KOÇ UNIVERSITY

Best Paper and Best Student Paper Nominee at SC19

ComDetective: A Lightweight Tool for Detecting Inter-Thread Communication

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parcorelab.com

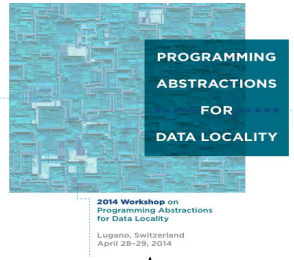
About me?

BİLİM AKADEMİSİ

MARIE CURIE ACTIONS

TEDx Istanbul
x = independently organized TED event

KOÇ UNIVERSITY
PARALLEL AND MULTICORE COMPUTING LABORATORY



Abstract Machine Models and Proxy Architectures for Exascale Computing

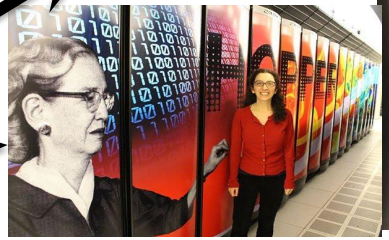
Rev 1.1

J.A. Ang[1], R.F. Barrett[1], R.E. Benner[1], D. Burke[2], C. Chan[2], D. Donofrio[2], S.D. Hammond[1], K.S. Hemmert[1], S.M. Kelly[1], H. Le[1], V.J. Leung[1], D.R. Resnick[1], A.F. Rodrigues[1], J. Shalf[2], D. Stark[1], D. Unat[2], N.J. Wright[2]

Sandia National Laboratories, NM[1]
Lawrence Berkeley National Laboratory, CA[2]

May, 16 2014

BERKELEY LAB
Lawrence Berkeley National Laboratory



Research Interests

- Address software challenges of emerging architectures
- Develop tools in collaboration with computational scientists
  - Programming models and runtime systems
    - Data locality is at the center
    - Focus on homogeneous and heterogeneous large-scale systems
    - Embrace asynchrony to scale on thousands of processors
  - Tools for performance monitoring and modeling
    - Design and develop tools for performance modeling and optimization on multicore and heterogeneous architectures

TiDA | Perilla | ExaSAT | TaskSanitizer | ComDetective

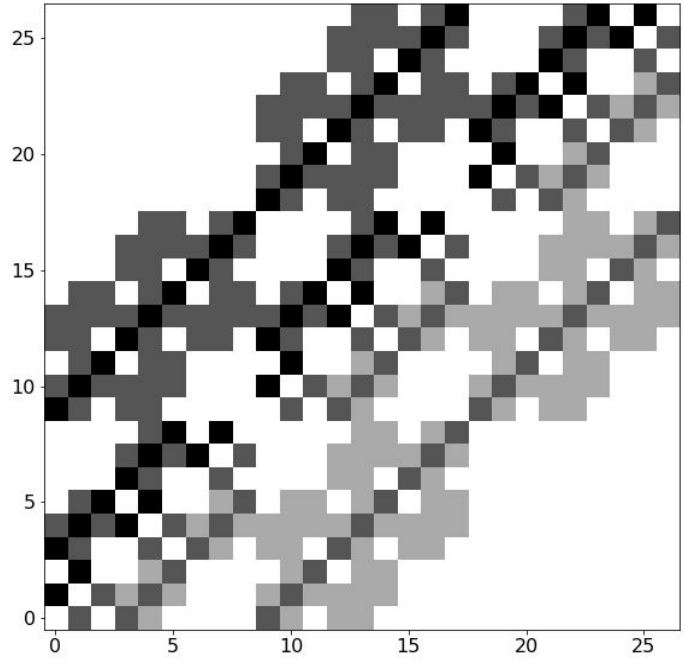
Modern HPC Applications

- Employ multi-socket, multicore, many-core CPUs within a node
- Use MPI+Threads
  - MPI for communication among nodes
  - OpenMP or other threading models for intra-node communication
- Do **explicit inter-process** communication
  - Managed via message passing (e.g., MPI) Send/Recv primitives
- Do **implicit inter-thread** communication
  - Hidden by standard load/store CPU instructions

Regardless of communication type, data transfer is dominant in performance and energy consumption.

Need Communication Detection Tools

MPI communication matrix for LULESH via EZTrace

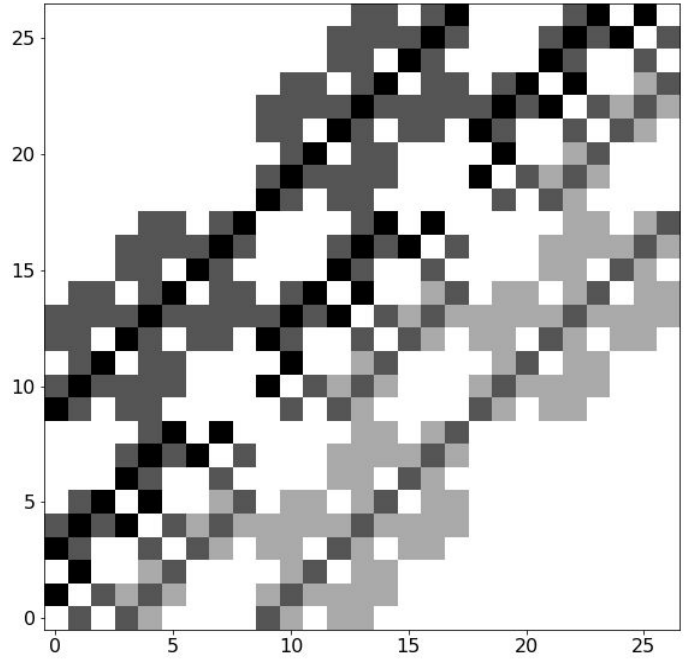


Inter-thread communication matrix

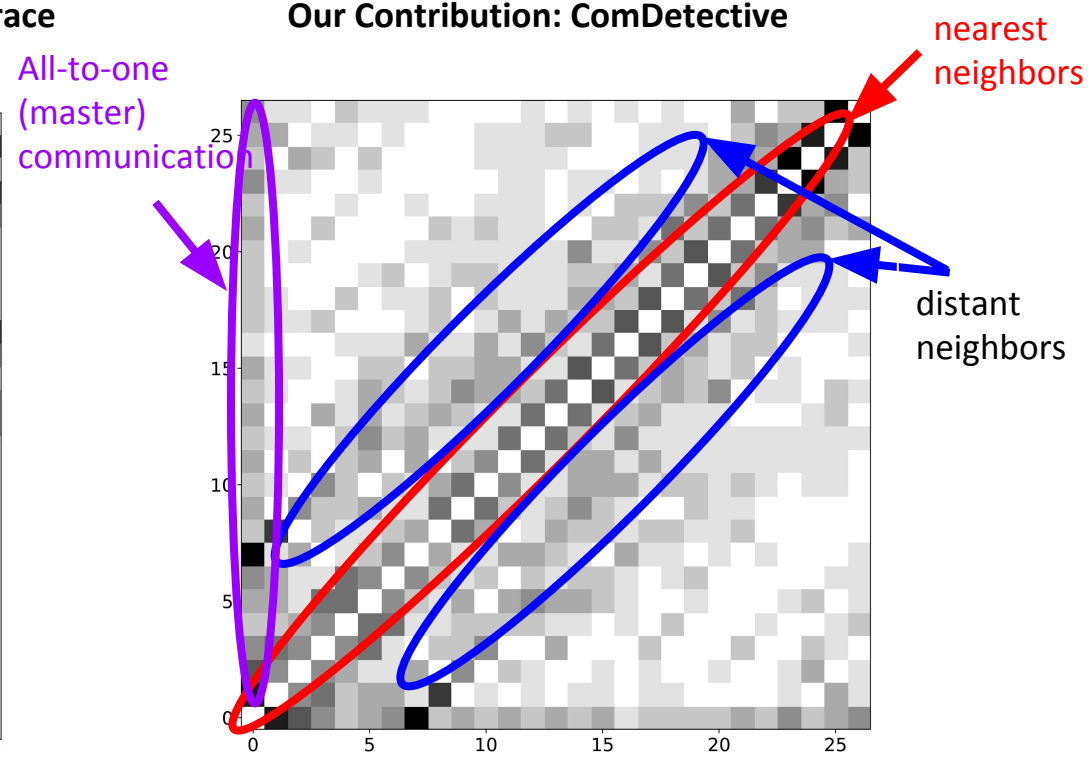
?

Need Communication Detection Tools

MPI communication matrix for LULESH via EZTrace

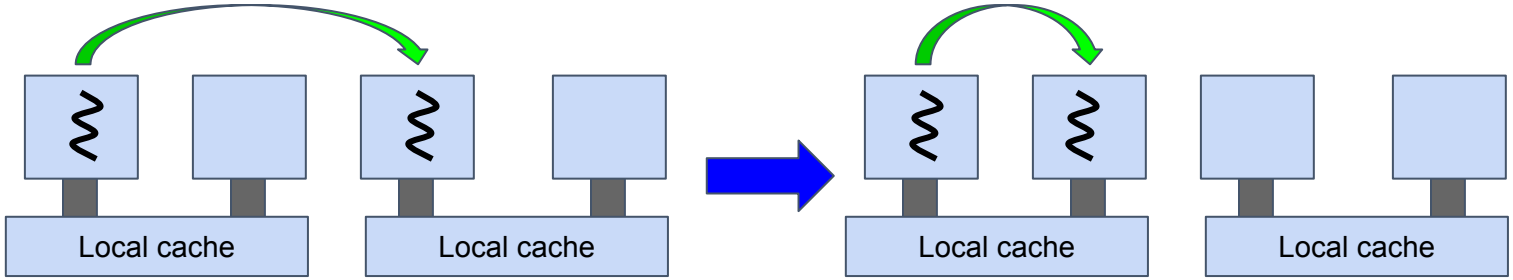


Our Contribution: ComDetective



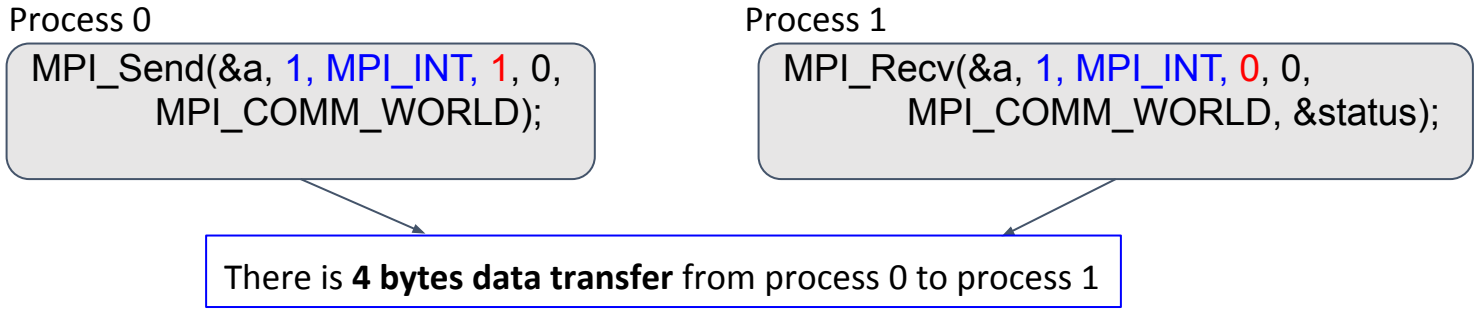
Why Detect Inter-Thread Communication?

- Identify possible sources of performance bottlenecks
- Help explain why one threading library is better than another
  - e.g. Intel OpenMP vs GNU OpenMP
- Guide performance optimizations such as
  - thread binding
  - data structure modification
  - false sharing elimination
- Hardware design: on-chip network design, cache coherence protocol



Challenges

- Inter-process communication detection in MPI is relatively straightforward



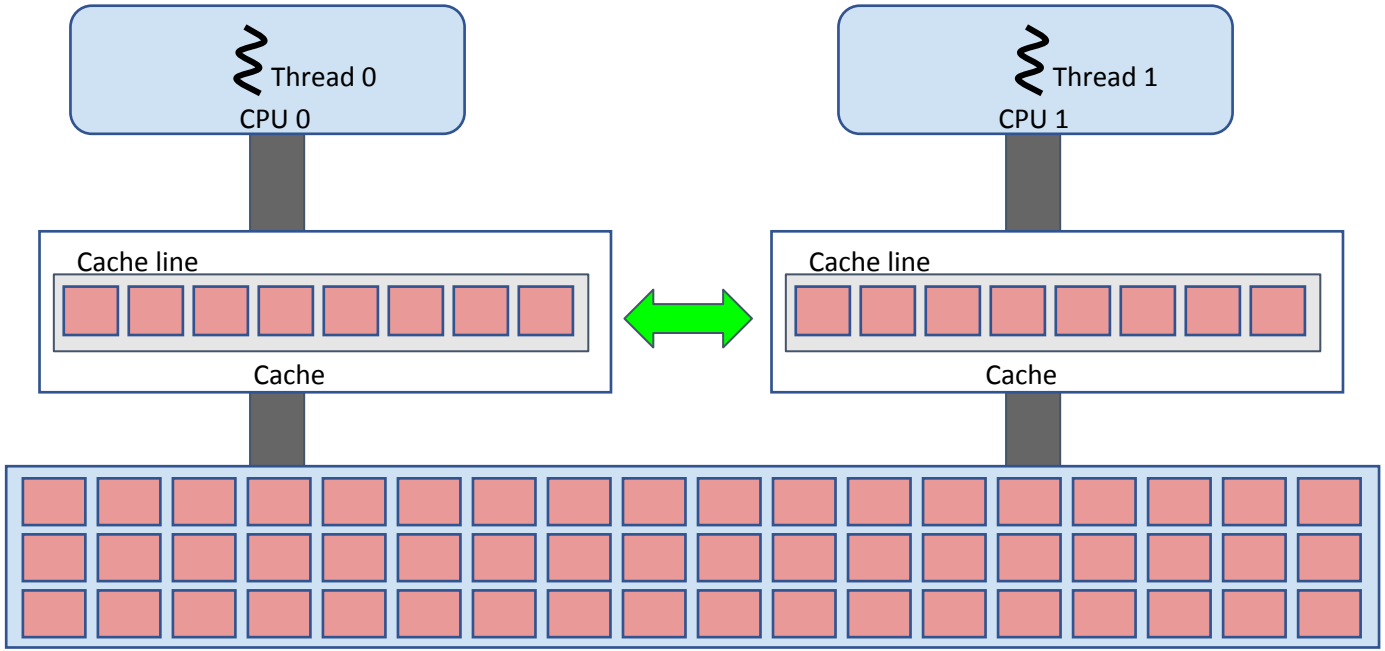
- Exact inter-thread communication detection poses some challenges
  - requires **interception of load and store** operations
  - incurs **huge space and time overheads** if all load and store operations are intercepted
  - **dilates execution** and changes program behavior
  - **scales poorly** with increasing number of threads

ComDetective: Salient Features

- **Accurate**
  - Validated against several benchmarks and HPC applications
- **Lightweight**
  - Space overhead (1.3x) and time (1.3x) overhead
- **Sampling-based**
  - Uses hardware performance monitoring units
- **Differentiates the kind of communication**
  - True sharing (necessary) vs. false sharing (unnecessary)
- **Data objects**
  - Attributes communication to program data objects
- Open source: https://github.com/comdetective-tools

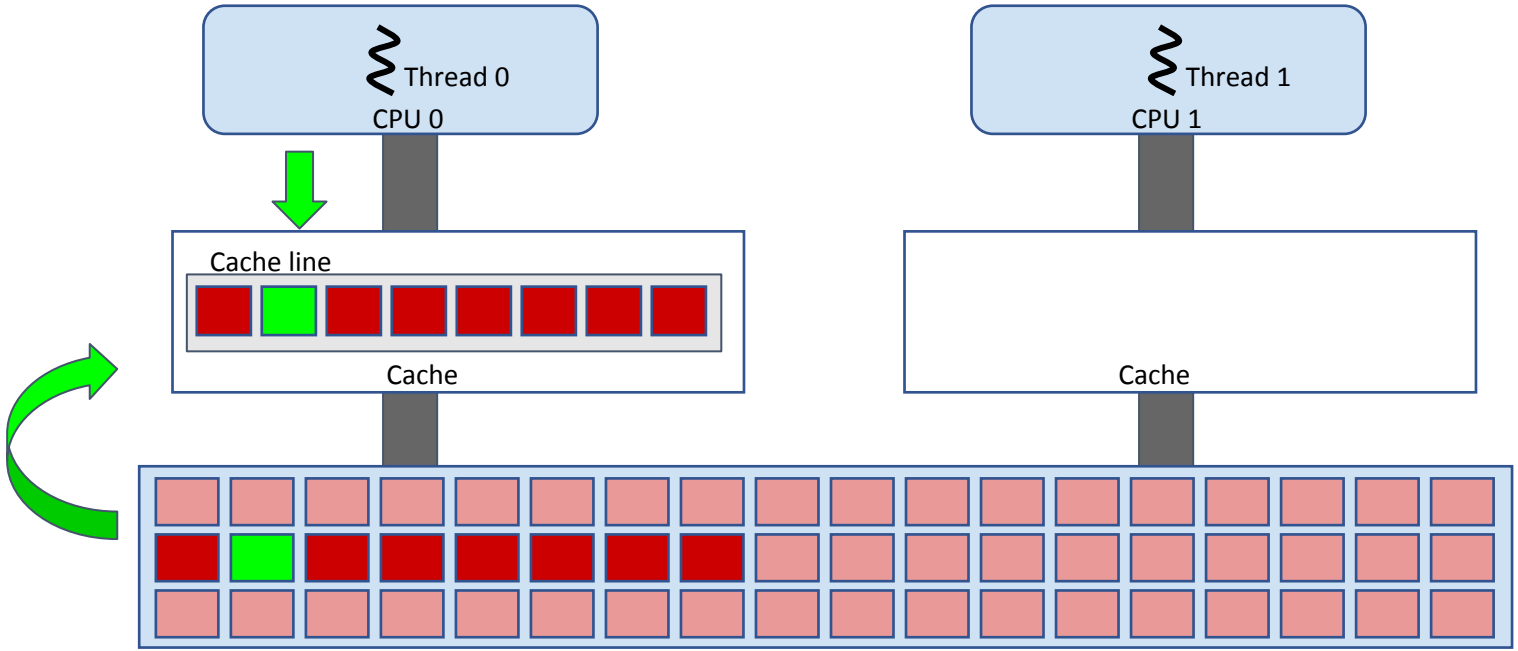
Inter-Thread Communication

- Occurs in multi-threaded programs or hybrid programs (e.g. MPI+OpenMP hybrid)
- Occurs at CPU cache line granularities



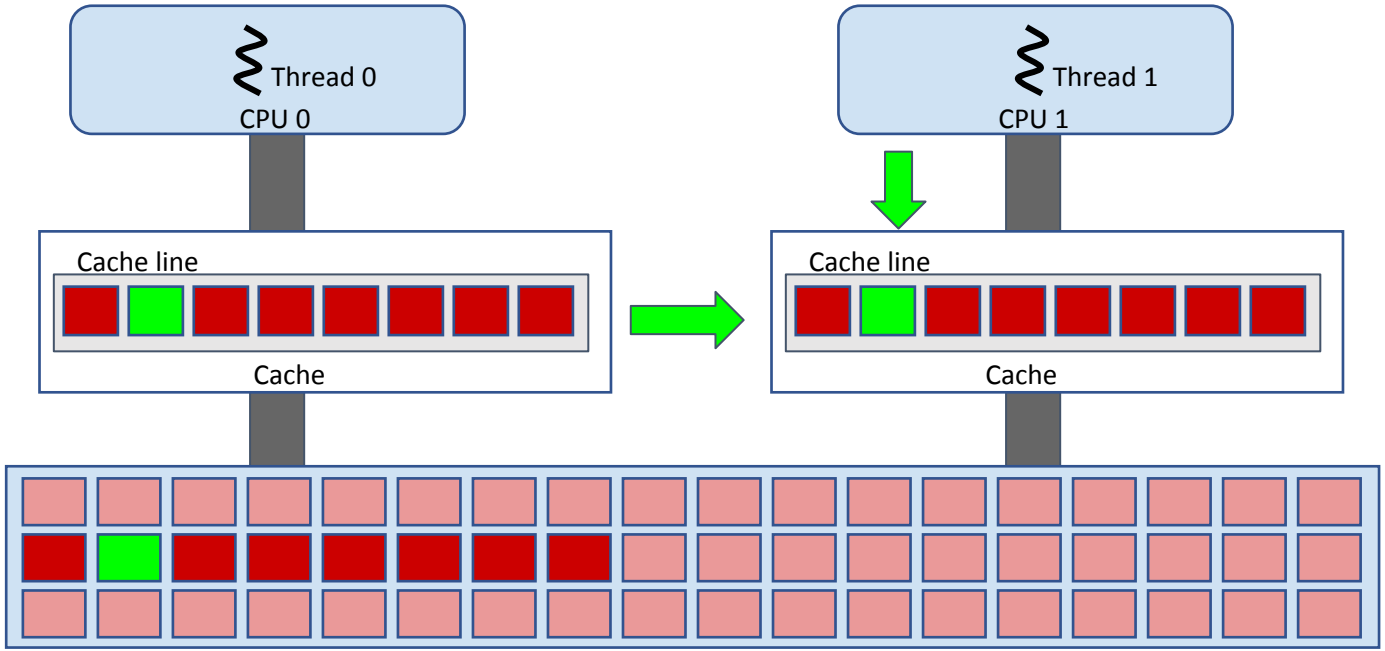
Inter-Thread Communication

- Memory access by CPU 0



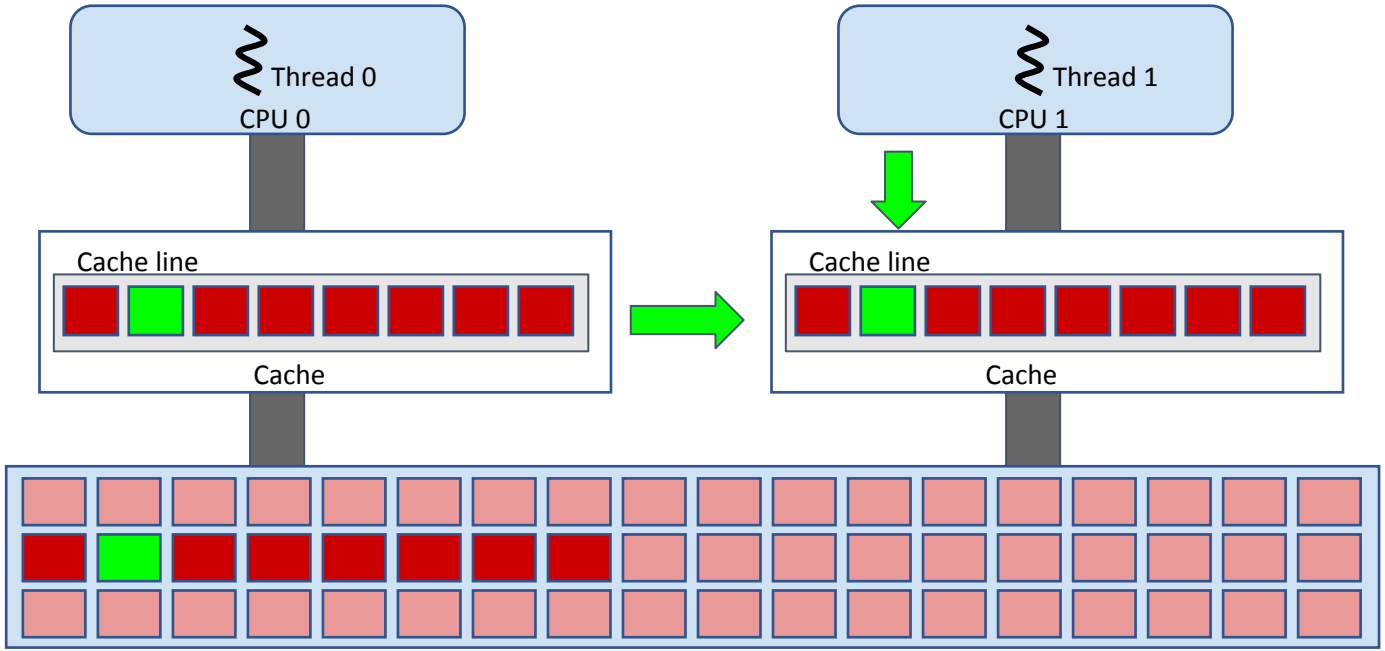
Inter-Thread Communication

- Memory access by CPU 1



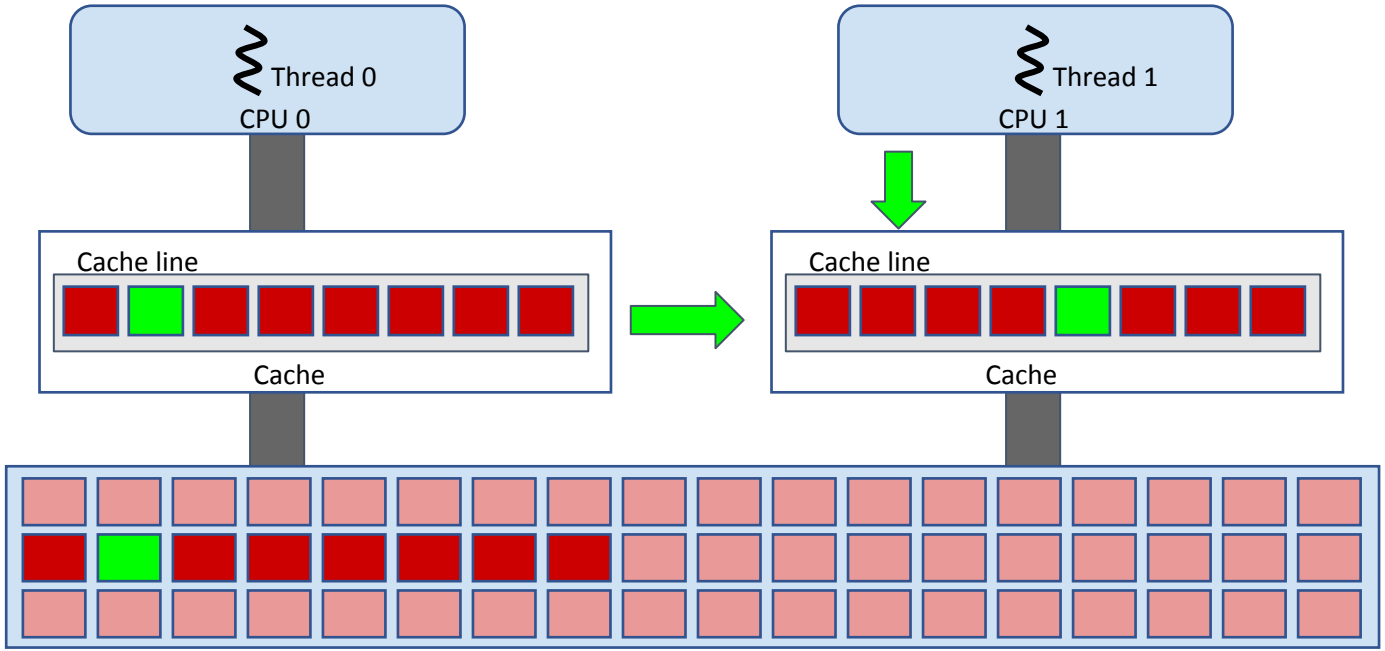
Inter-Thread Communication: Necessary

- This type of communication is called **true sharing**

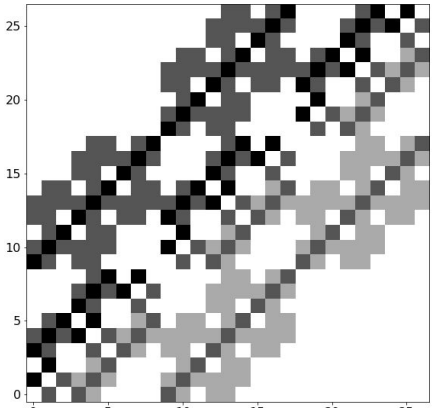


Inter-Thread Communication: Unnecessary

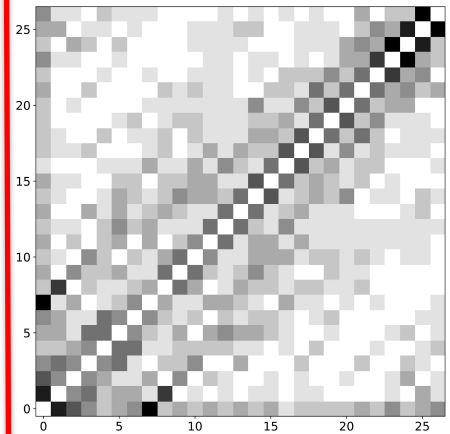
- Another possible type is **false sharing**
- Threads 0 and 1 access different memory regions in the same cache line



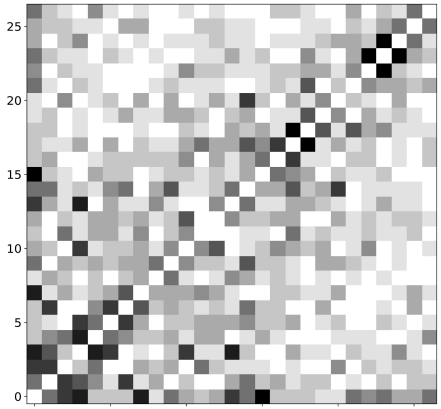
An Example Output from LULESH



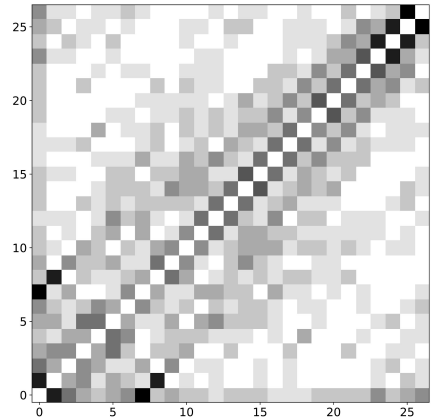
MPI communication matrix



communication matrix



true sharing matrix



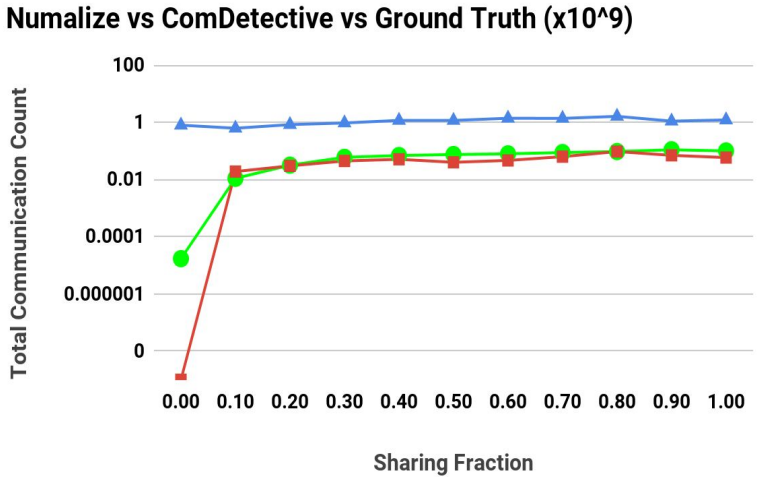
false sharing matrix

- In addition to communication matrix, ComDetective also produces true sharing and false sharing matrices
- It took only **1.28x** performance and **1.11x** memory footprint overhead to generate these matrices with ComDetective

Existing Tools

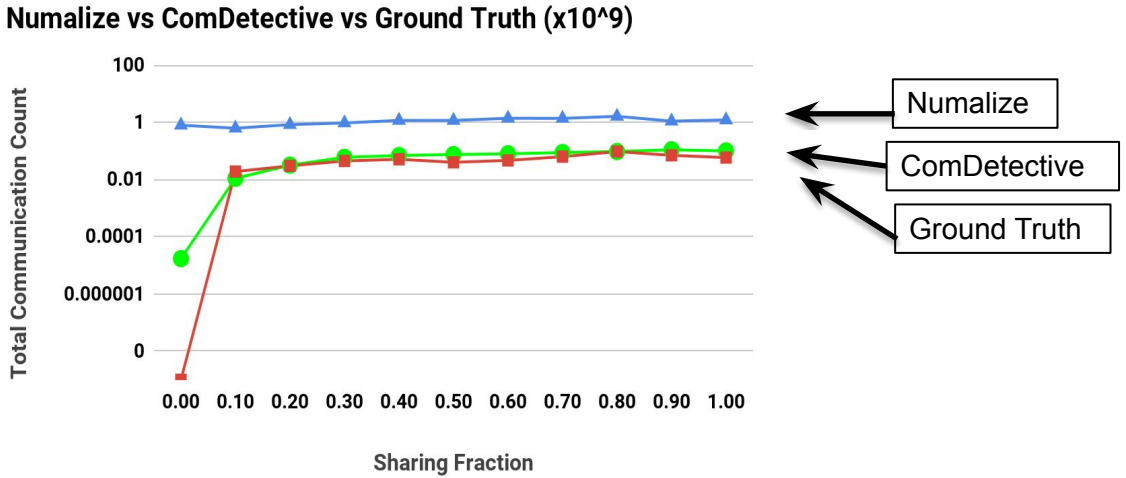
- Prior works on identifying inter-thread communication employed **hardware simulators** or **binary instrumentation**
  - Suffered from inaccuracy or high overhead
- Simulator-based tools [Barrow-Williams, et al, IISWC 2009] [Molina da Cruz, et al, IPDPSW 2011] [Diener, et al, PDP 2016]
  - Incurring huge memory footprints and very slow
  - Requires offline profiling
  - Not running on real hardware, so execution behavior can change.
- Performance monitoring units (PMUs)-based tools [Azimi, et al. ACM SIGOPS Operating Systems Review 2009][Tam, et al. EuroSys 2007].
  - Can be intrusive as it requires modification of kernel source code

Existing Tools



- Code instrumentation: binary [Diener, et al. Performance Evaluation 2015][Diener, et al, PDP 2016] (Numalize) and compiler-assisted [Mazaheri, et al. ICPP 2015][Mazaheri, et al. ICPP 2018]
  - Can suffer from large slowdown and memory overhead
  - We have found that Numalize is not accurate.

Existing Tools



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  - Can suffer from large slowdown and memory overhead
  - We have found that Numalize is not accurate.

ComDetective

- We develop a tool to detect inter-thread communication called **ComDetective**
- ComDetective is
  - **Fast --** uses **available hardware features**; PMUs and debug registers
  - **Accurate** -- has **been validated** in terms of correctness of **total communication volume** and correctness of **point-to-point communication ratio**
- ComDetective also
  - Differentiates **true sharing and false sharing** communications -- by detecting if **memory regions** accessed by communicating threads **overlap or not**
  - Associates communication matrices not only to the whole program but **to program objects** -- for global, stack, and heap objects

Outline

- Background Information on Inter-Thread Communication
- Motivation for Detecting Inter-Thread Communication
- Prior Arts
- Introduction to ComDetective
- Design Components
- Workflow
- Detailed Evaluation

Big Picture

- Inter-thread communication occurs between two threads if,

  Two threads access an address residing on the same cache line in a short interval

- Question: How to detect cache line communication?

Big Picture

- Inter-thread communication occurs between two threads if,

  Two threads access an address residing on the same cache line in a short interval

- Question: How to detect cache line communication?
  - A thread can **sample** its memory accesses via hardware performance counters (address sampling)
  - No load/store instrumentation ⇒ super low overhead

Big Picture

- Question: how can another thread know if it is accessing the same address **without instrumenting its loads and stores**?

Big Picture

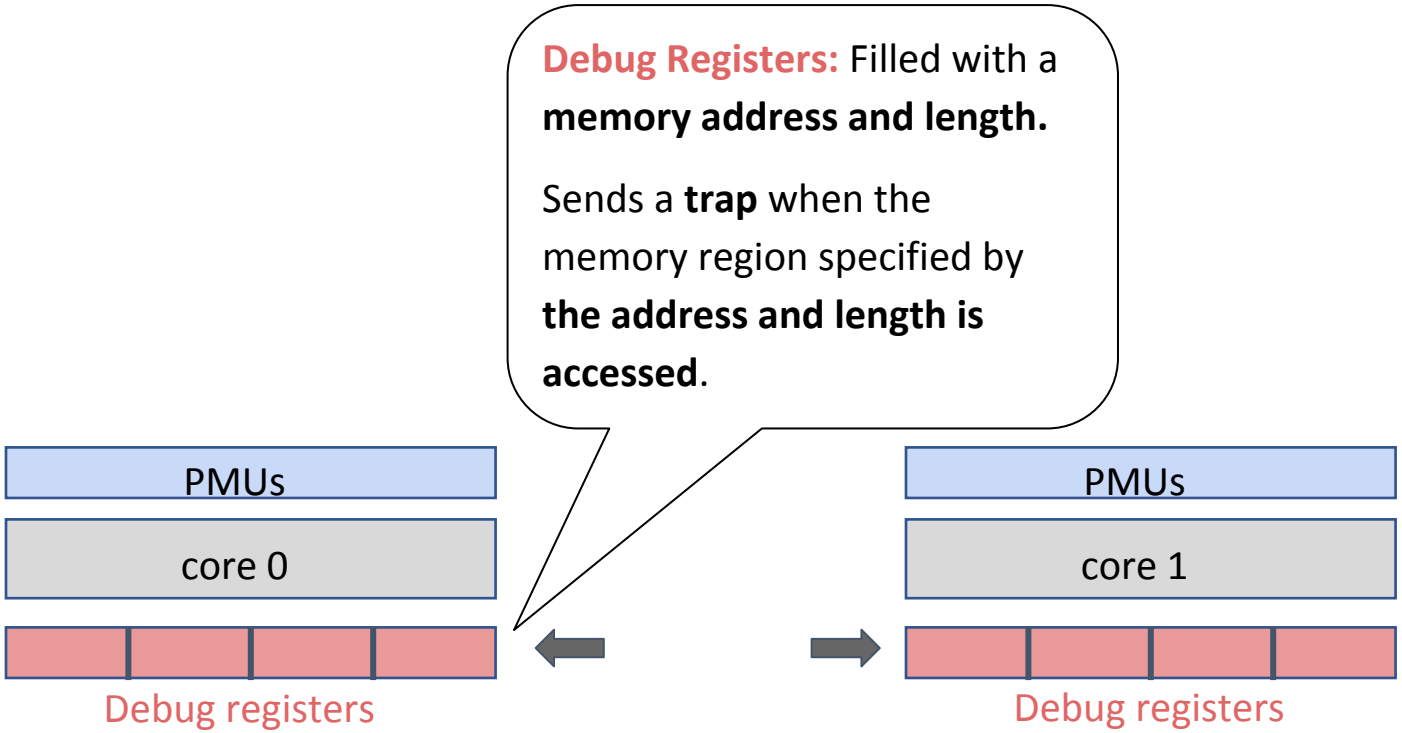
- Question: how can another thread know if it is accessing the same address **without instrumenting its loads and stores**?
- Answer:
  - The first thread
    - **publishes its sampled address** to a globally visible location
  - The second thread
    - **compares its sampled address** with the globally published addresses and if there is a match ⇒ inter-thread communication, or
    - uses **hardware-debug registers** (aka watchpoints) to monitor a globally published address
  - Watchpoint traps when the second thread accesses the same address ⇒ inter-thread communication

Design Components: PMU

PMU: Special registers that **count low-level events**, such as loads or stores.

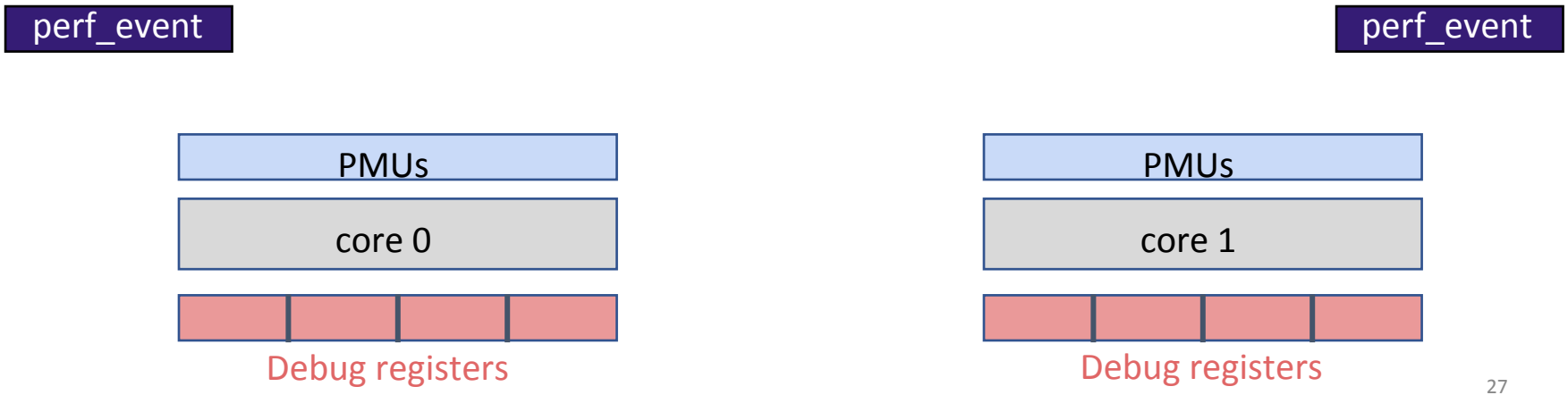
Sampling: PMUs can be configured to trigger interrupt f**or every N events.**

Design Components: Debug Registers

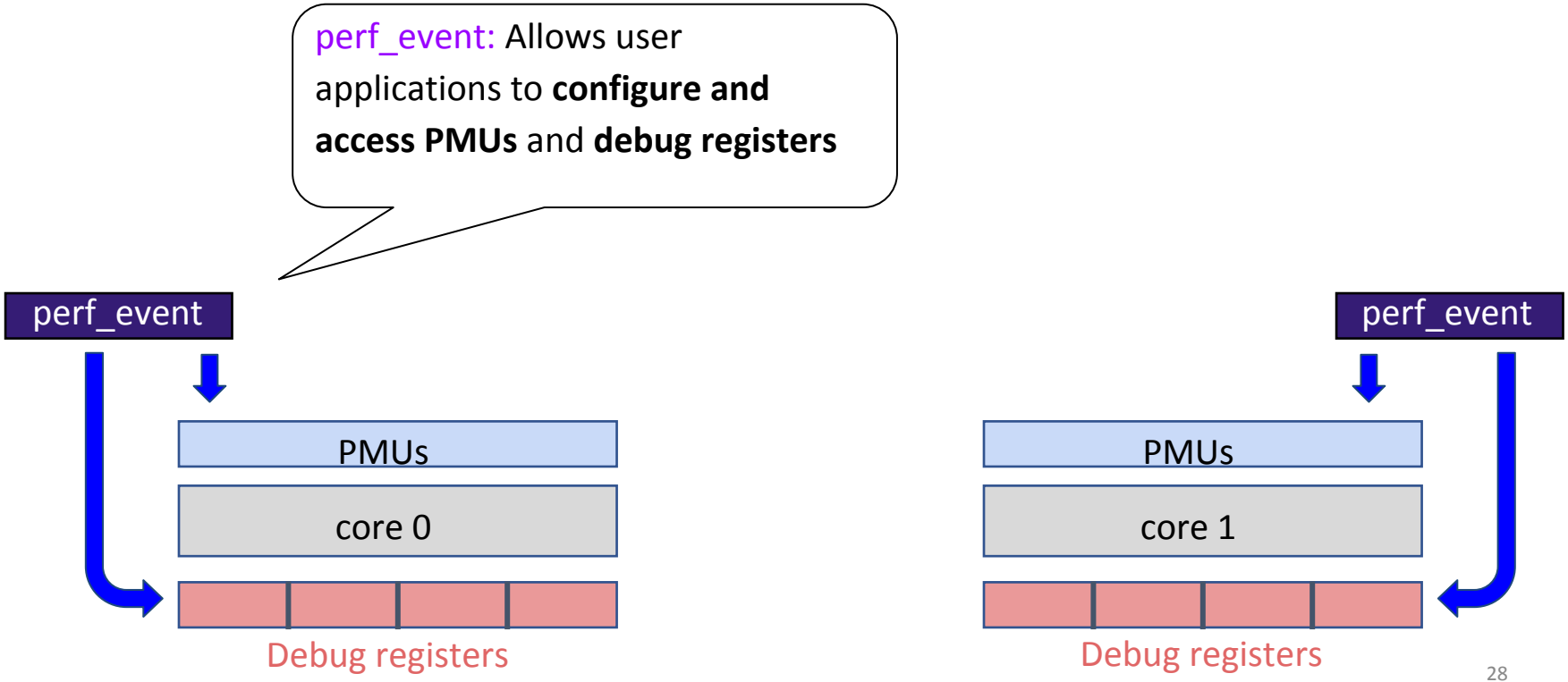


Design Components: perf_event

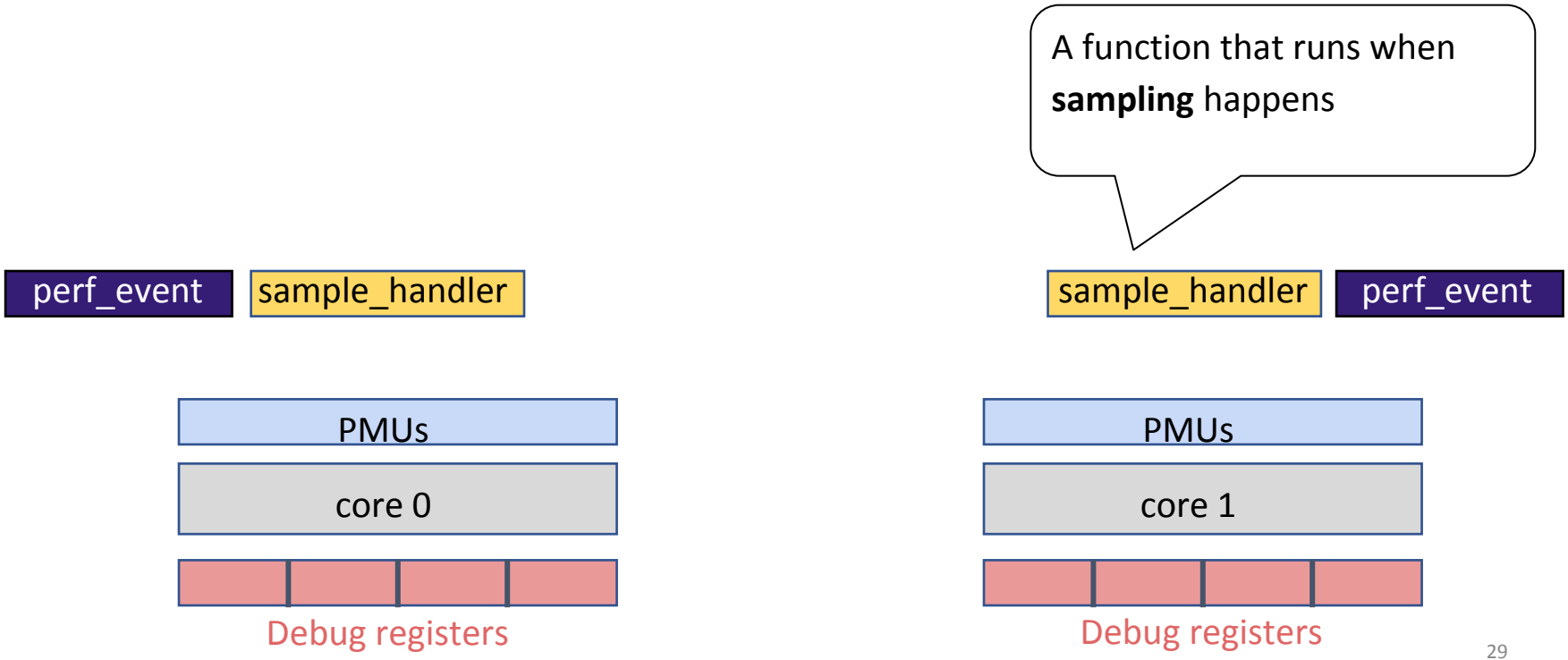
perf_event: Allows user applications to **configure and access PMUs** and **debug registers**



Design Components: perf_event



Design Components: ComDetective



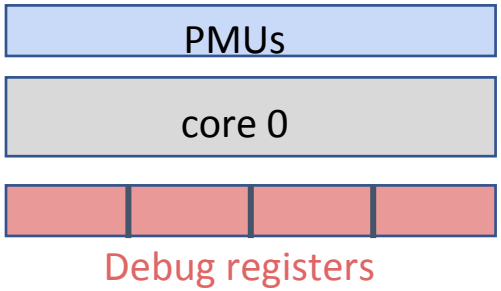
Design Components: ComDetective

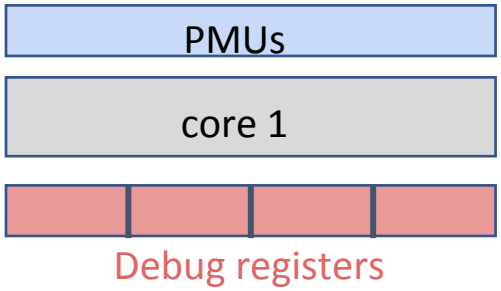
key	attributes

Bulletin Board: A **hash table** that publishes some of the **sampled data**

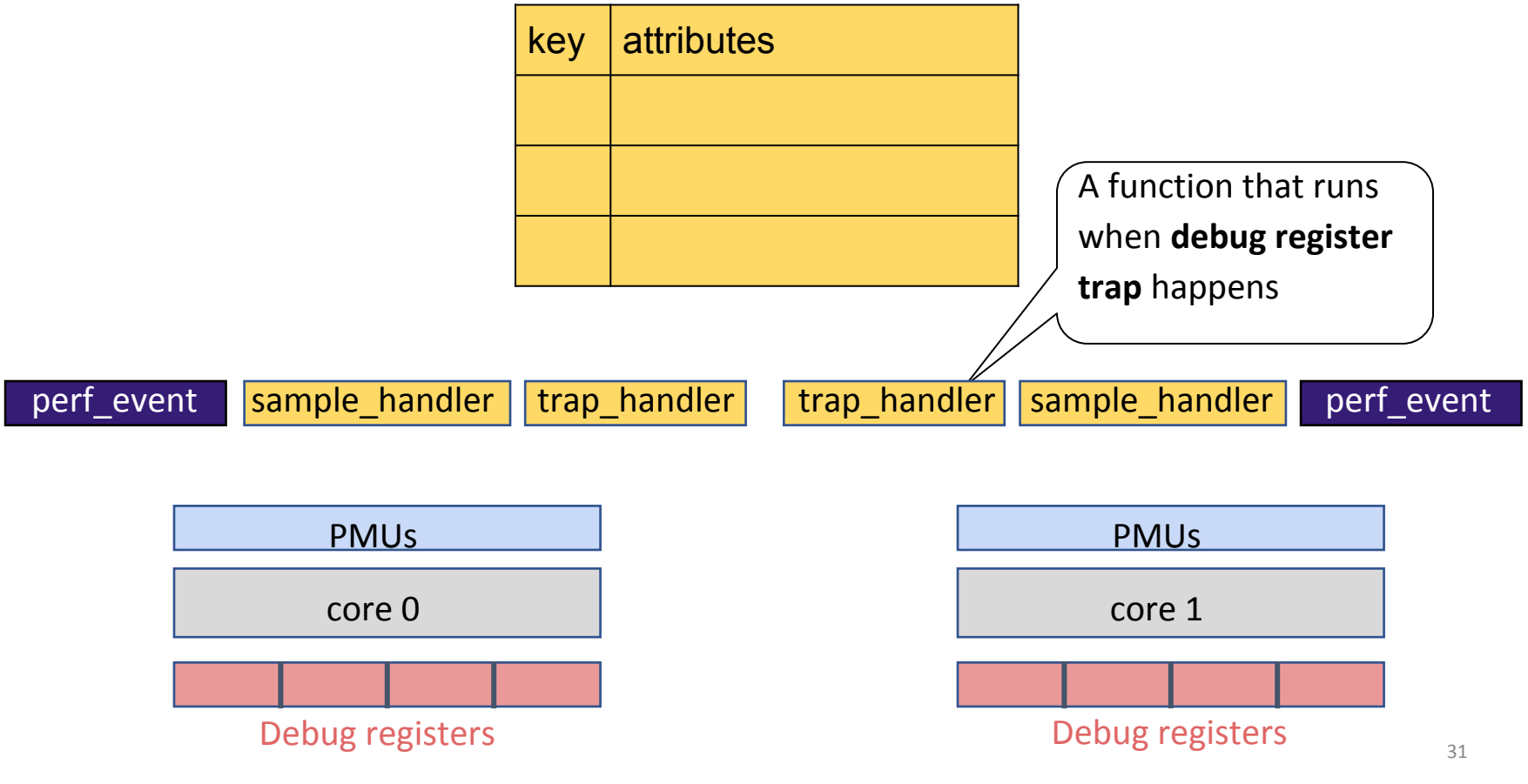
perf_event | sample_handler

sample_handler | perf_event

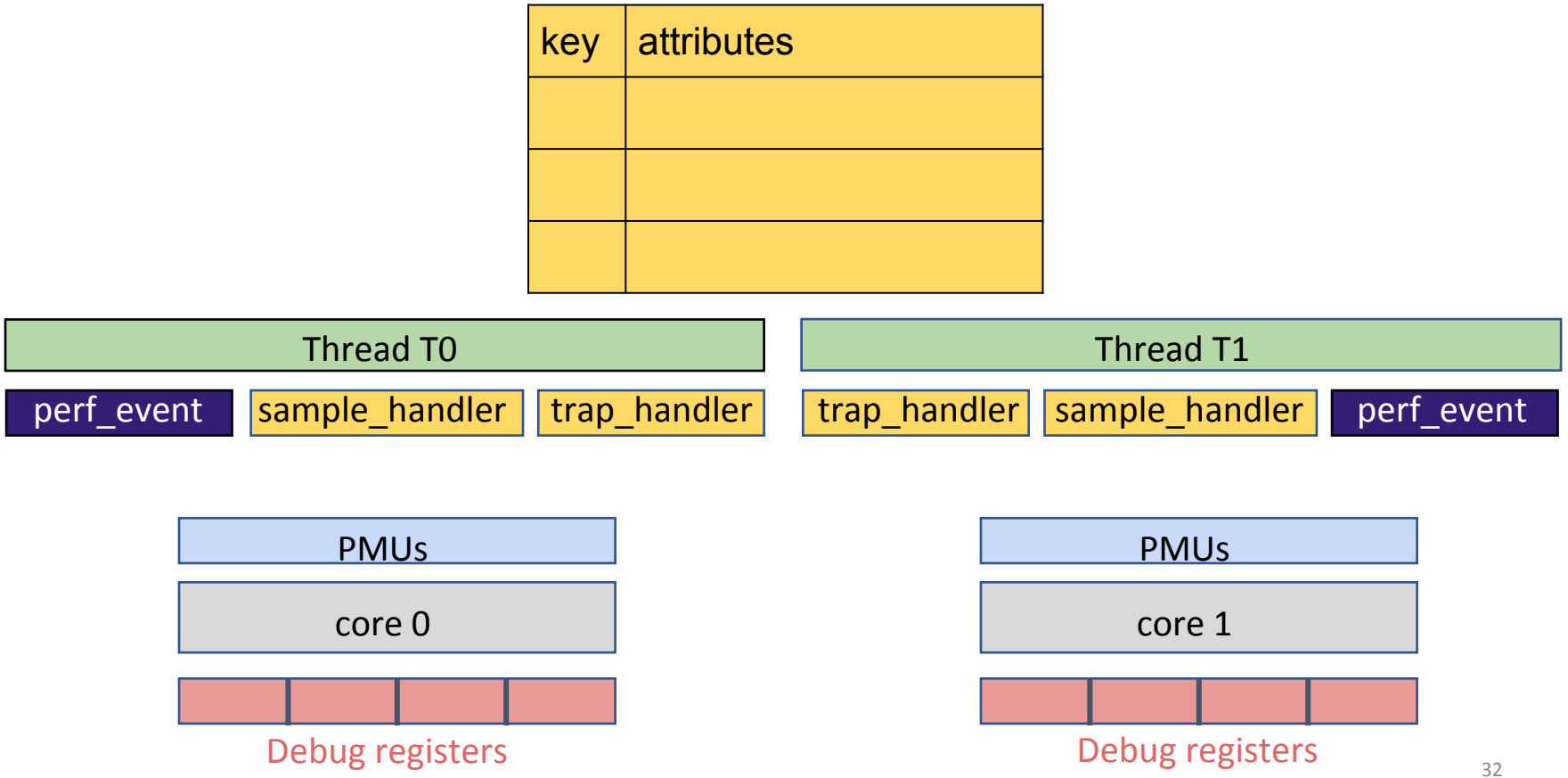




Design Components: ComDetective



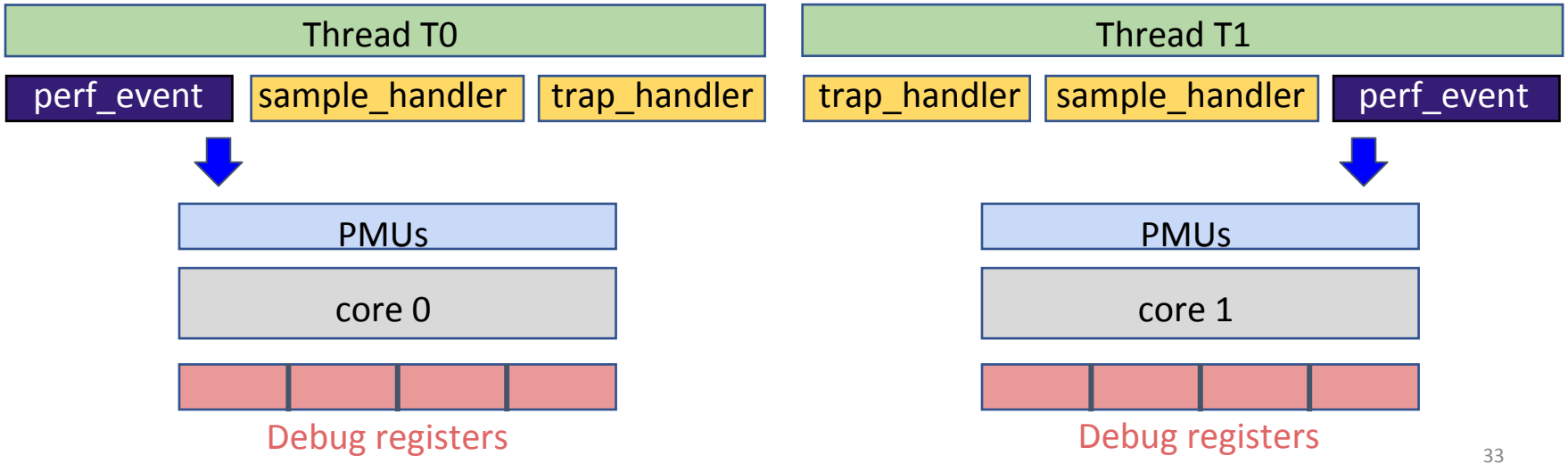
Design Components



An Example Workflow

perf_event is configured so that **loads** and **stores** to be sampled for every **N events**.

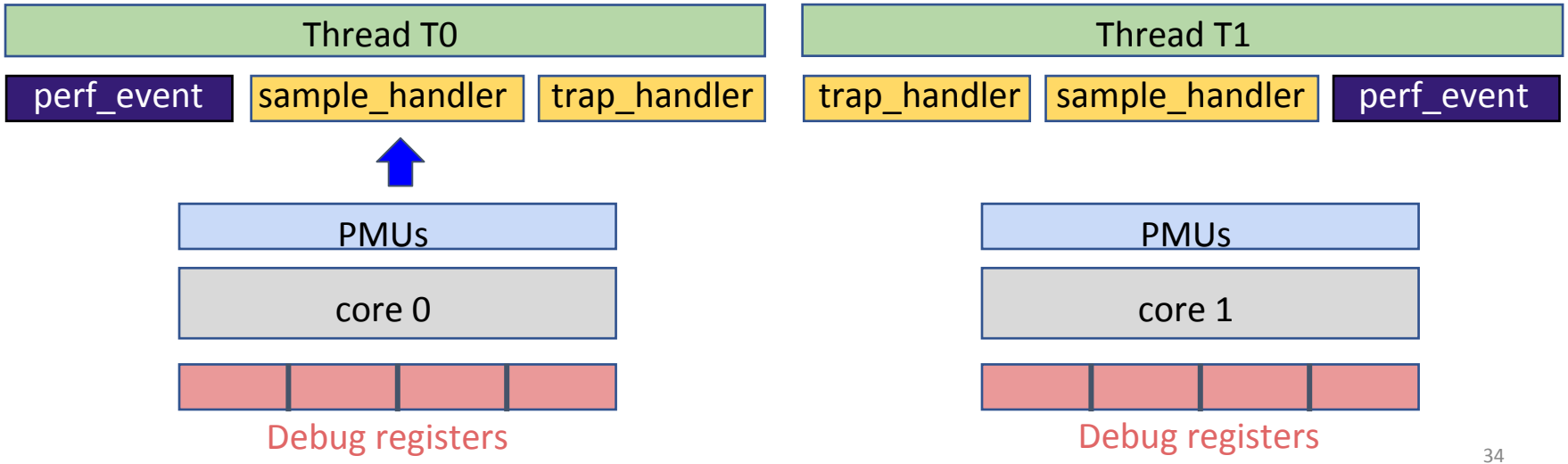
key	attributes
-1	
-1	
-1	



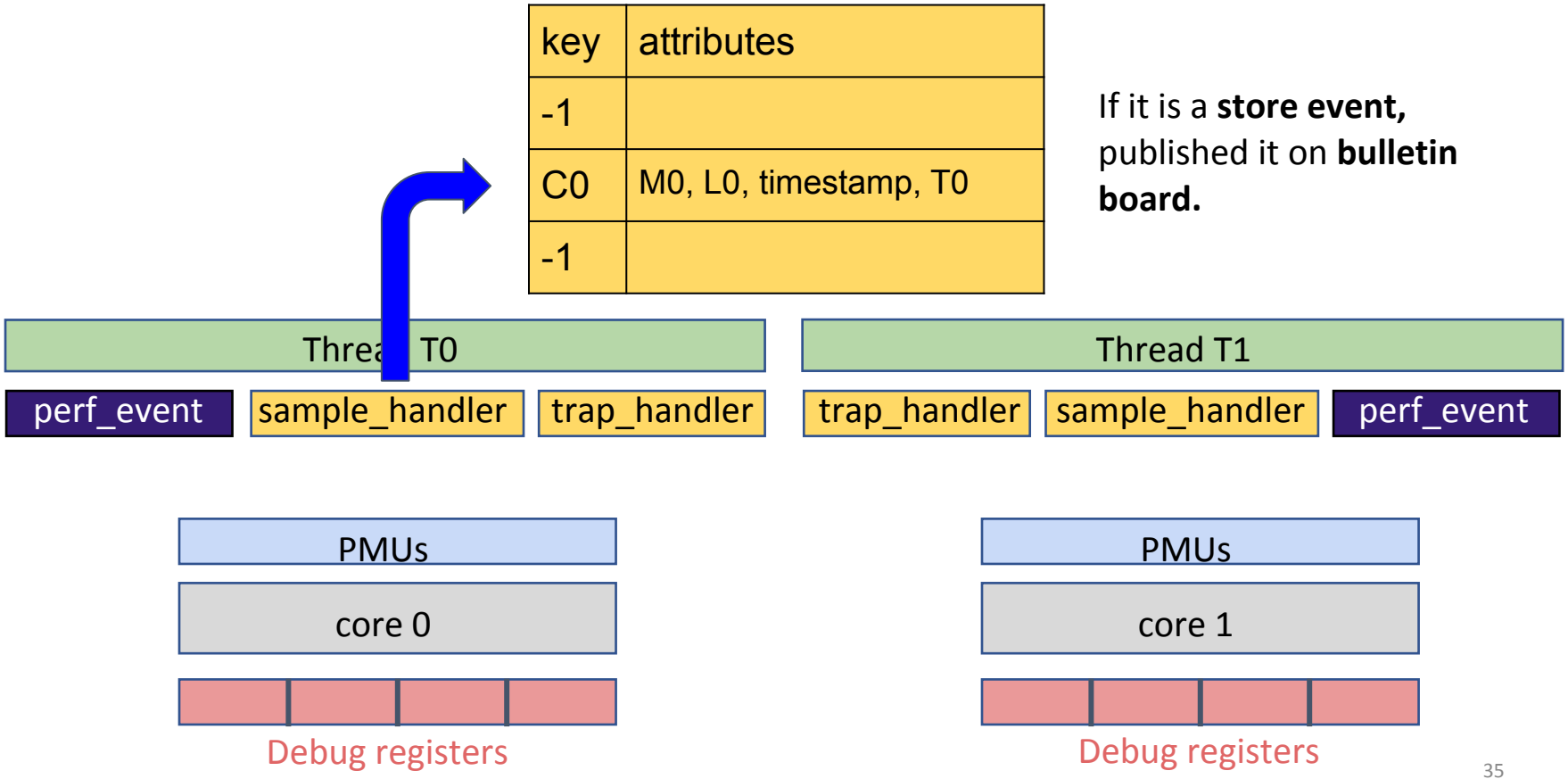
Workflow

Interrupt happens in core 0 after N events.

key	attributes
-1	
-1	
-1	



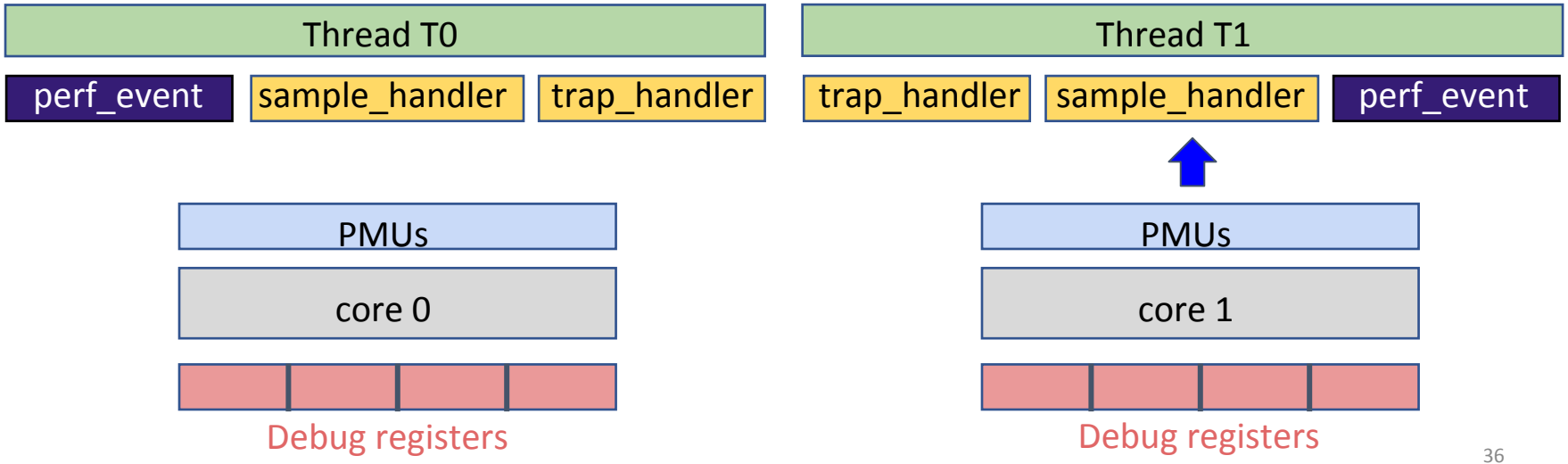
Workflow


key
attributes
-1
C0
M0, L0, timestamp, T0
-1
If it is a **store event,** published it on **bulletin board.**
Thread T0
Thread T1
perf_event
sample_handler
trap_handler
trap_handler
sample_handler
perf_event
PMUs
core 0
Debug registers
PMUs
core 1
Debug registers

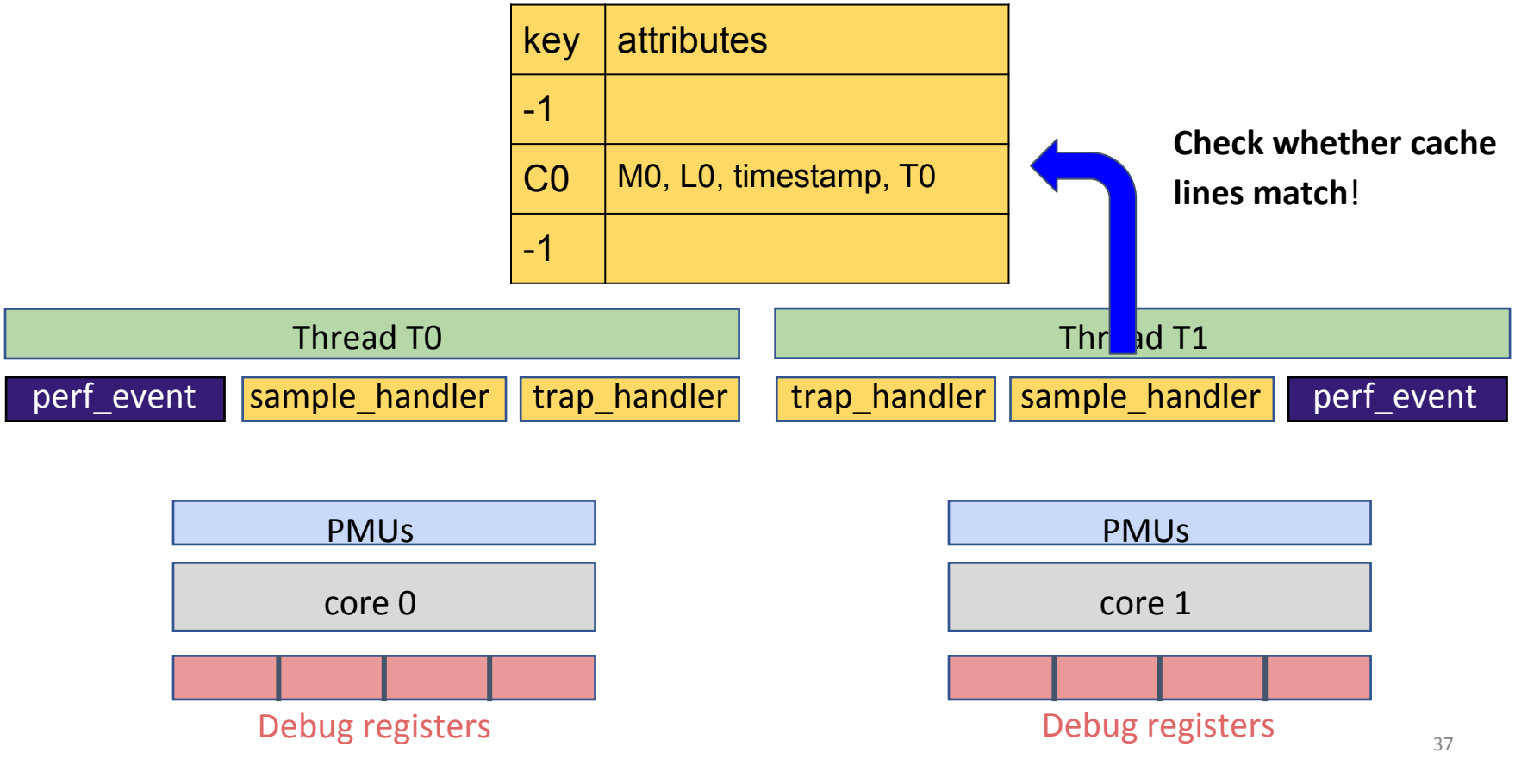
Workflow

key	attributes
-1	
C0	M0, L0, timestamp, T0
-1	

Interrupt happens in core 1. The triggering event is **a store to memory address M1.**



Workflow

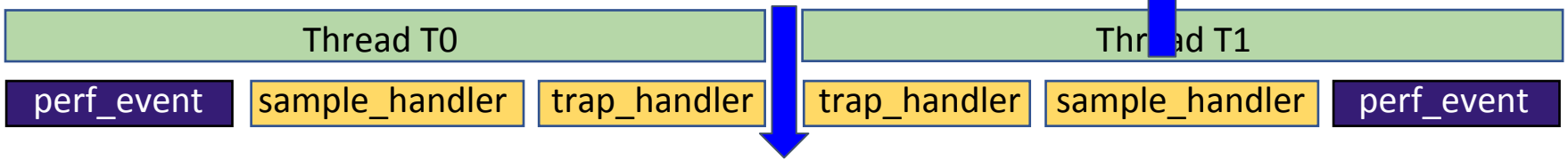

key
attributes
-1
C0
M0, L0, timestamp, T0
-1
Check whether cache lines match!
Thread T0
Thread T1
perf_event
sample_handler
trap_handler
trap_handler
sample_handler
perf_event
PMUs
core 0
Debug registers
PMUs
core 1
Debug registers

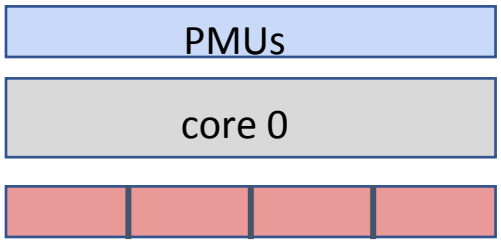
Workflow

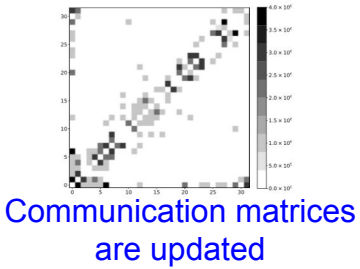
Check hash table entry whether there is the entry is 'recent'.

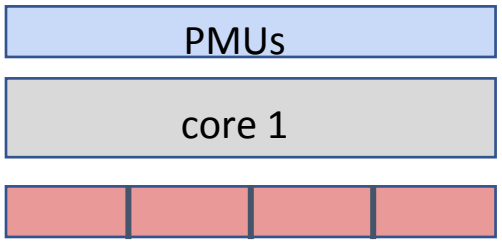
key	attributes
-1	
C0	M0, L0, timestamp, T0
-1	

If C0's entry is 'recent', **communication is detected** between T0 and T1.





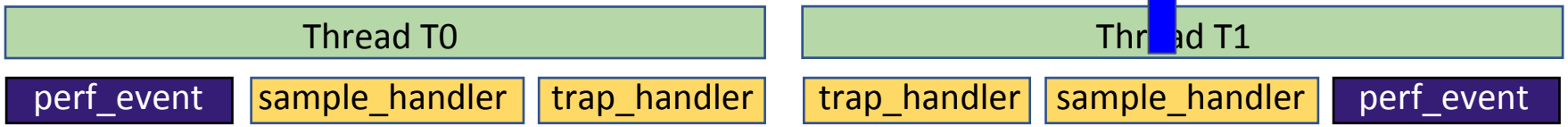


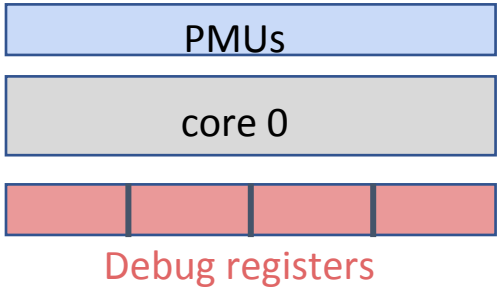


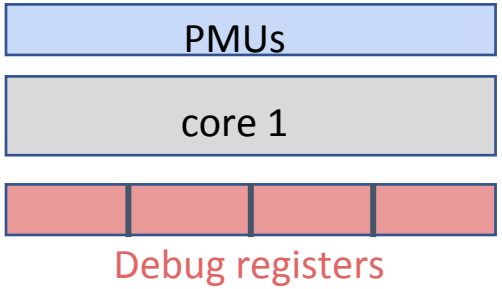
Workflow

key	attributes
-1	
C1	M1, L1, timestamp, T1
-1	

If C0's entry is **not 'recent'**, **replace** the entry with M1.





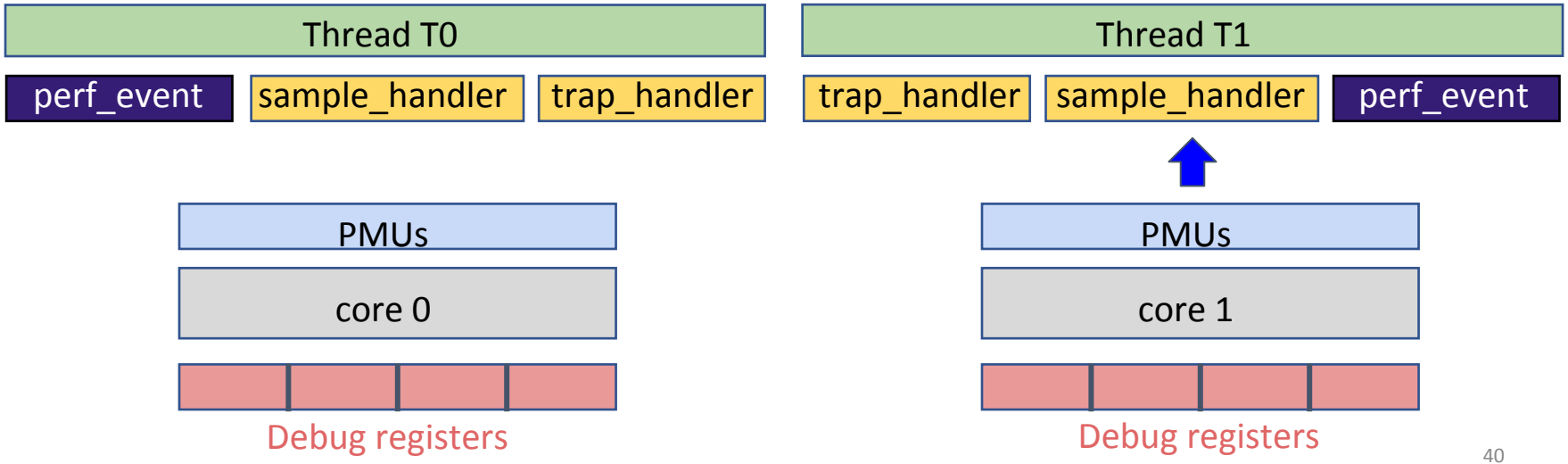


Workflow

key	attributes
…	…..
…	……
…	……

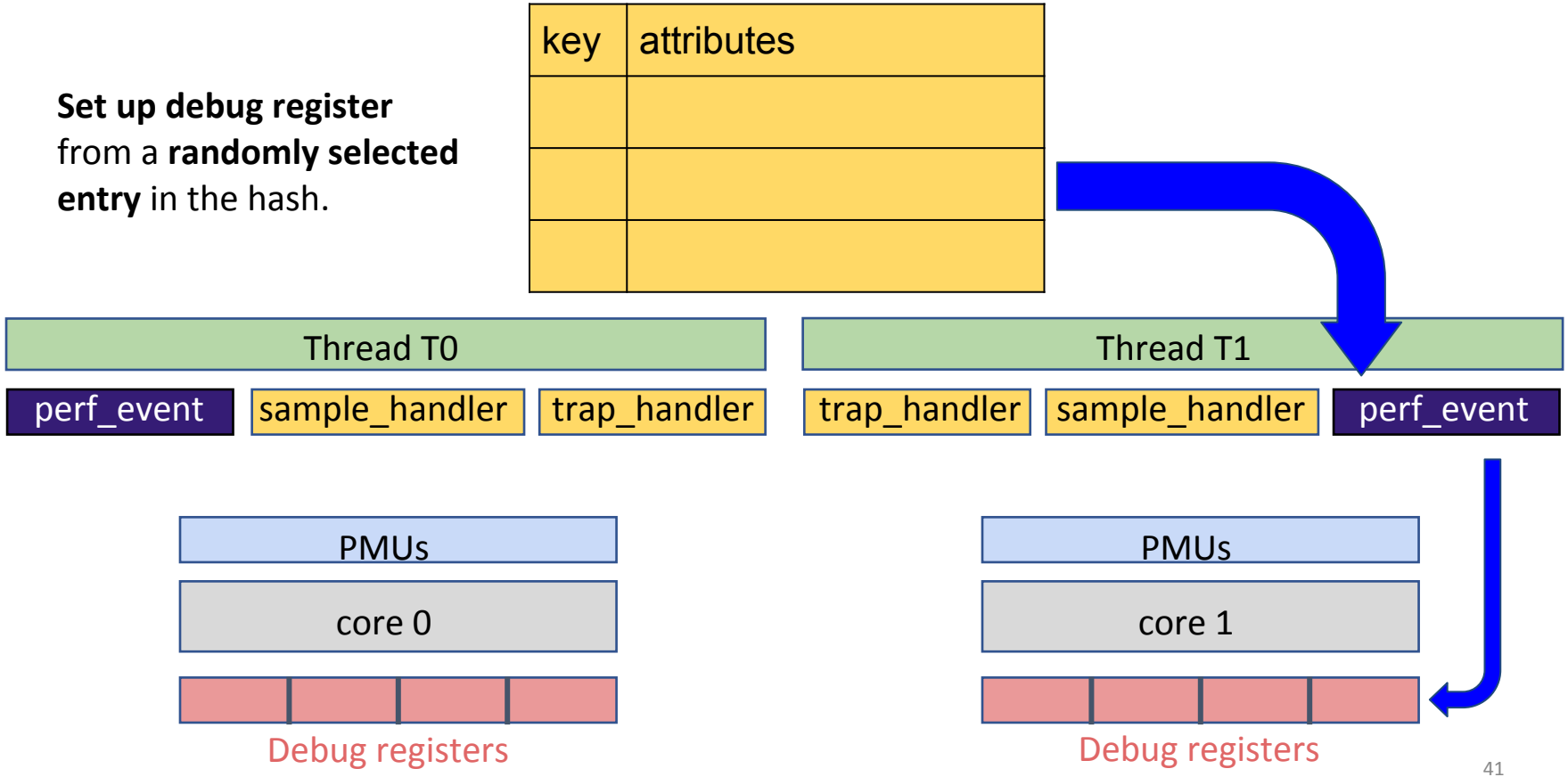
Another store sample happens on address M3.

No matching cache line and all entries are **‘recent’**, so **none can be replaced**.



Workflow

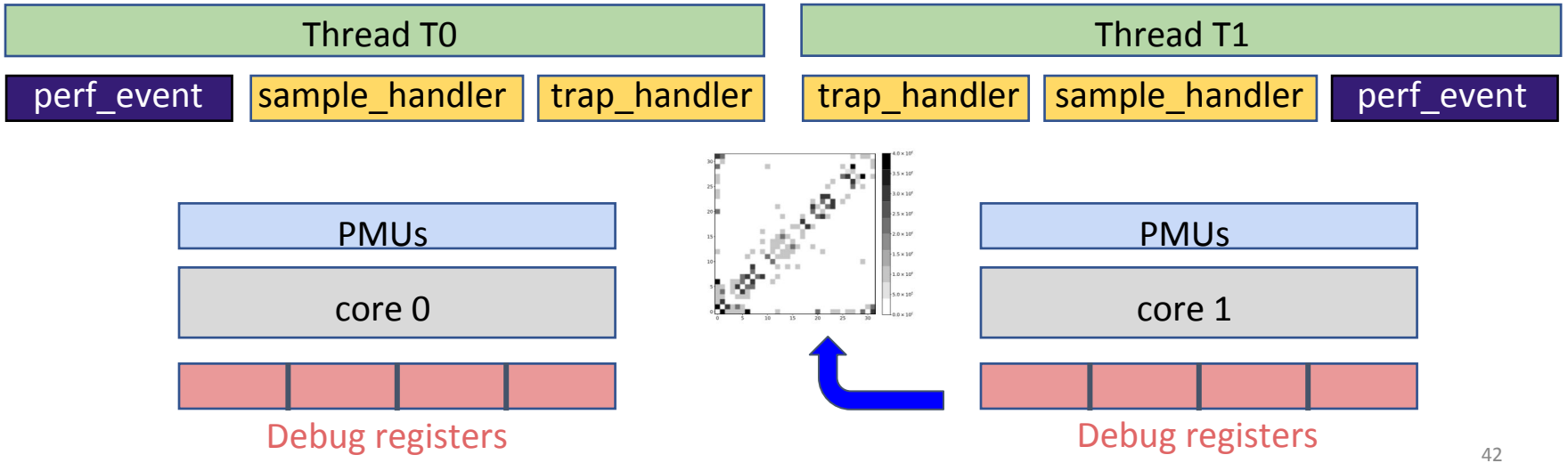
Set up debug register from a **randomly selected entry** in the hash.



Workflow

When **trap in a debug register** happens, **communication matrices** are updated.

key	attributes



Evaluation

- Accuracy verification with micro-benchmarks
  - Communication volume
  - True/false sharing ratio (reported only in our paper)
  - Point-to-point communication ratio
  - Read/write communication volume (reported only in our paper)
- Communication matrices of large benchmarks
  - 12 PARSEC and 6 CORAL applications
- Use cases: code refactoring
- Sensitivity Analysis (reported only in our paper)
  - Sampling interval impact
  - Debug register count
  - Hash table size

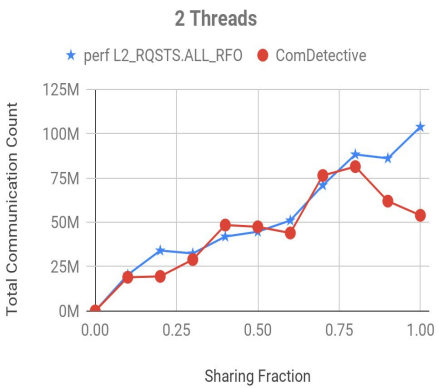
Communication Volume Verification

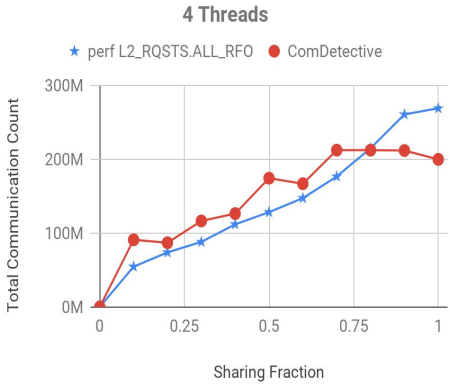
- Communication volume verification microbenchmark
  - Each thread performs **only store operations** to either **shared data** or **private data** depending on **sharing fraction parameter.**

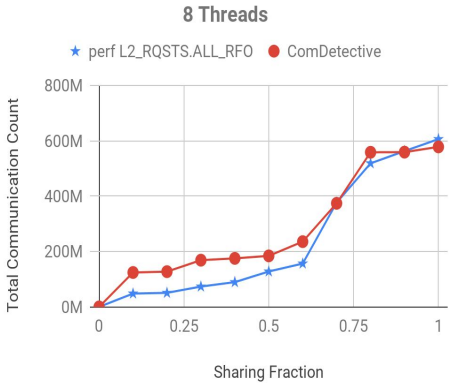
```
1  #pragma omp parallel shared(sharedData) private(privateData) \
2   num_threads(nThreads)
3  {
4    for(int i = 0 ; i < N_ITER; i++) {
5      int rNum  = rand_r(); // thread private
6      If (rNum < SHARING_FRACTION)  {
7        sharedData = rNum;
8      } else {
9        privateData = rNum;
10 }}}
```

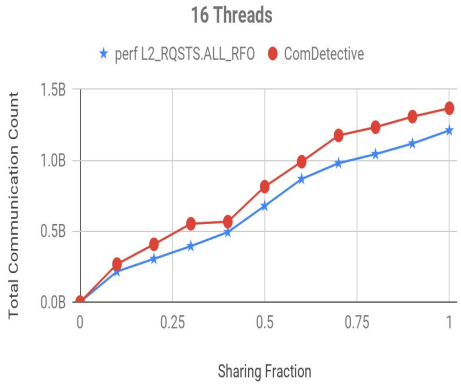
Listing 1: Write-Volume Benchmark

Communication Volume Verification





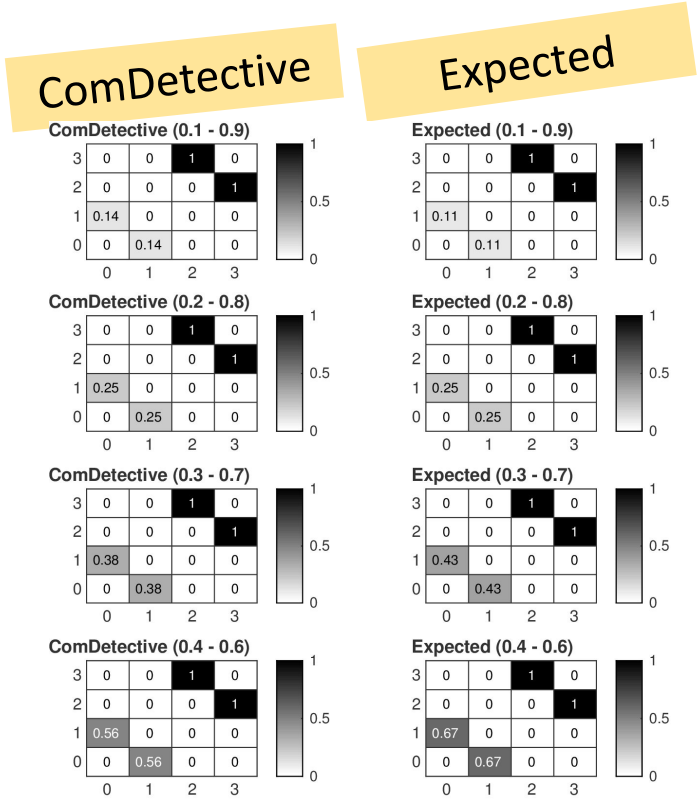




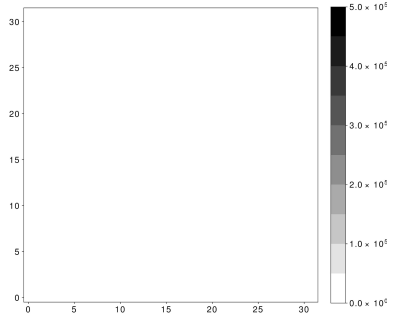
- ComDetective count vs **RFO** (request for ownership) count when 2-16 threads are mapped to 2 sockets.
- Each thread **only performs store operations to shared data**.
  - Real total communication count (ground truth) is RFO count

Point-to-point Communication Ratio Verification

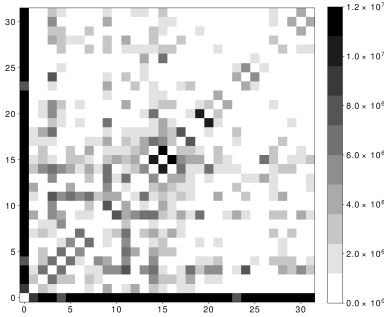
- Point-to-point communication microbenchmark
  - Enables selection of threads which communicate in pairs.
  - In all cases, thread 0 communicates with thread 1 and thread 2 communicates with thread 3.



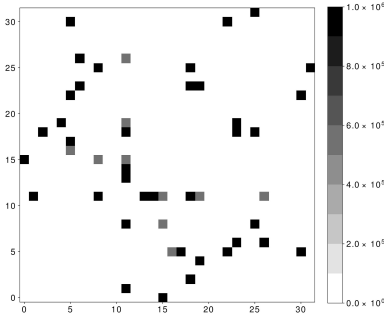
Snapshot of PARSEC Matrices (only 6 shown)



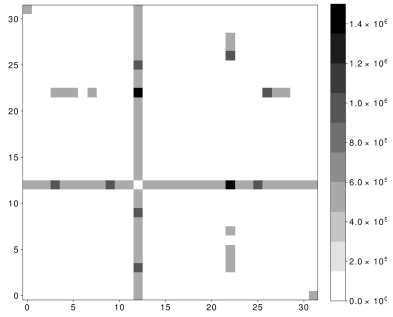
(a) Blackscholes



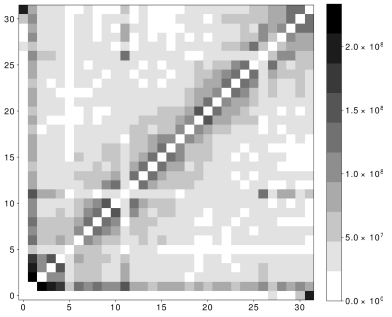
(b) Bodytrack



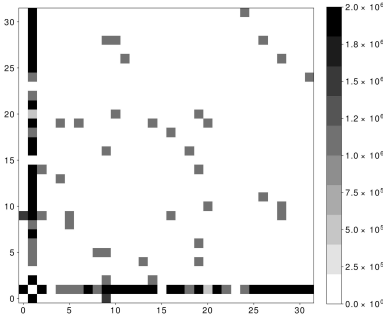
(c) Canneal



(d) Dedup

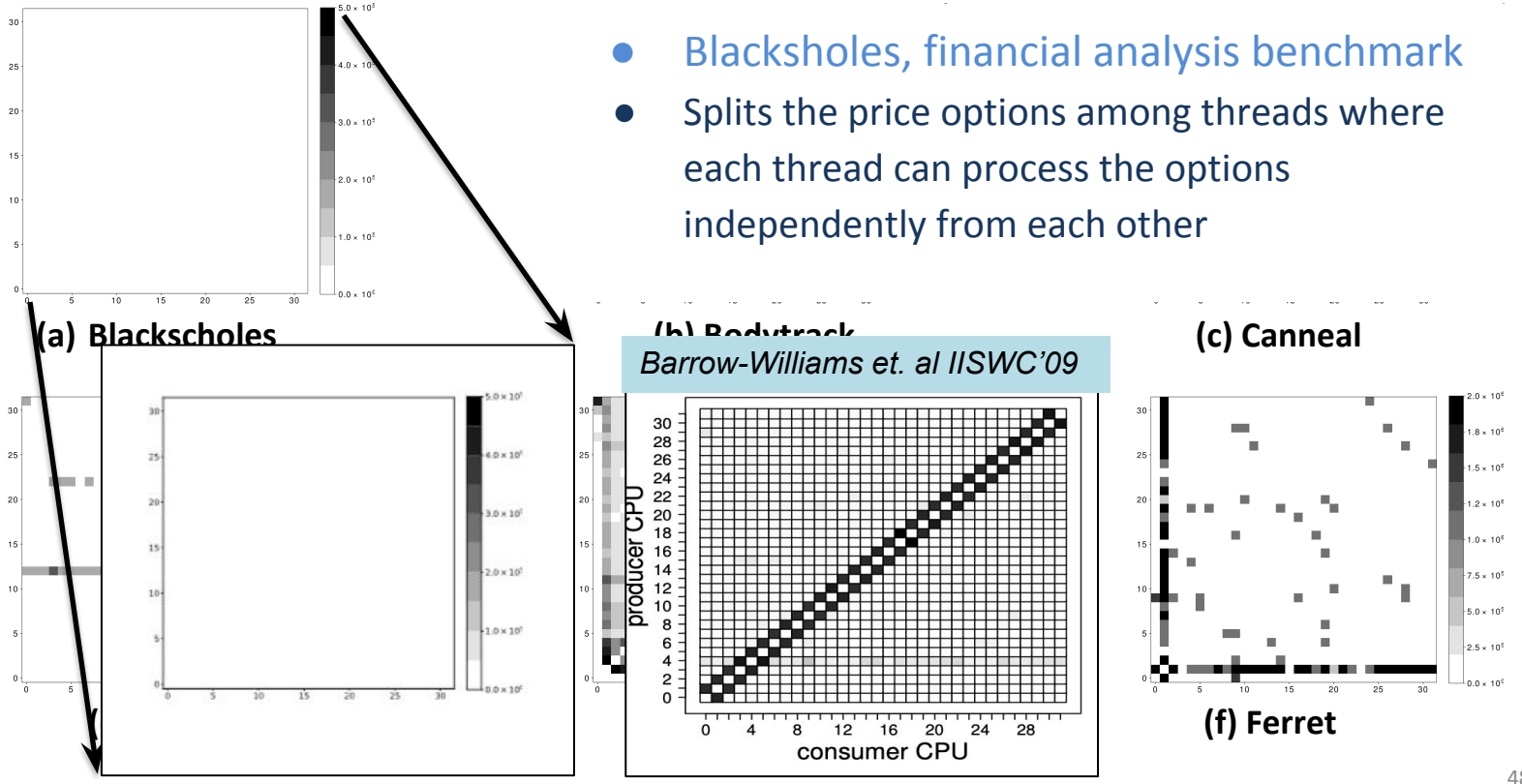


(e) Facesim



(f) Ferret

Snapshot of PARSEC Matrices (only 6 shown)



- Blacksholes, financial analysis benchmark
- Splits the price options among threads where each thread can process the options independently from each other

CORAL Benchmarks

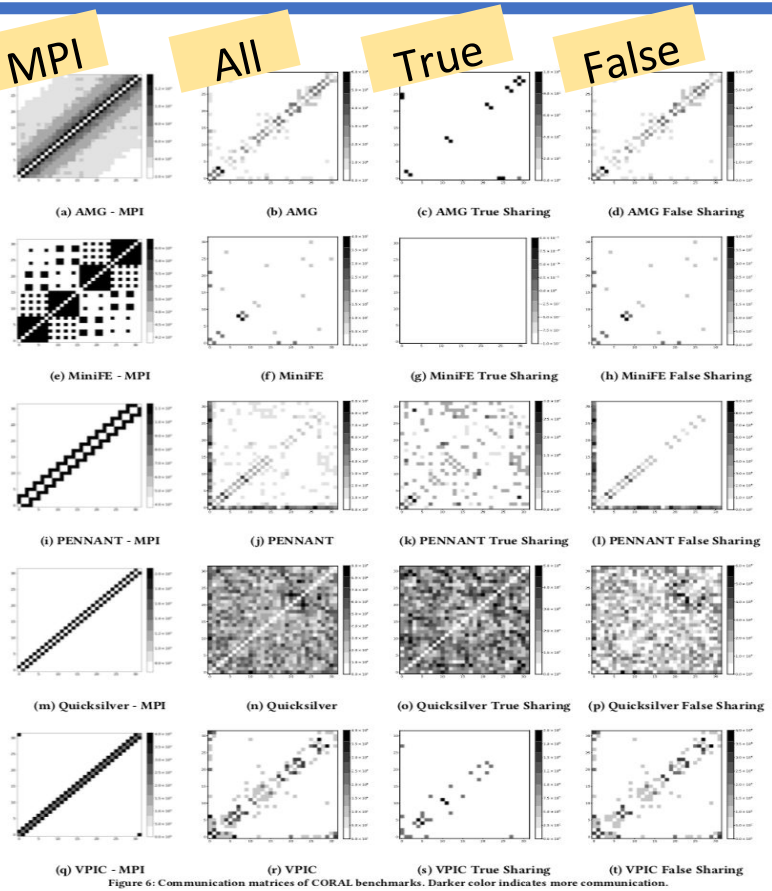


Figure 6: Communication matrices of CORAL benchmarks. Darker color indicates more communication.

AMG

MiniFE

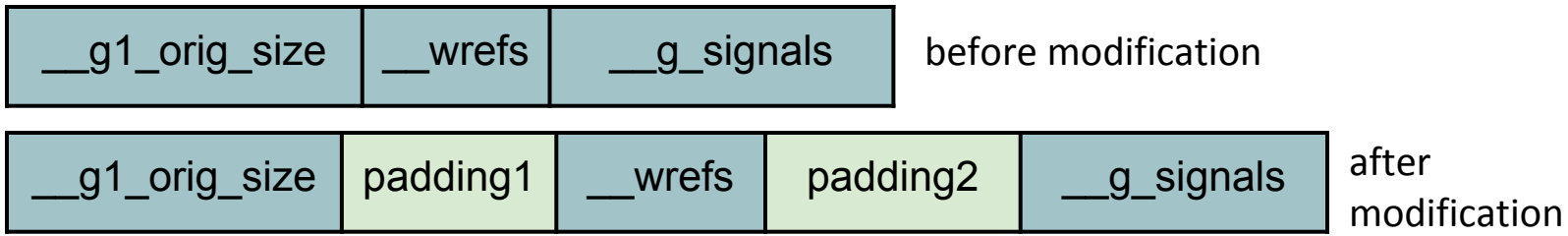
PENNANT

QuickSilver

VPIC

Use Cases: Code Refactoring

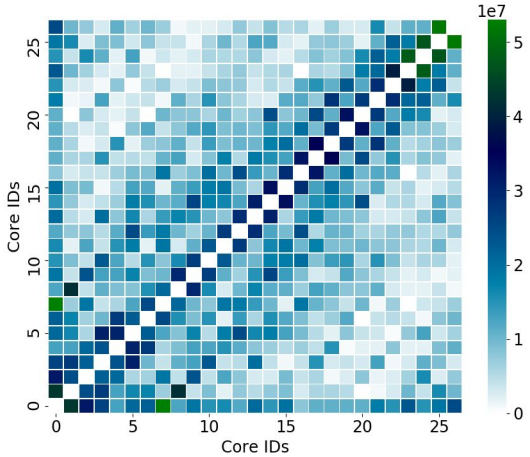
- **False sharing** in **streamcluster** happens on **pthread_mutex_t** typed variables
  - **6% improvement** is achieved after we put paddings among attributes in pthread_mutex_t struct
- **False sharing** in **fluidanimate** happens on a **pthread_cond_t** typed variable
  - **13% improvement** is achieved after we put paddings among attributes in pthread_cond_t struct



Summary

A practical tool for capturing inter-thread communication

- Low overhead: 1.27x runtime and 1.3x memory
- High accuracy
- Ability to quantify communication
- Ability to distinguish true vs. false sharing
- Attribute communication to program objects

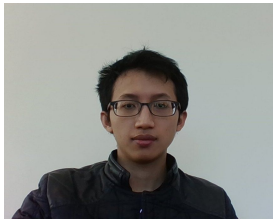


[Available for download: https://github.com/comdetective-tools]

ParCoreLab@ Koç

http://parcorelab.com

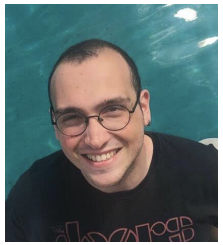
Optimization of Sparse Solvers



Detecting thread communication

Quantum computing

Accelerated Deep Learning



GPU Communication Optimization

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[3] Matthias Diener, et al. 2016. Communication in Shared Memory: Concepts, Definitions, and Efficient Detection. In 2016 24th Euromicro International Conference on Parallel, Distributed, and Network-Based Processing.

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[8] Matthias Diener, et al. 2016. Communication in Shared Memory: Concepts, Definitions, and Efficient Detection. In 2016 24th Euromicro International Conference on Parallel, Distributed, and Network-Based Processing.

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