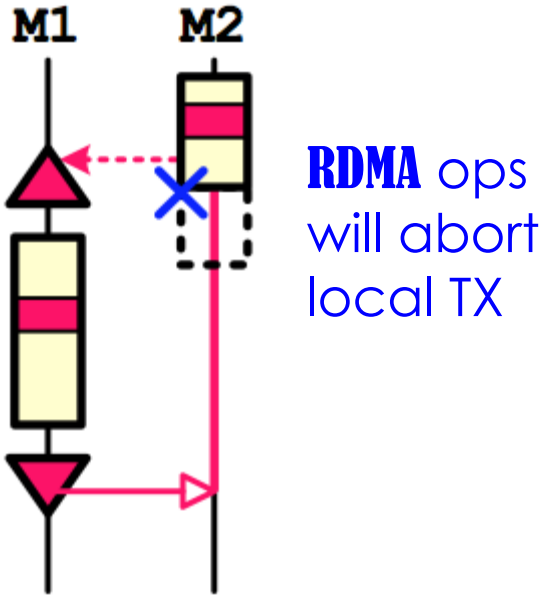
Local TX vs. Local TX: **HTM**

Distributed TX vs. Distributed TX: 2PL

Local TX vs. Distributed TX: abort local TX

**Local TX prior to Dist. TX**

→ **RDMA** ops abort local **HTM** tx



# Concurrency Control Protocol

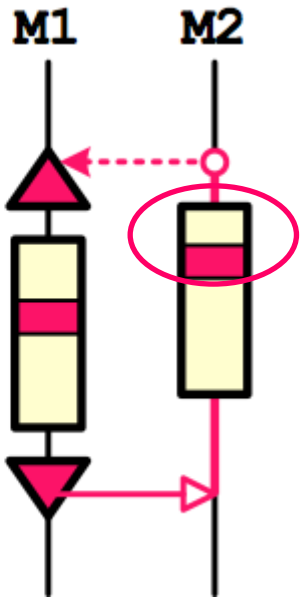
Local TX vs. Local TX: **HTM**

Distributed TX vs. Distributed TX: 2PL

Local TX vs. Distributed TX: abort local TX

**Dist. TX prior to local TX**

→ Local **HTM** TX checks (not locks) records




Local accesses need check the state of 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?

# RDMA-based Lock

RDMA CAS: atomic compare-and-swap

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

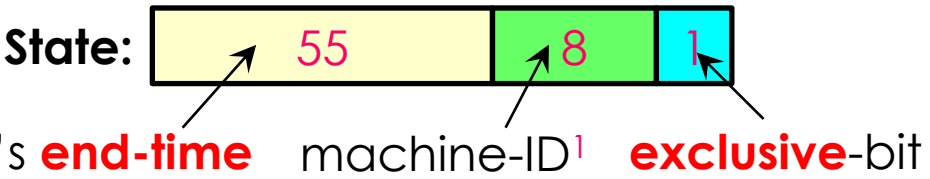
1. exclusive lock
   - ► Spinlock: use RDMA CAS to acquire & release
2. shared lock
   - ► Lease-based protocol

# 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

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

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

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

State is atomically compare and swap using RDMA CAS

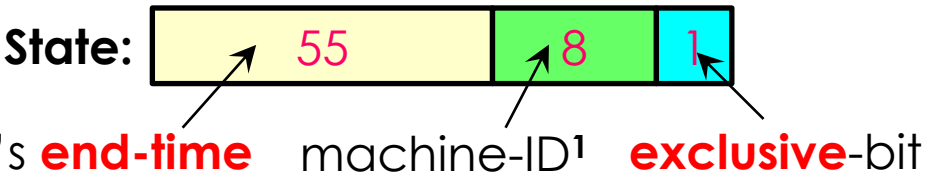
[1] Machine ID is only used by recovery

# 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

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

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

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

**EXPIRED: if now > end-time + DELTA**

**INVALID: if now < end-time - DELTA**

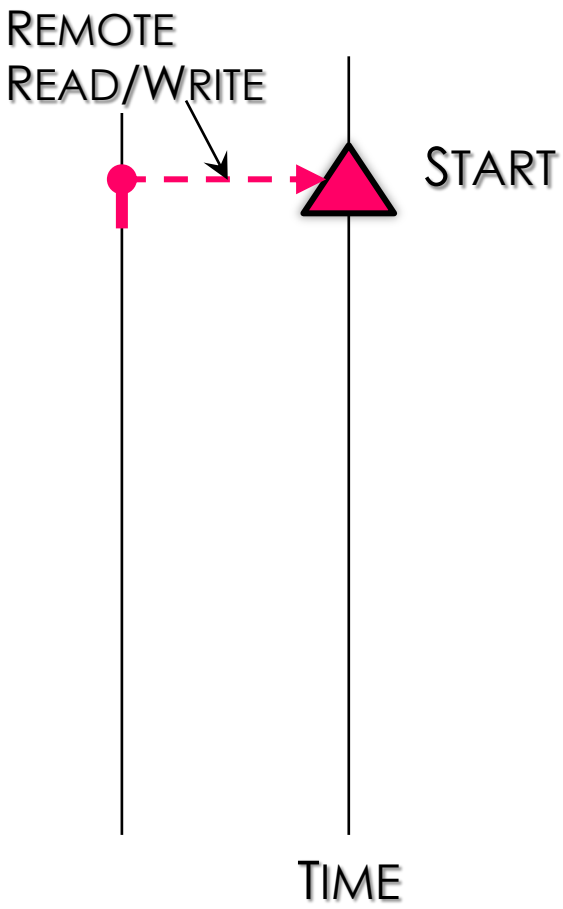
DELTA is used to tolerate the time bias among machines

[1] Machine ID is only used by recovery

[2] PTP: precision time protocol, http://sourceforge.net/p/ptpd/wiki/Home/

# Transaction Execution Flow

## Transaction Protocol: **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()
```

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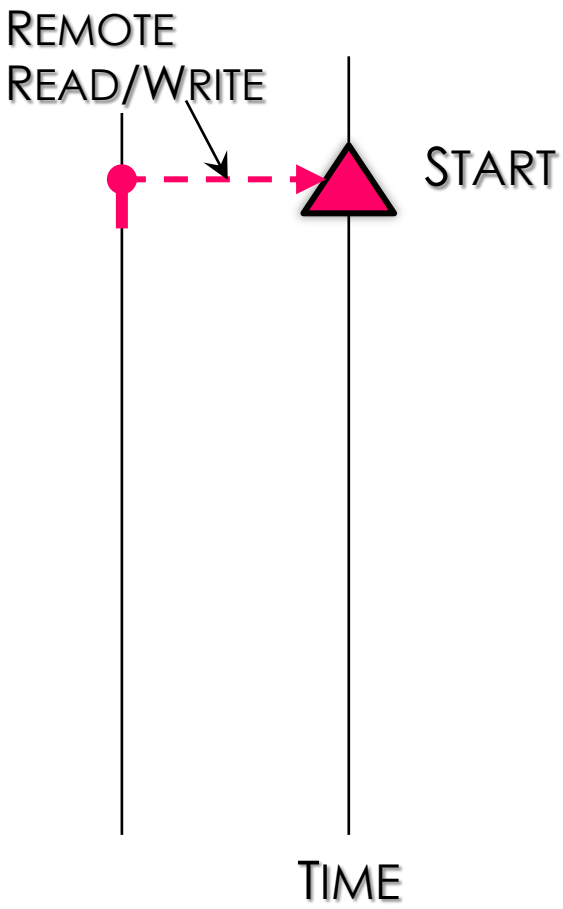


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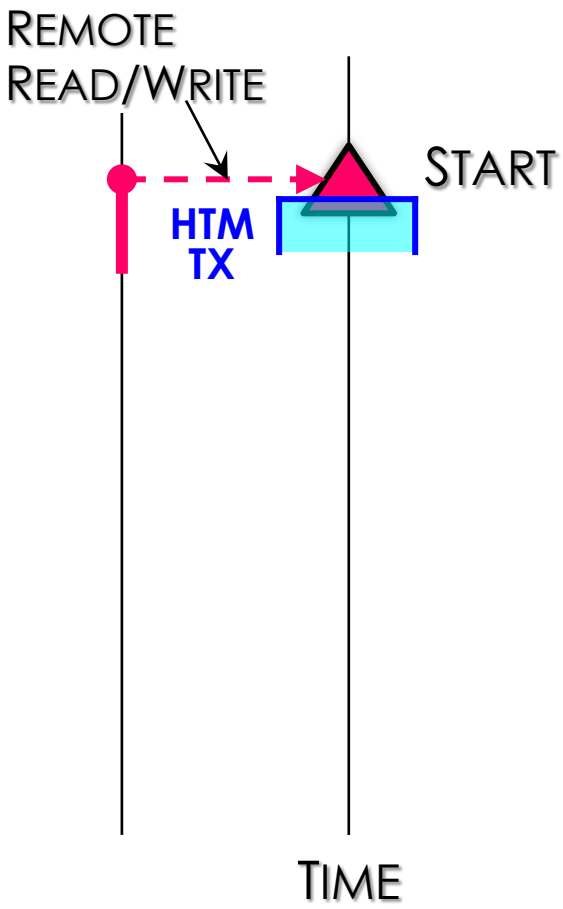


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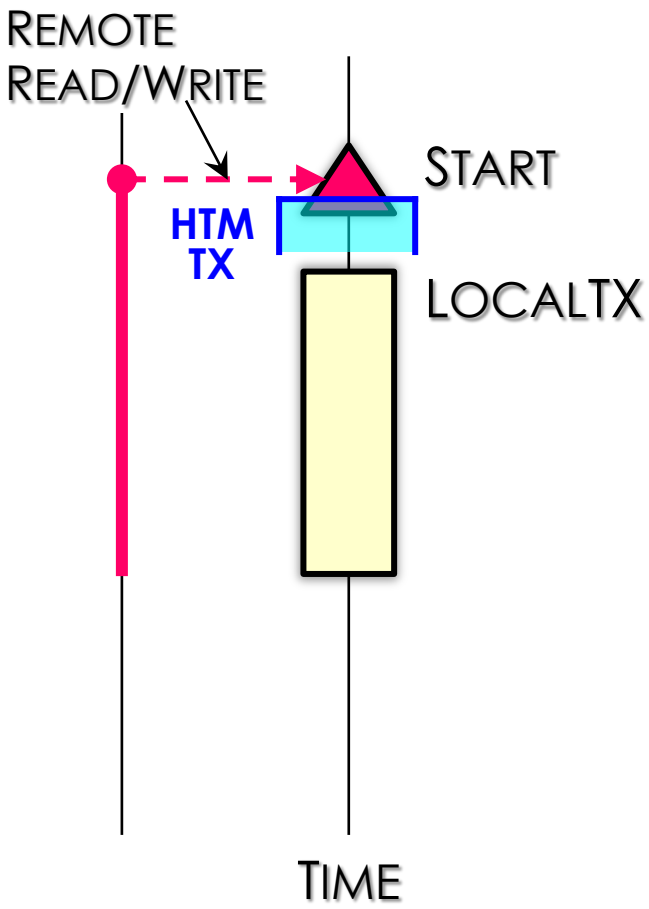
# Transactional Read & Write

## Transaction Protocol: START + LOCALTX + COMMIT

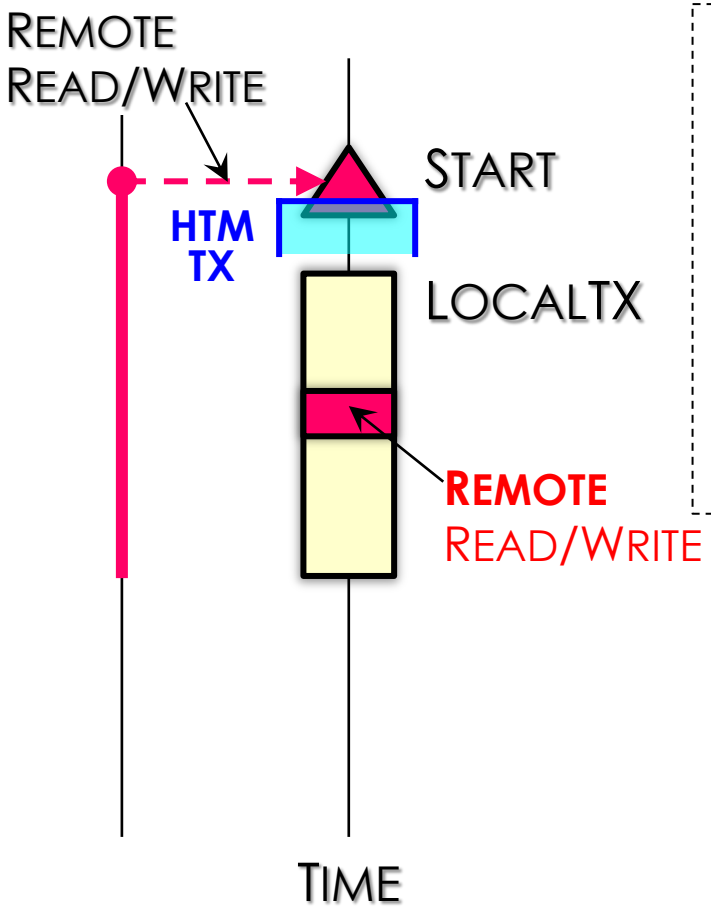



```
READ(key)
  if key.is_remote() == true
    return cache[key]
  else return LOCAL_READ(key)

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

# Transactional Read & Write

## Transaction Protocol: **START** + **LOCALTX** + **COMMIT**

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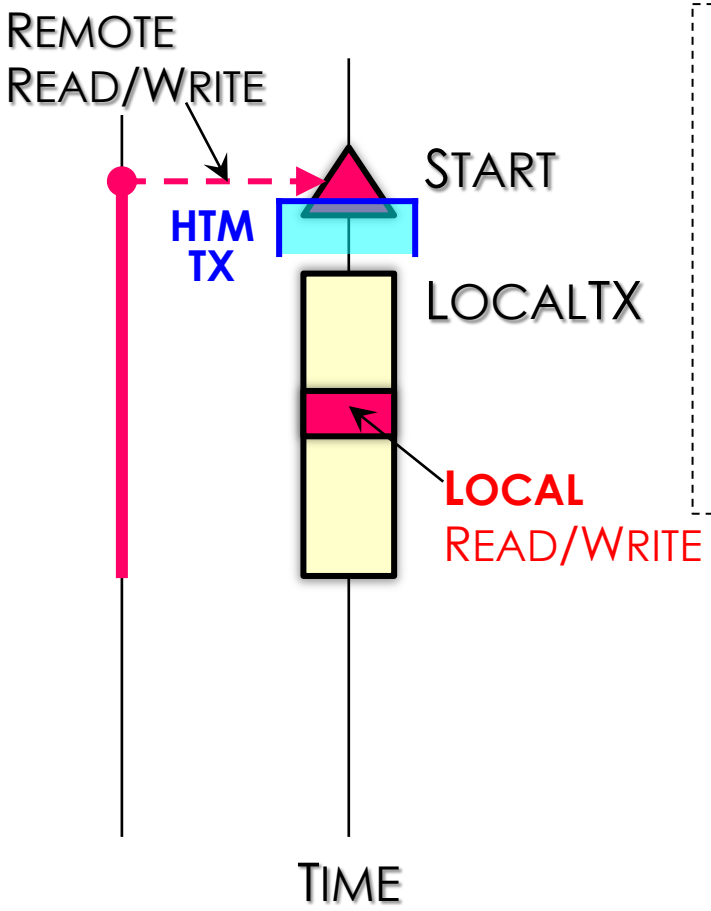


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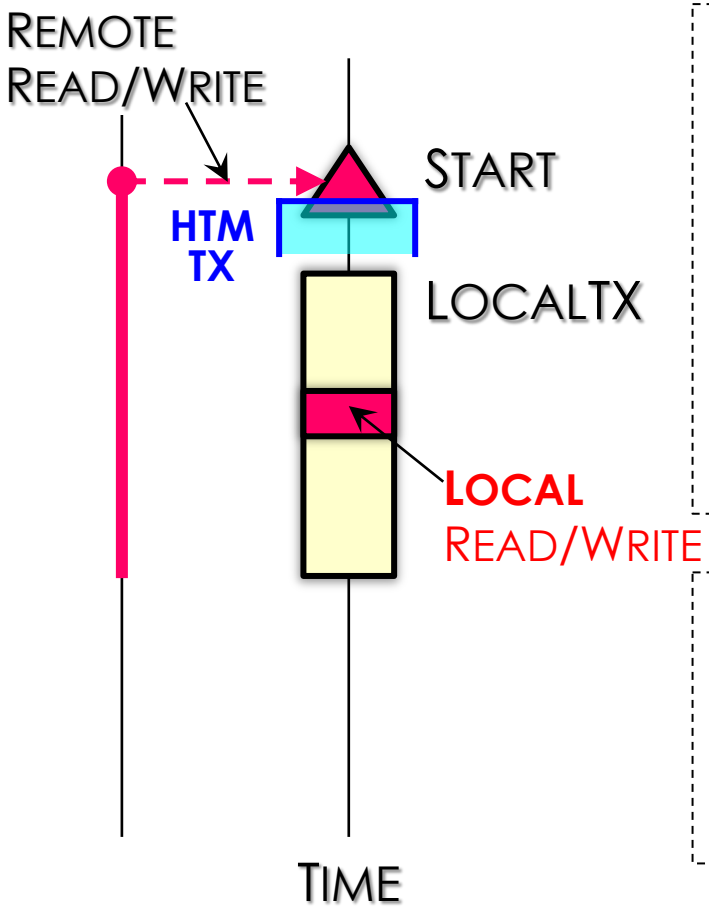


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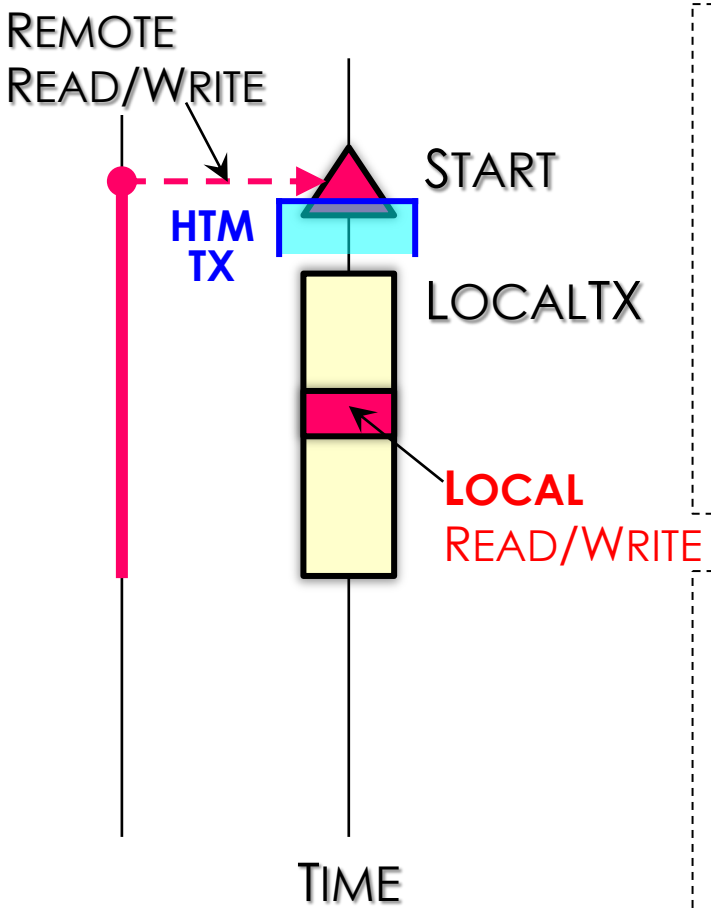
  else LOCAL_WRITE(key, value)
```

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

# Transactional Read & Write

## Transaction Protocol: START + LOCALTX + COMMIT

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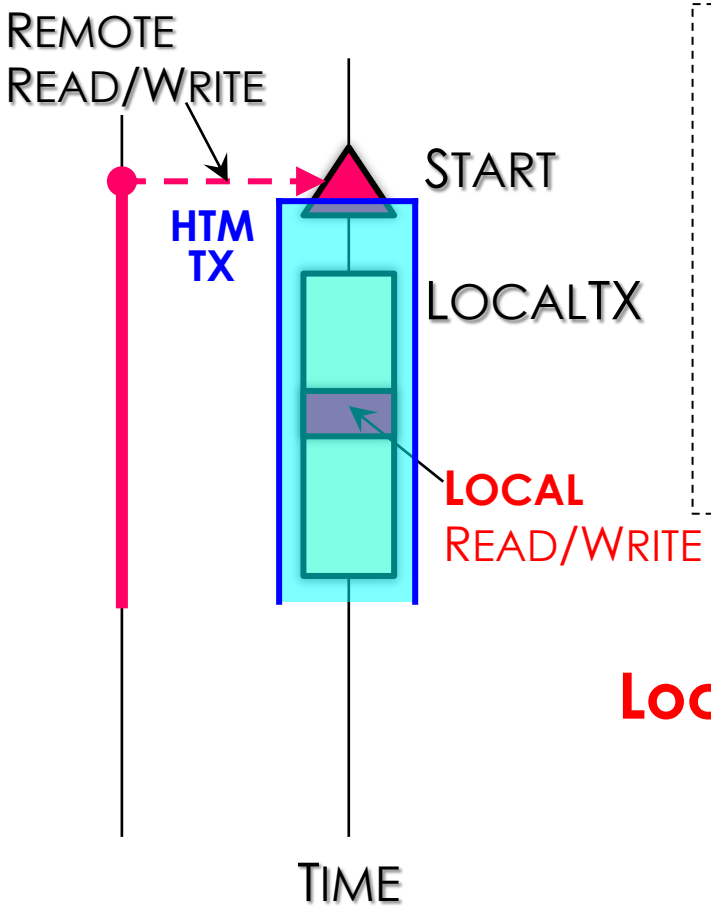
WRITE(key, value)
  if key.is_remote() == true
    cache[key] = value
  else LOCAL_WRITE(key, value)
```

```
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

## Transaction Protocol: START + LOCALTX + COMMIT



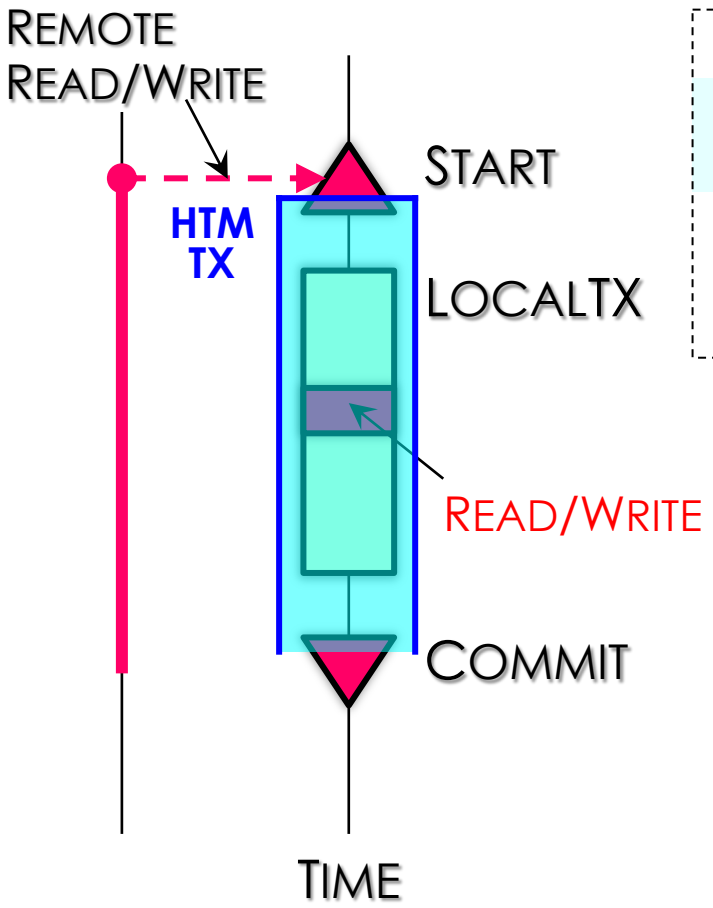

```
READ(key)
  if key.is_remote() == true
    return cache[key]
  else return LOCAL_READ(key)

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

**Local conflicts** are detected by **HTM**

# Transaction Execution Flow

## Transaction Protocol: START + LOCALTX + COMMIT



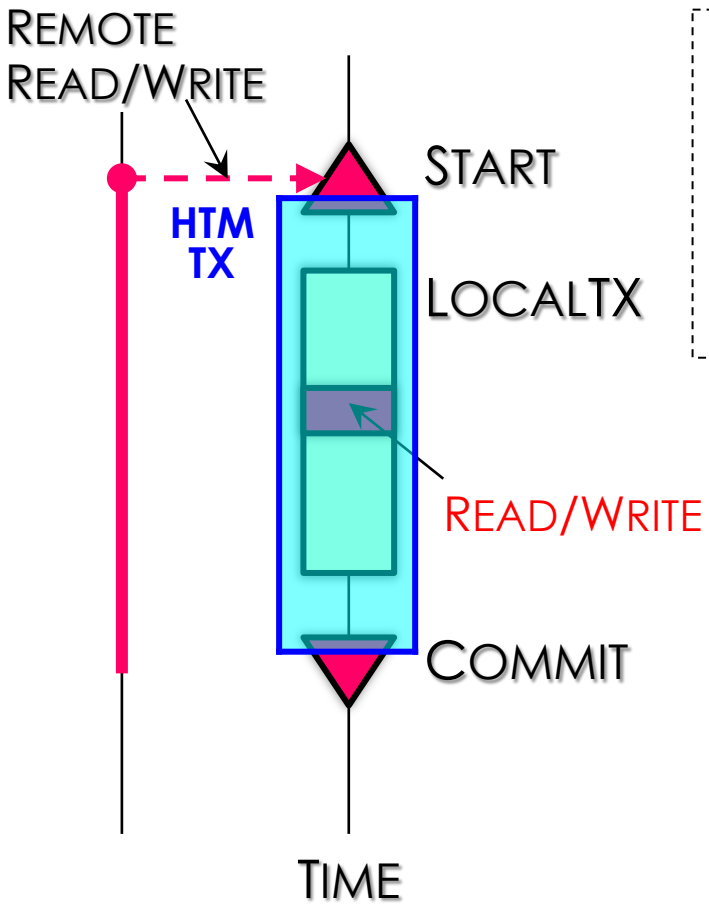

```
COMMIT(remote_writeset,remote_readset)
  if !VALID(end_time)
    ABORT()
  XEND()
  foreach key in remote_writeset
    RELEASE_WRITE_BACK(key,cache[key])
```

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

- Insert validation to all leases just before **HTM** commit

# Transaction Execution Flow

## Transaction Protocol: **START** + **LOCALTX** + **COMMIT**

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

# Transaction Execution Flow

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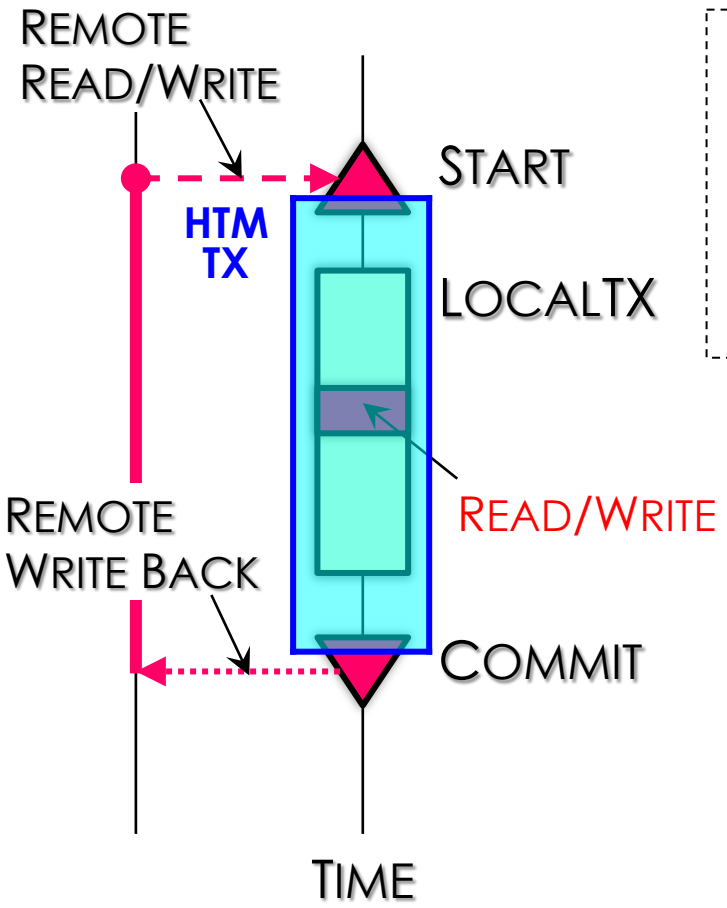


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  if !VALID(end_time)
    ABORT()
  XEND()
  foreach key in remote_writeset
    RELEASE_WRITE_BACK(key,cache[key])
```

**2PL & HTM → Serializability**

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

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

# Read-only Transaction

Read-only TX usually has a very large read set

- Likely abort an HTM transaction due to capacity

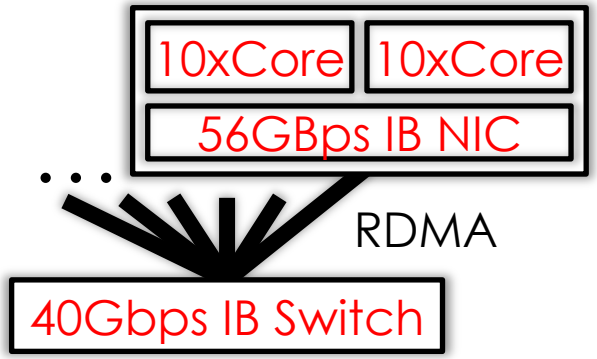
Two-round schema (read & confirm)

- Similar to ROCOCO @OSDI'14
- Using lease & uniform end-time to avoid twice read

```
START_RO(readset)
L:end_time = now + duration
  foreach key in readset
    end_time = MIN(end_time, Set_lease(key, end_time))
  if !VALID(end_time) goto L //round2: confirm

READ_RO(key)
  return read_cache[key]
```

# 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]

**Benchmarks**[2]

- TPC-C
- SmallBank

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

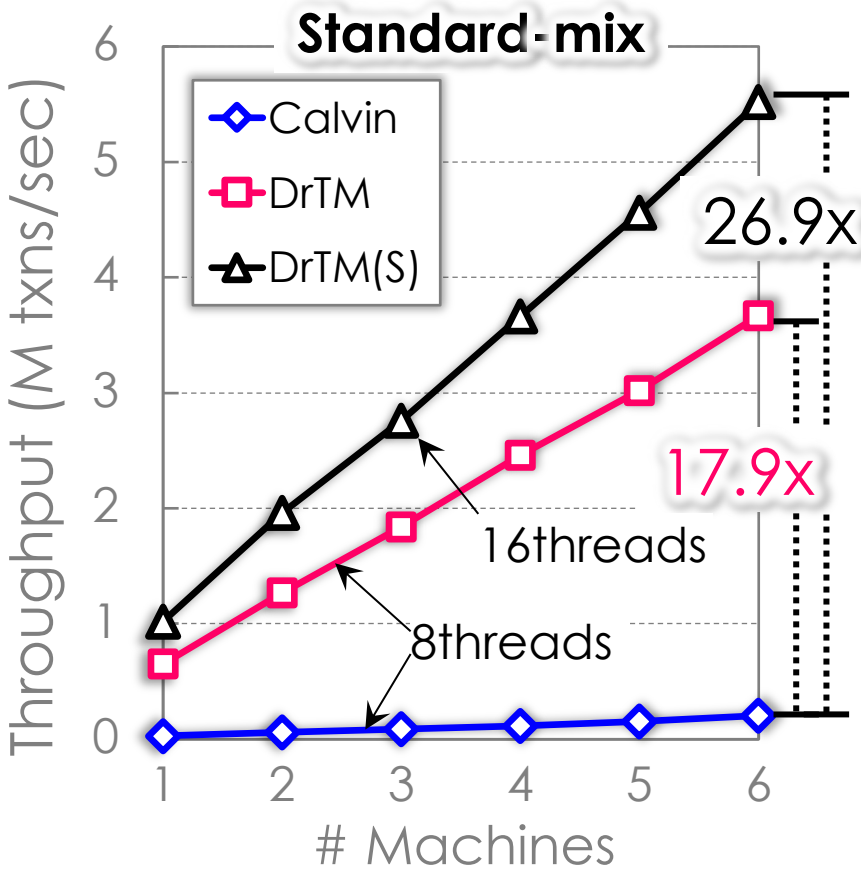
| SmallBank | SP | AMG | BAL | DC | WC | TS |
|---|---|---|---|---|---|---|
| Ratio | 25% | 15% | 15% | 15% | 15% | 15% |
| Type | d+rw | d+rw | l+ro | l+rw | l+rw | l+rw |

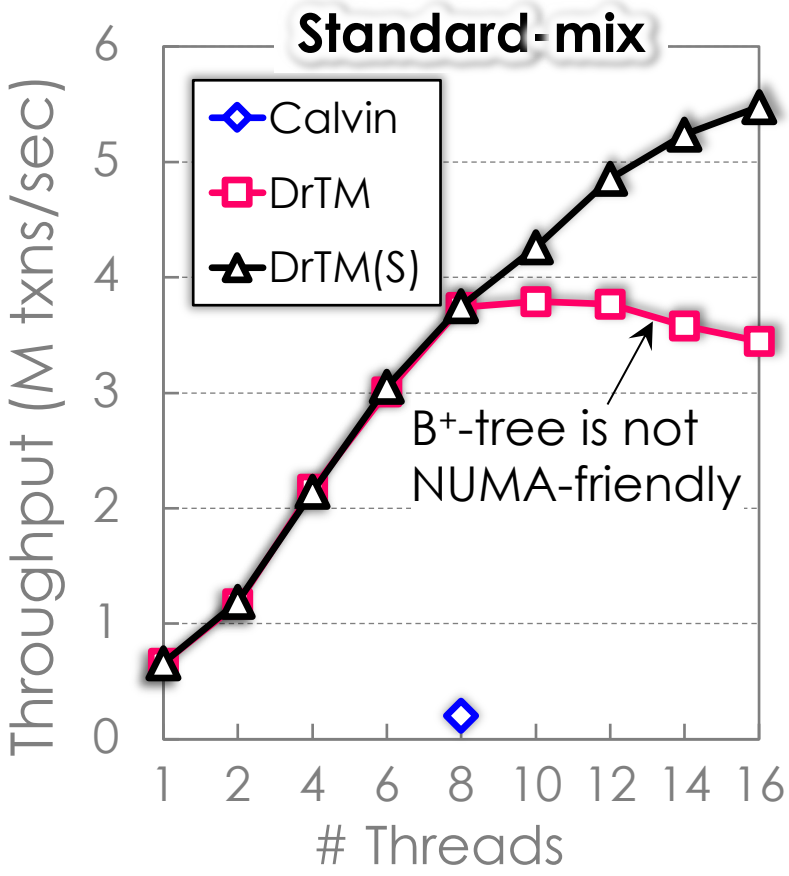
[1] All machines run Ubuntu 14.04 with Mellanox OFED v3.0-2.0.1 stack.
[2] **d** and **l** stand for distributed and local. **rw** and **ro** stand for read-write and read-only.

# Performance on TPC-C

New-order TX
≈ Standard-mix x45%

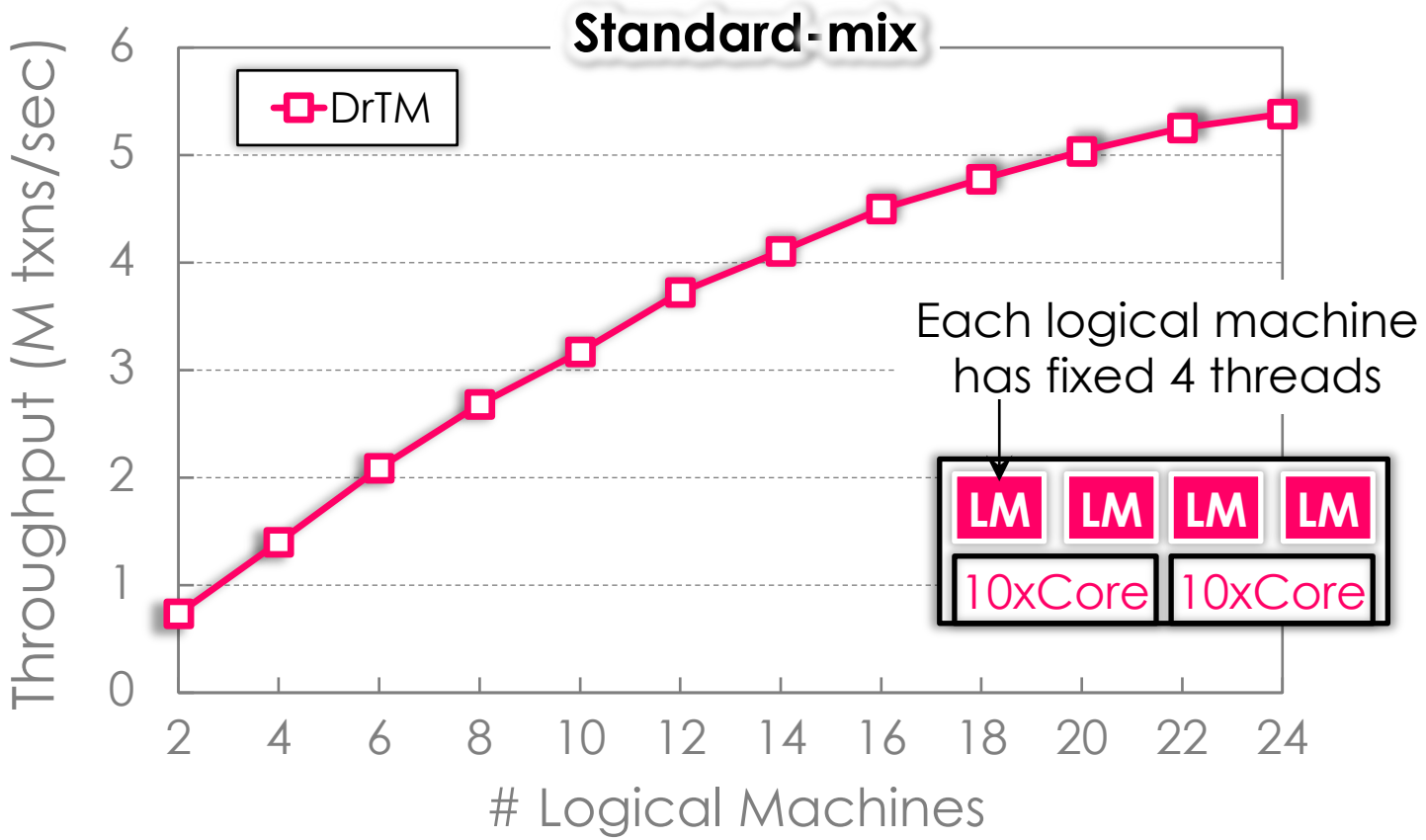
**DrTM(S)**: run a separate logical node on each socket



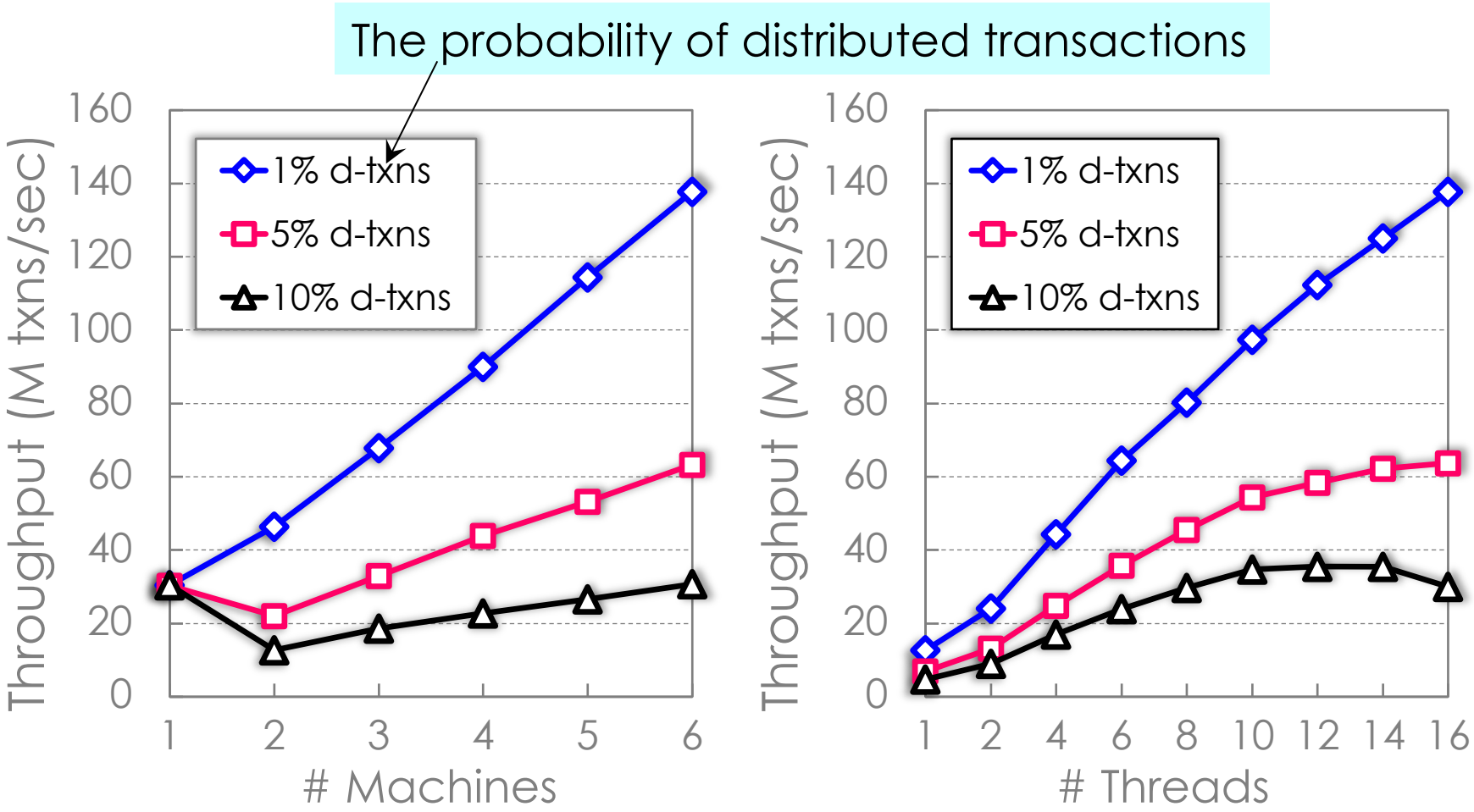
# Scalability on TPC-C

New-order TX
≈ Standard-mix x45%




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

# Performance on SmallBank



# Extended Reading

Transaction chopping: reduce **HTM** working set

Fine-grained RTM's fallback handler

Atomicity Issues: **RDMA** CAS vs. Local CAS

Horizontal scaling across socket: logical node

**Reference**


1. *Fast In-memory Transaction Processing using RDMA and HTM*. SOSP 2015
2. *Fast In-memory Transaction Processing using RDMA and HTM*. ACM TOCS.

# This Course

101 of New Hardware Features


Distributed Transaction Protocol


In-memory Key-Value Store


High Availability with Replication

# Memory Store

Separating ordered and unordered store

- Ordered store: B+ tree from DBX @EuroSys'14

  No inevitable remote accesses to ordered stores in our OLTP workloads (i.e. TPC-C & SmallBank)

- Unordered store: **RDMA/HTM**-based hash table

Architecture

- Symmetric: each node is both a server and a client
- Most memory accesses are local with **HTM**

# Existing Approach

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

- Complicated INSERT: hard to leverage **HTM**
- Only leverage one-sided **RDMA** to read
- No **RDMA**-based 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

# General Design

- ✓ Simple hash structure to fully leverage **HTM**
- ✓ Decouple race detection from memory store
  - Rely on transaction layer (**HTM** & Locking)
  - Use one-sided **RDMA** ops for remote read & write
- ✓ Location-based and fully transparent cache

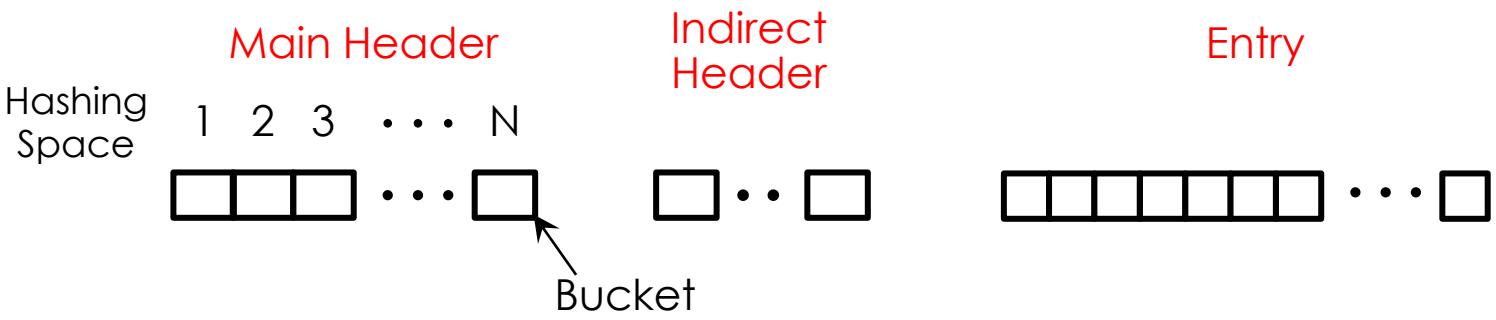
| | Pilaf | FaRM | DrTM |
|---|---|---|---|
| **Hashing** | Cuckoo | Hopscotch | Chaining |
| **Race Detection** | Checksum | Versioning | L:HTM / D: Lock |
| **Remote Read** | One-sided RDMA | | One-sided RMDA |
| **Remote Write** | Messaging | | |
| **Caching** | No | | Yes |

Simple

Efficient

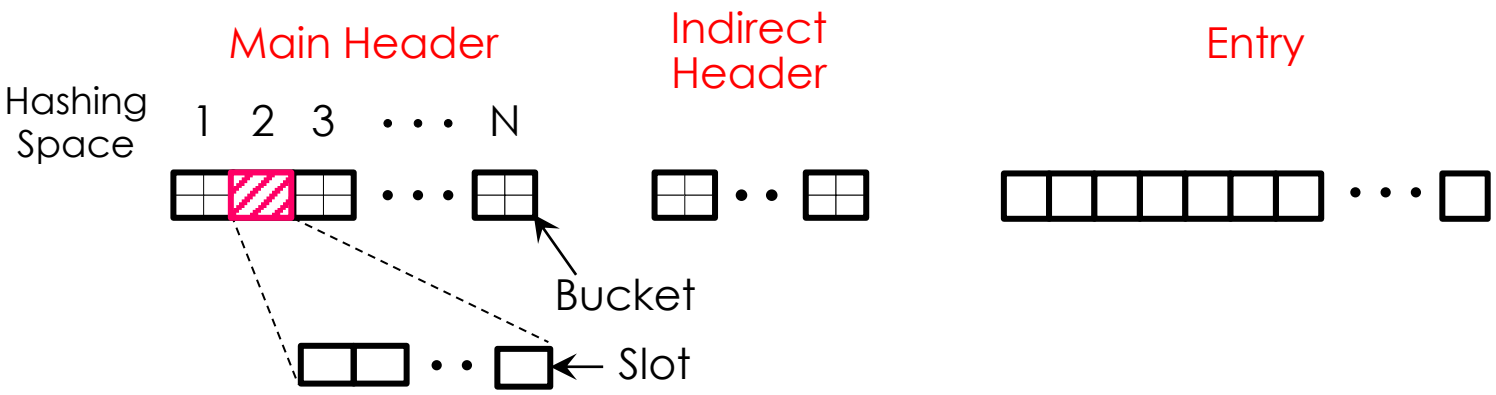
# Cluster Chaining

- ✓ Decoupled memory region: index & data



# Cluster Chaining

- ✓ Decoupled memory region: index & data
- ✓ Similar to traditional chaining HT with associativity



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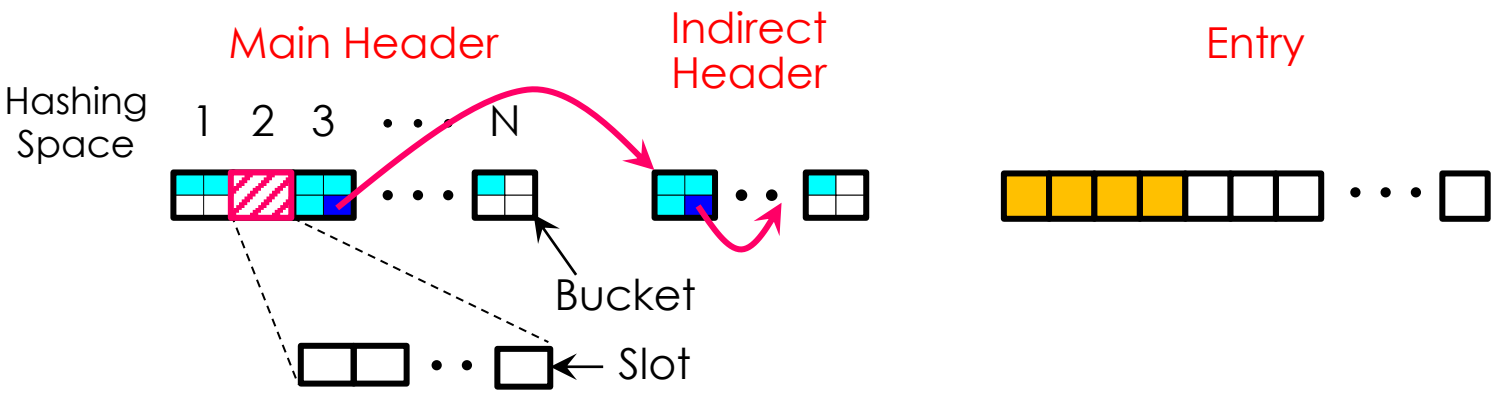
- ✓ Decoupled memory region: index & data
- ✓ Similar to traditional chaining HT with associativity
- ✓ Shared indirect headers: high space efficiency



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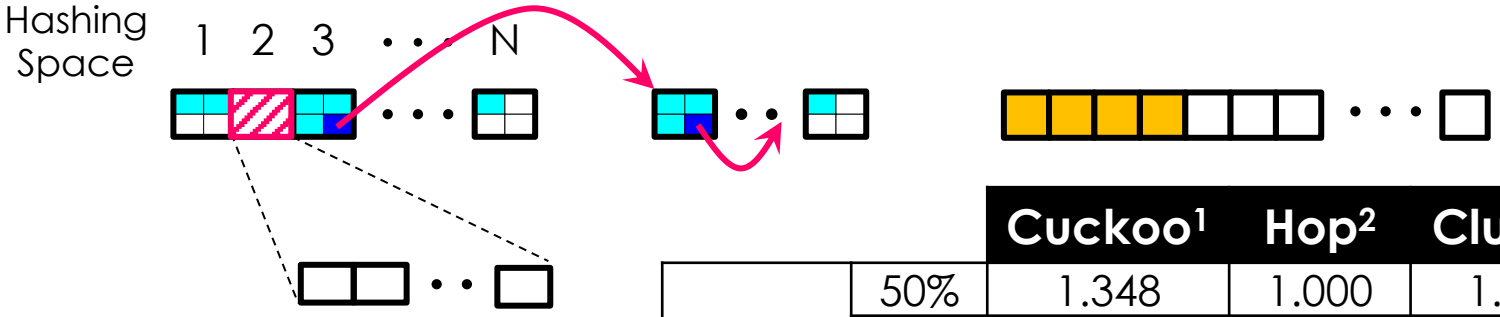


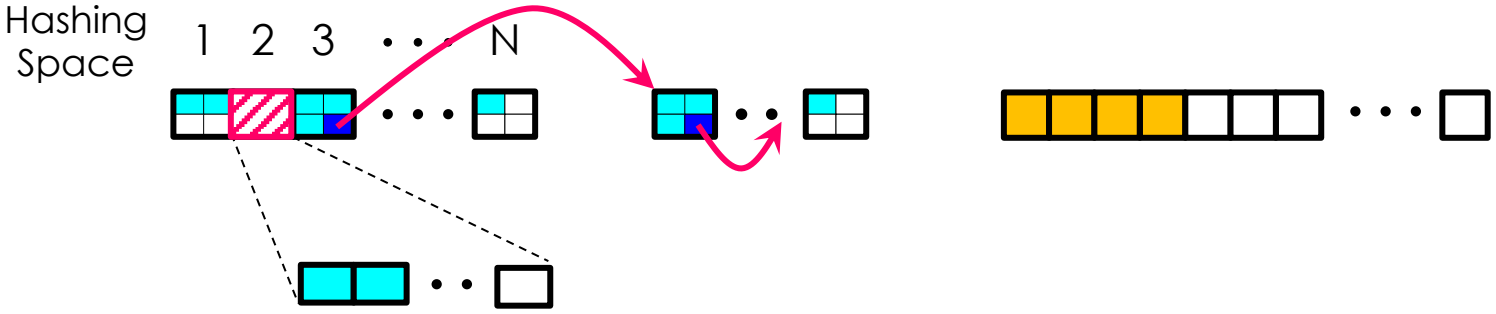

The average number of RDMA READs for lookups at different occupancies

| | | 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 |

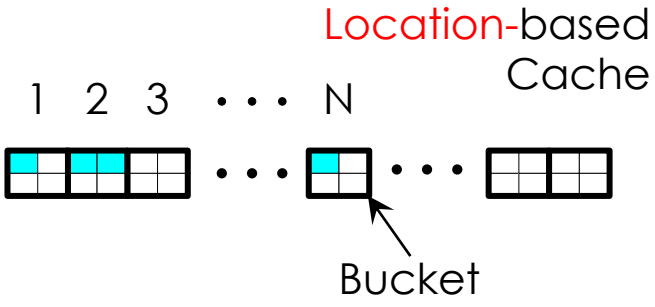
[1] Hopscotch hashing in FaRM configures the neighborhood with 8 (H=8).
[2] Cuckoo hashing in Pilaf uses 3 orthogonal hash functions and each bucket contains 1 slot.
[3] Cluster hashing in DrTM configures the associativity with 8.

# Location-based Caching

✓ **RDMA**-based: focus on minimizing the lookup cost

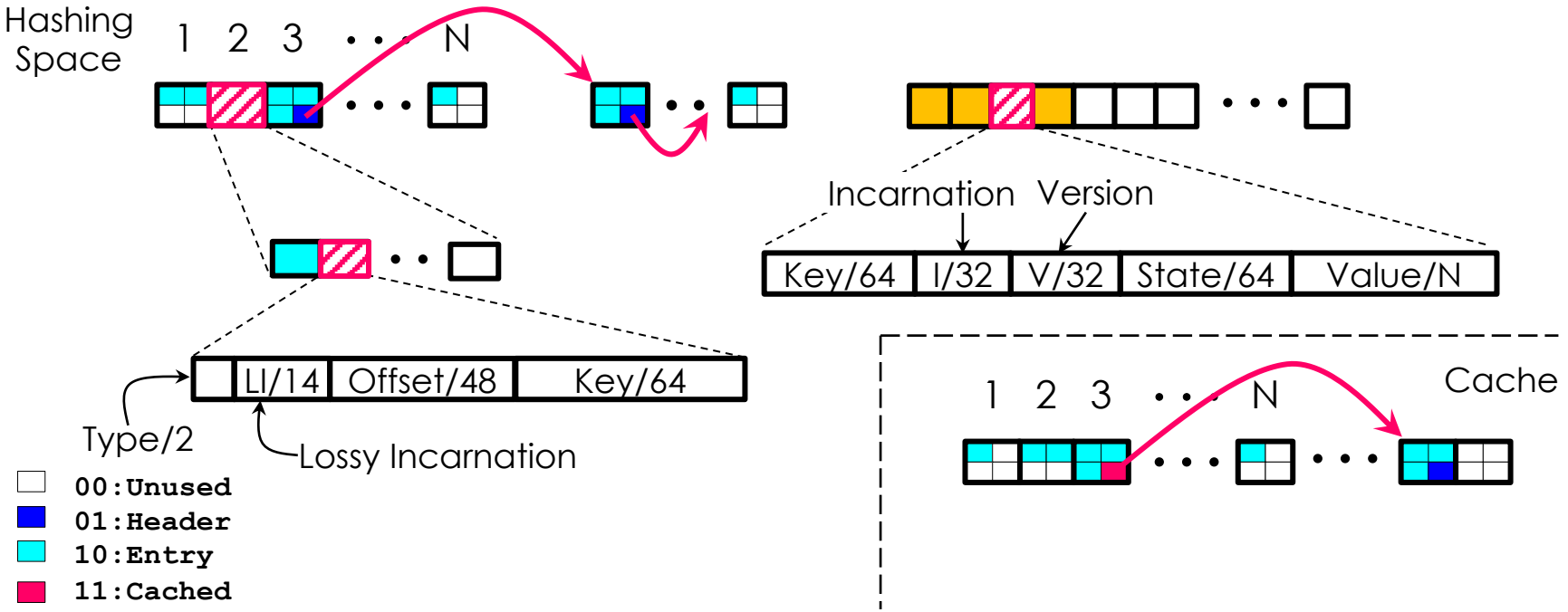



*Treat cache as a partially stale* snapshot of headers



# Location-based Caching

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



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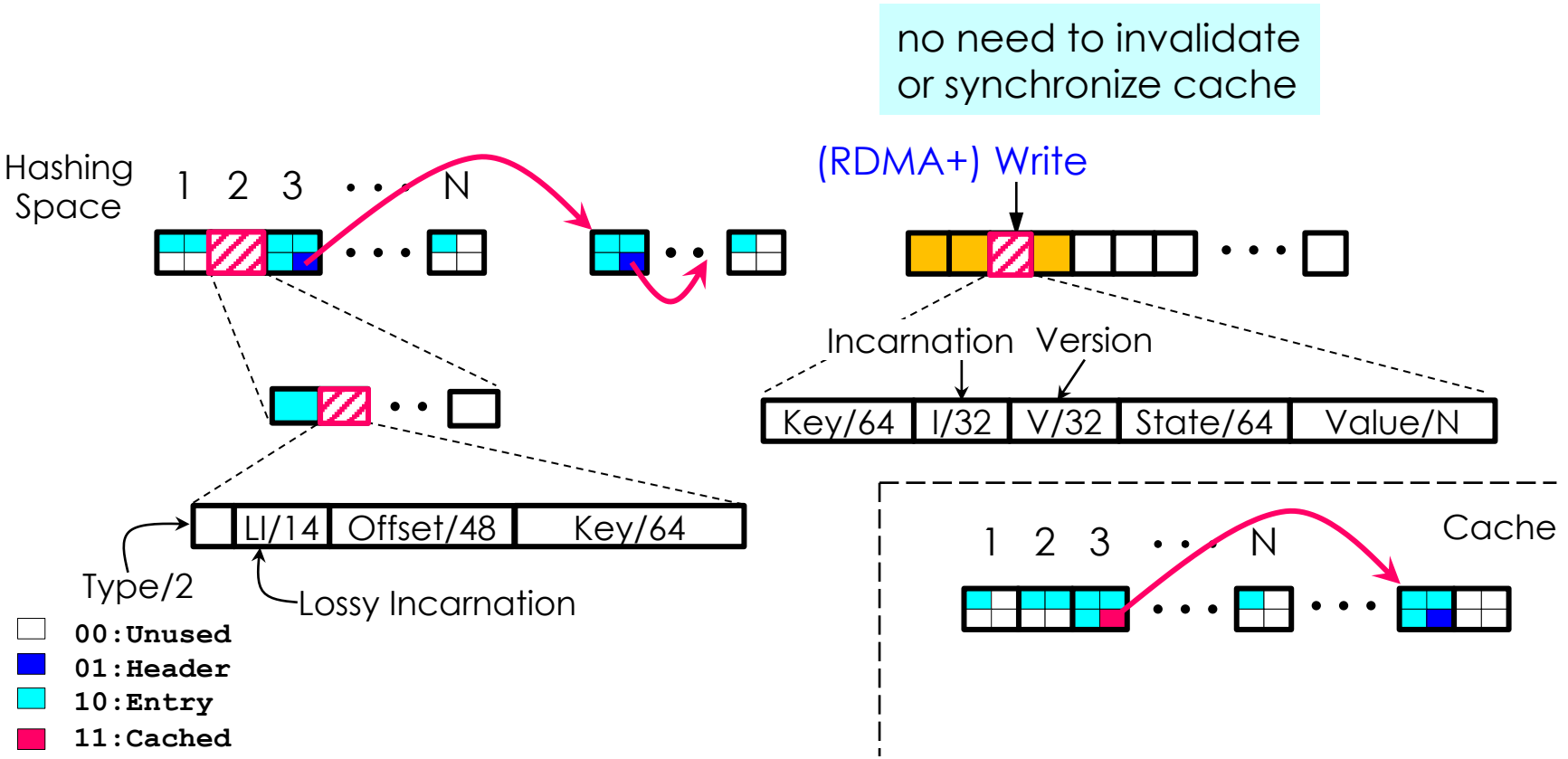

# Location-based Caching

- ✓ **RDMA**-based: focus on minimizing the lookup cost
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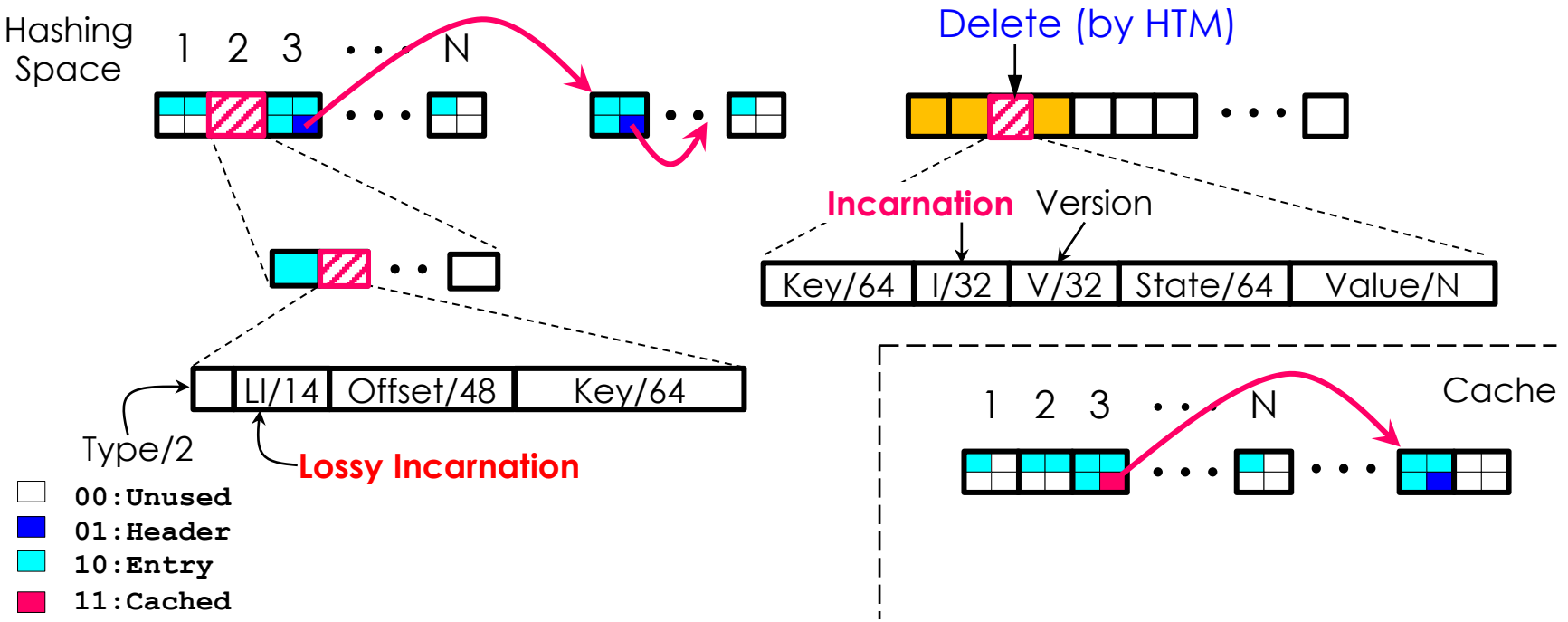
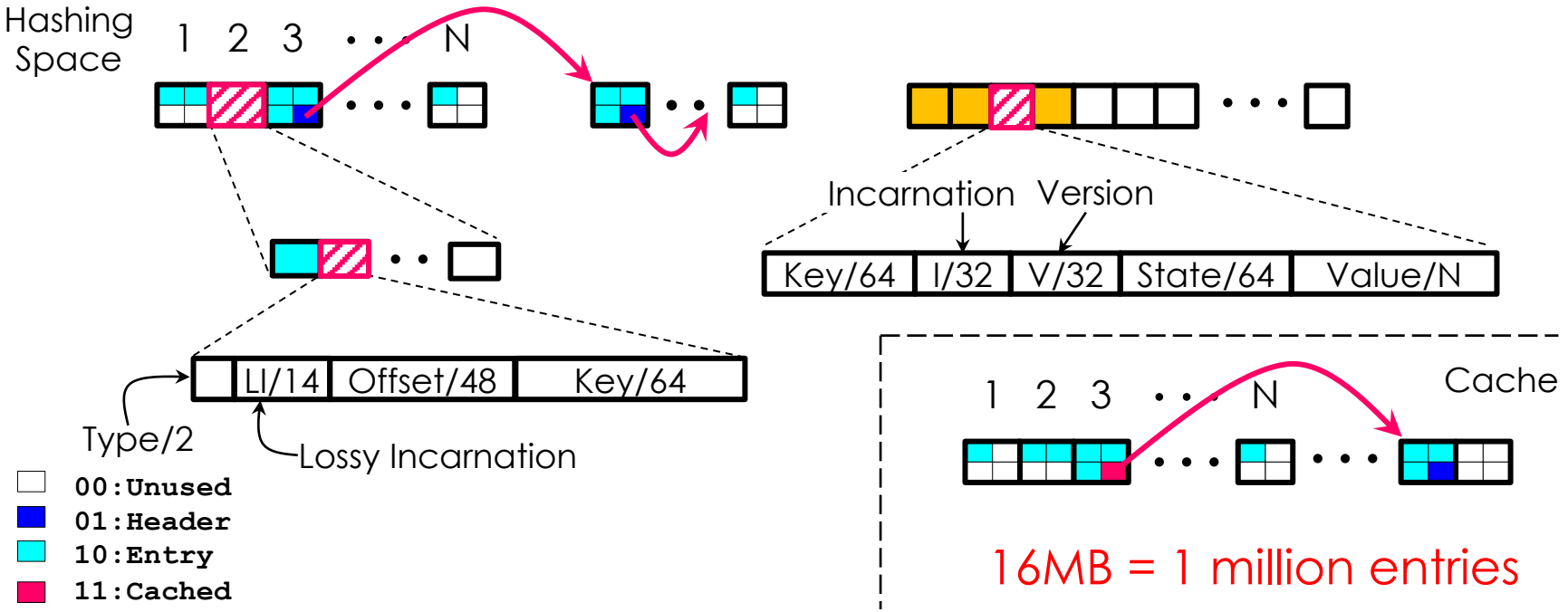
detect stale read by incarnation, treat it as a cache miss and refill



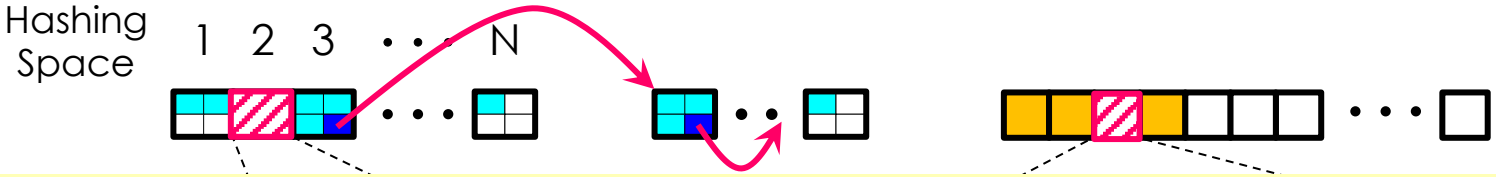
# Location-based Caching

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



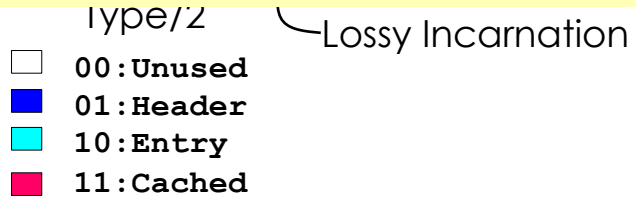
# Location-based Caching

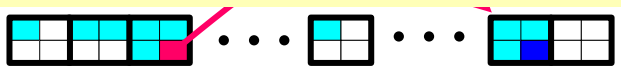
- ✓ **RDMA**-based: focus on minimizing the lookup cost
- ✓ Retain the full transparency to the host
- ✓ The size of cache for location is small
- ✓ All client threads can directly share the cache




The average lookup cost = **0.178**

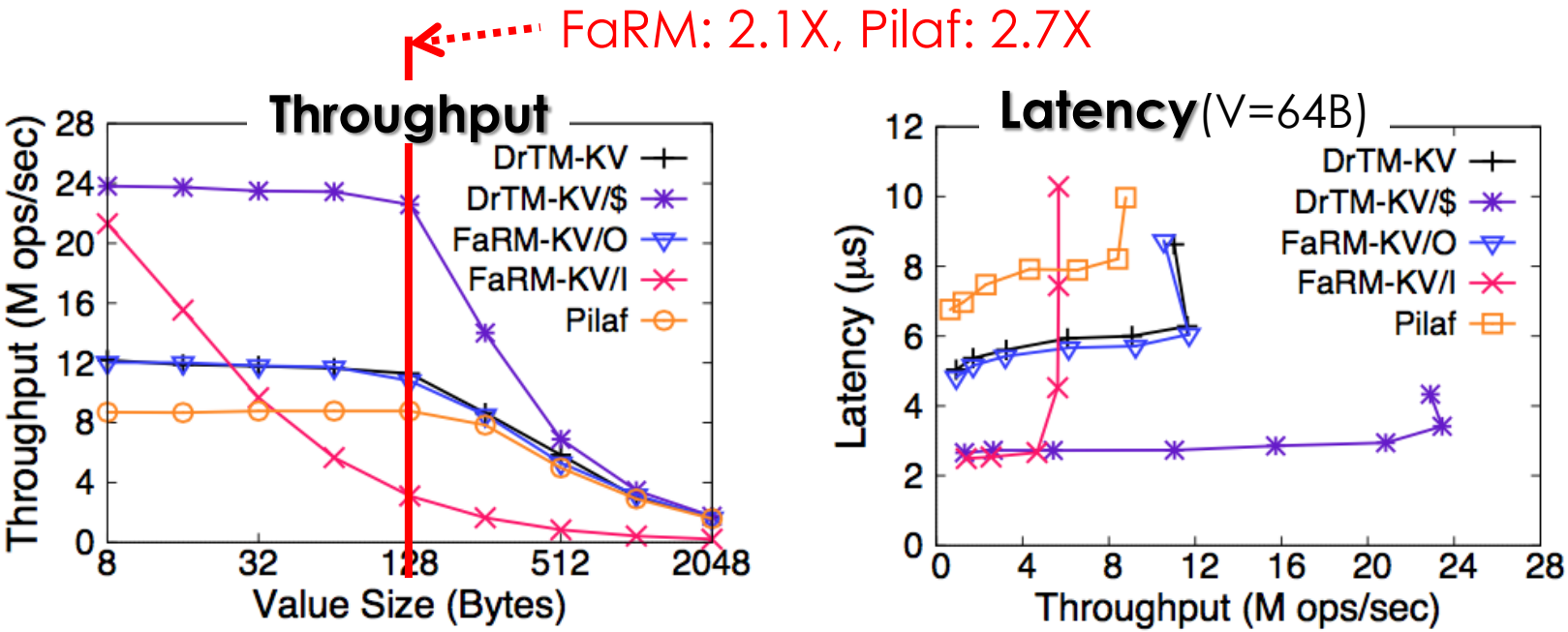
20 million kv-pairs (>40 GB), 20MB cache (from empty),
8 client threads, skewed workload (Zipf θ=0.99)



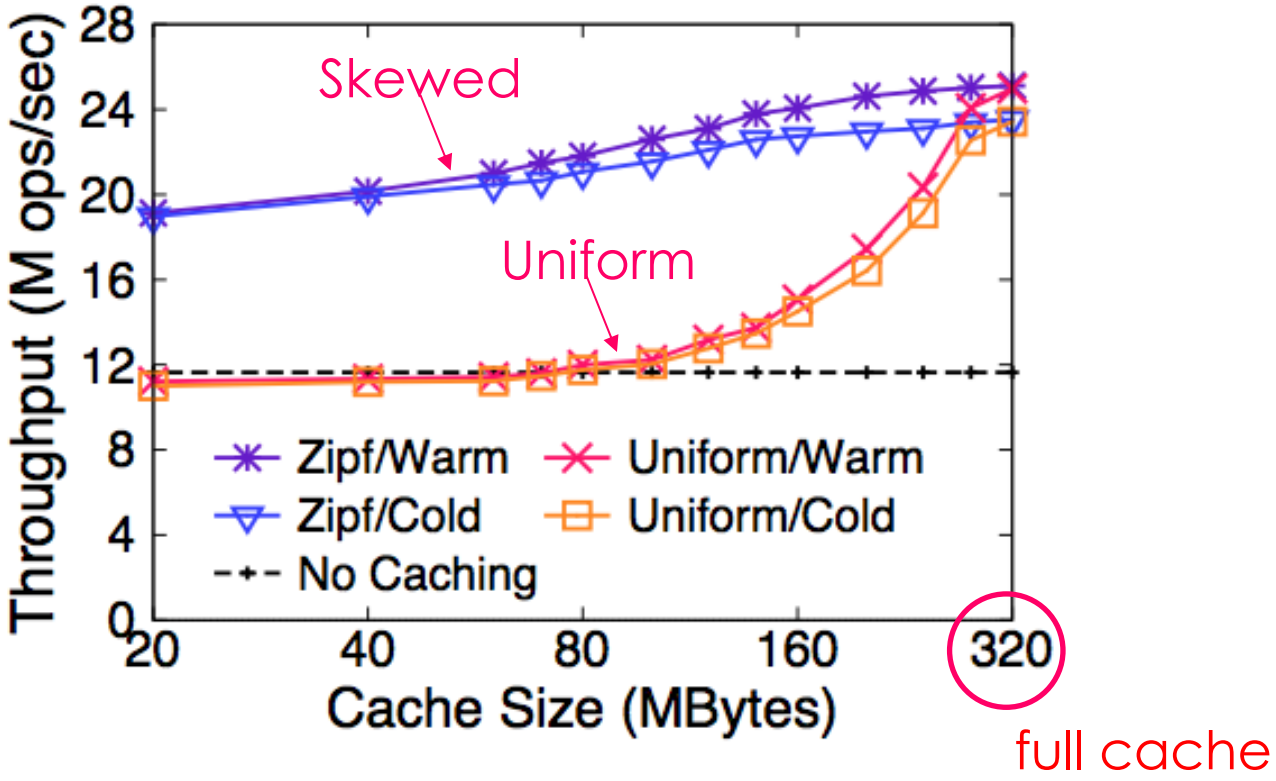
# Read Performance

- ✓ DrTM-KV w/o caching provides a comparable perf.
- ✓ DrTM-KV w/ caching (DrTM-KV/$) can achieve both lowest latency (3.4 µs) and highest thpt (23.4 Mops/s)




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

# Location-based Cache




**Setting**: 1 server and 5 clients (up to 8 threads), 20 million k/v pairs
Traditional replacement policy (i.e., LRU)

# Extended Reading

**RDMA**-based KV store for range query

**RDMA**-based index caching for B$^+$Tree

Supporting variable-length key

Scale-out ordered store and durability


**Reference**

1. *FaRM: fast remote memory.* NSDI 2014
2. *Fast In-memory Transaction Processing using RDMA and HTM*. SOSP 2015
3. *Balancing CPU and Network in the Cell Distributed B-Tree Store*. Usenix ATC 2016.
4. *Fast RDMA-based Ordered Key-Value Store using Remote Learned Cache.* OSDI 2020.

# Conclusion

NEW hardware features open NEW opportunities


: The first design and impl. of combining HTM, RDMA and NVM to boost in-memory transaction processing with imperative functionality

Achieving orders-of-magnitude higher throughput and lower latency than prior traditional designs

# Thanks

DrTM

Questions

Home: http://ipads.se.sjtu.edu.cn/drtm

GitHub: https://github.com/SJTU-IPADS

IPADS, SJTU

# Backup