On-Demand Dynamic Software Analysis

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Software Errors Abound

- NIST: SW errors cost U.S. ~$60 billion/year as of 2002
- FBI CCS: Security Issues $67 billion/year as of 2005
  - >⅓ from viruses, network intrusion, etc.

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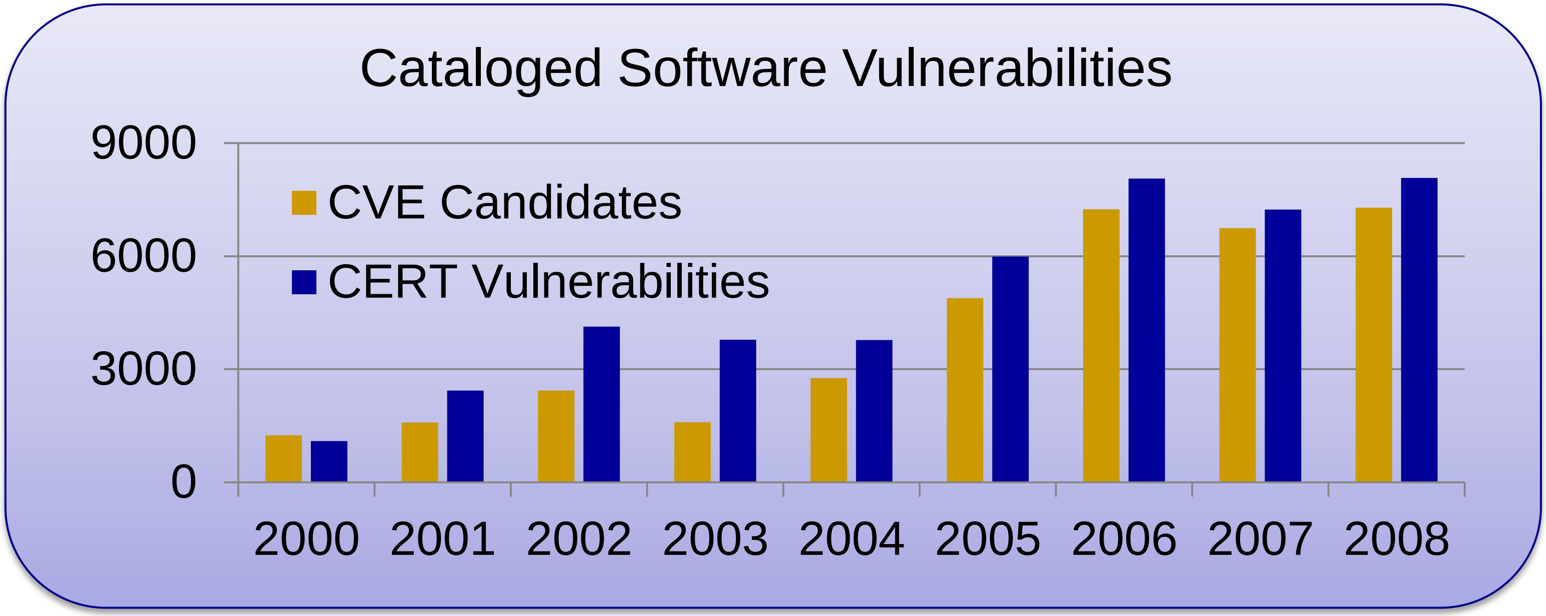

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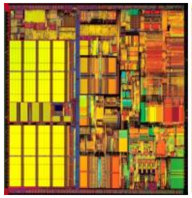
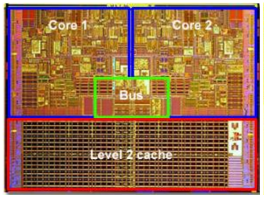
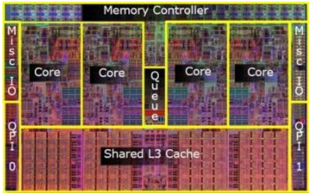
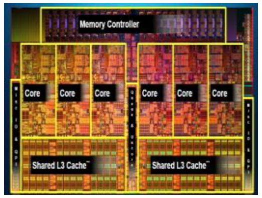
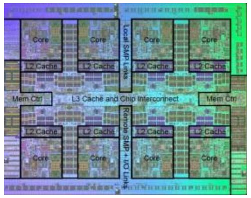
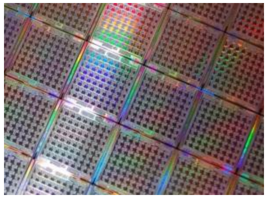
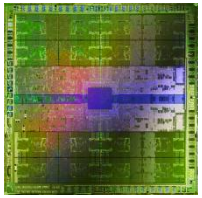
Hardware Plays a Role





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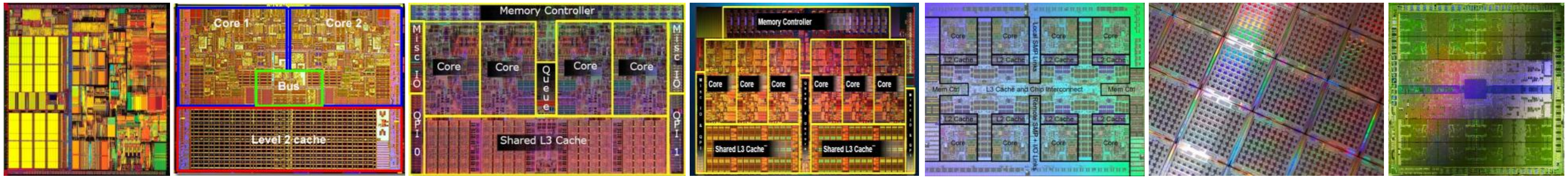


In spite of proposed solutions

Hardware Data Race Recording

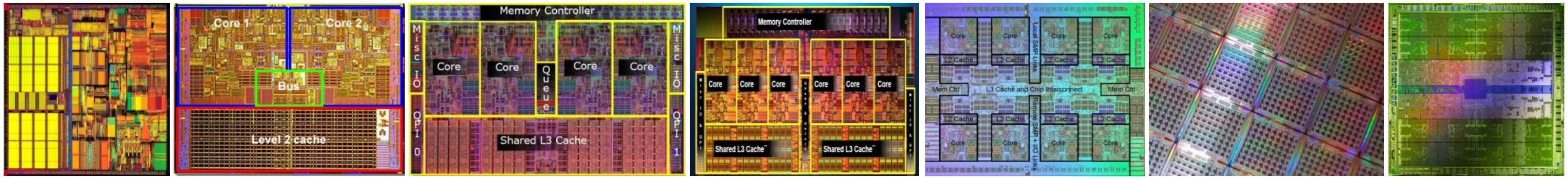
Bulk Memory Commits

Deterministic Execution/Replay

Bug-Free Memory Models

Atomicity Violation Detectors

Hardware Plays a Role



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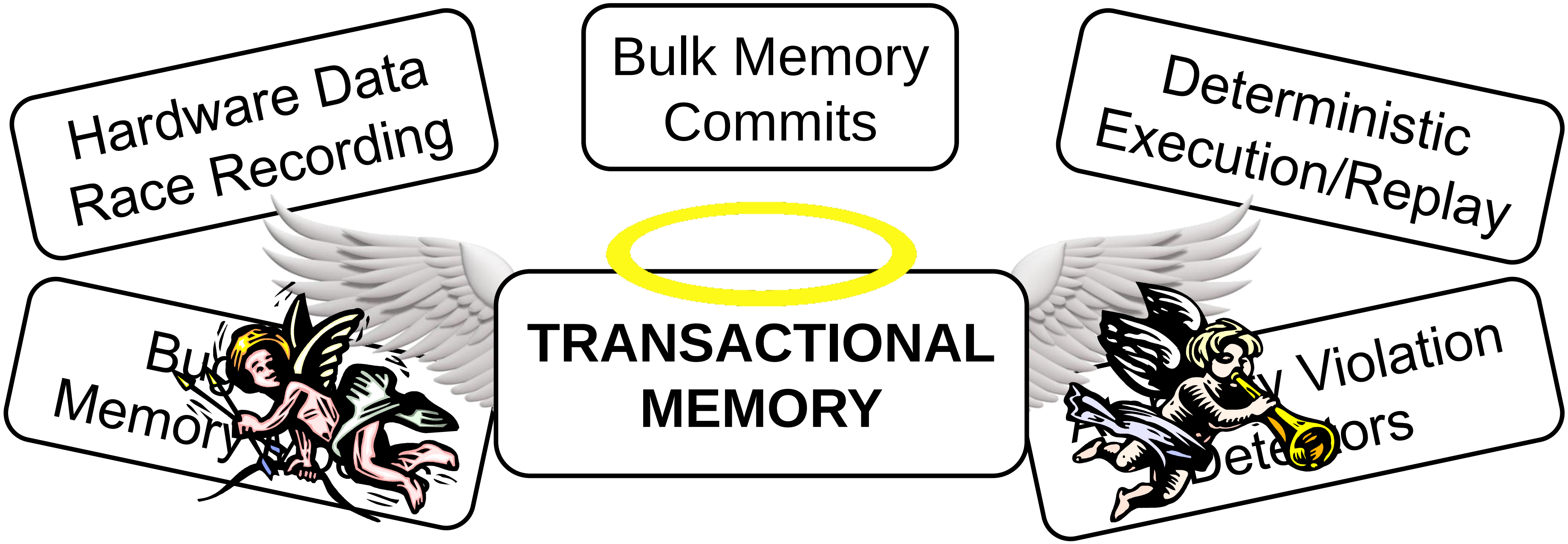

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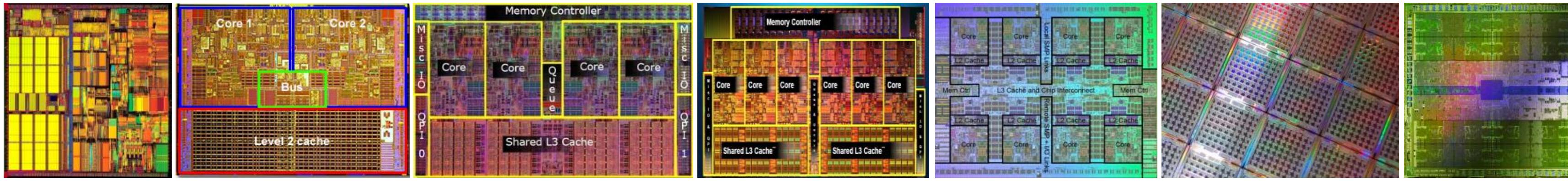

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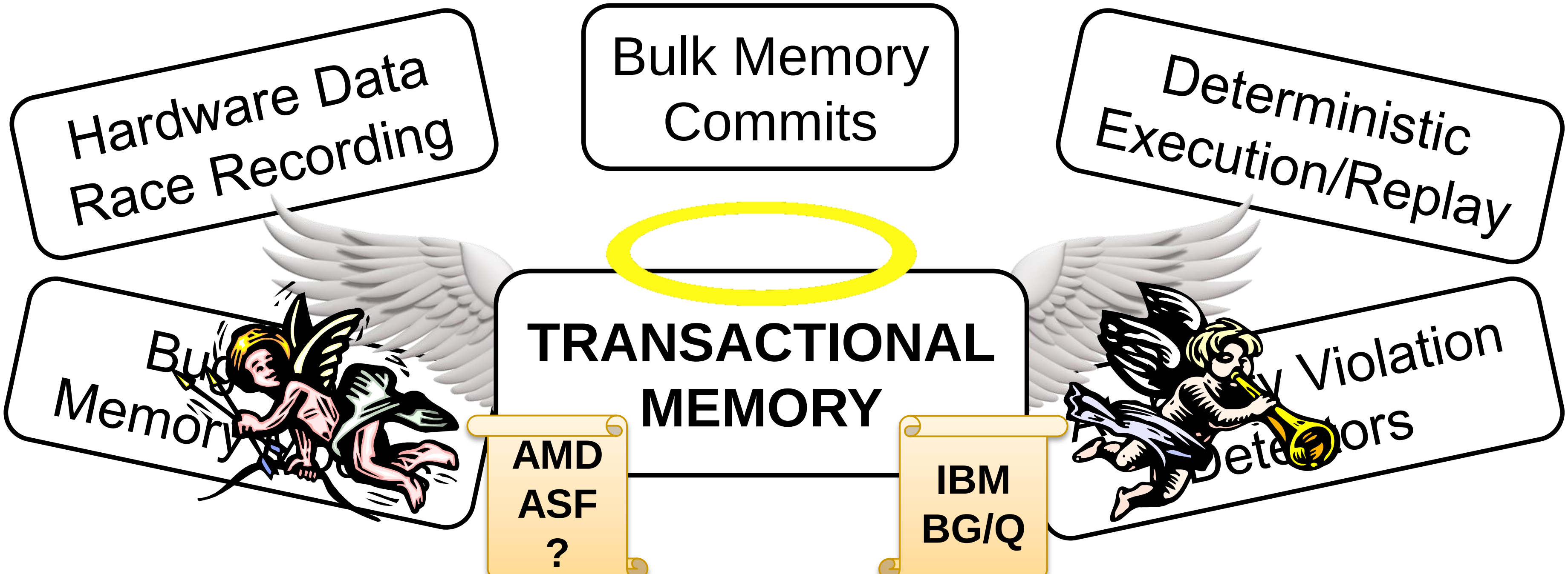
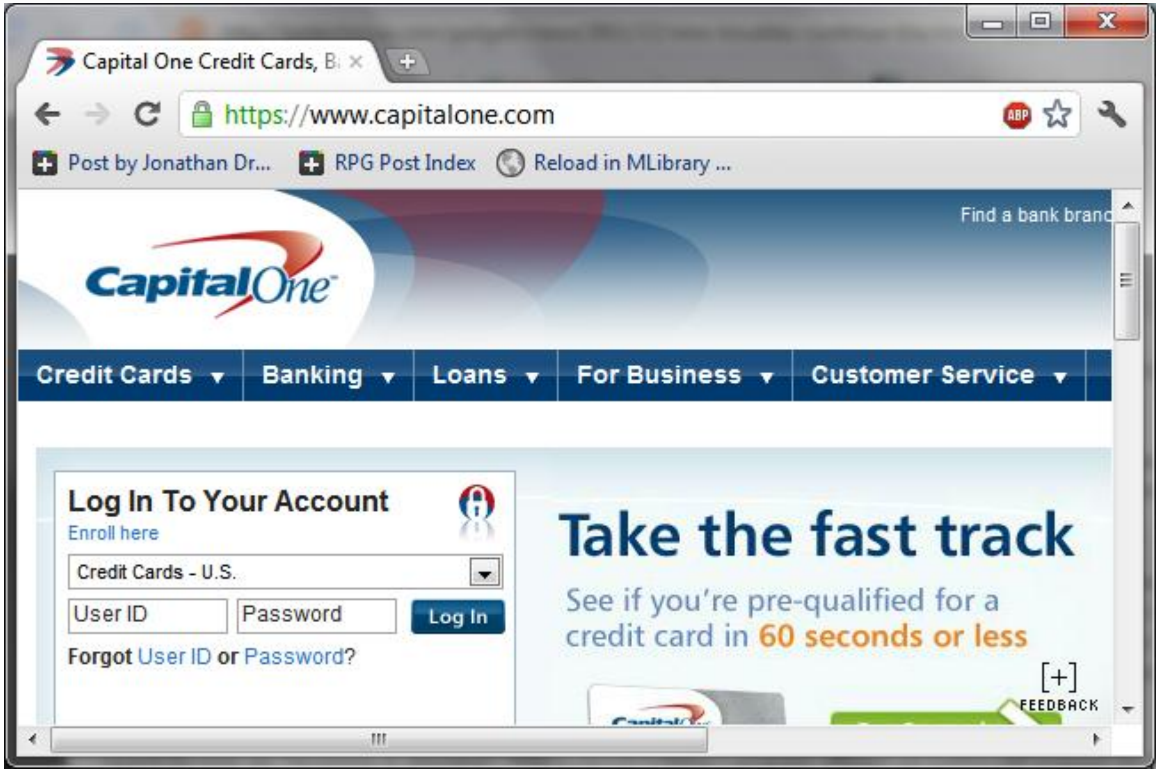


Example of a Modern Bug

Nov. 2010 OpenSSL Security Flaw

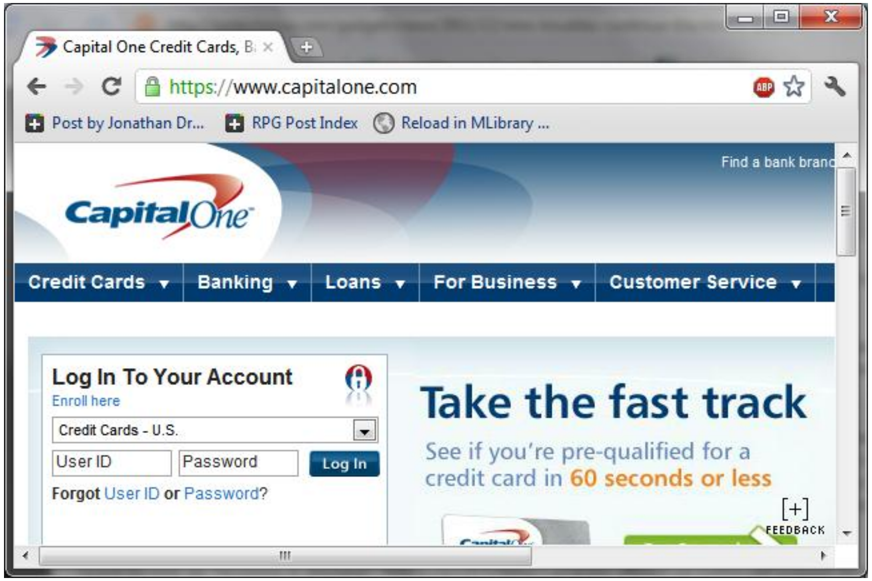


Example of a Modern Bug

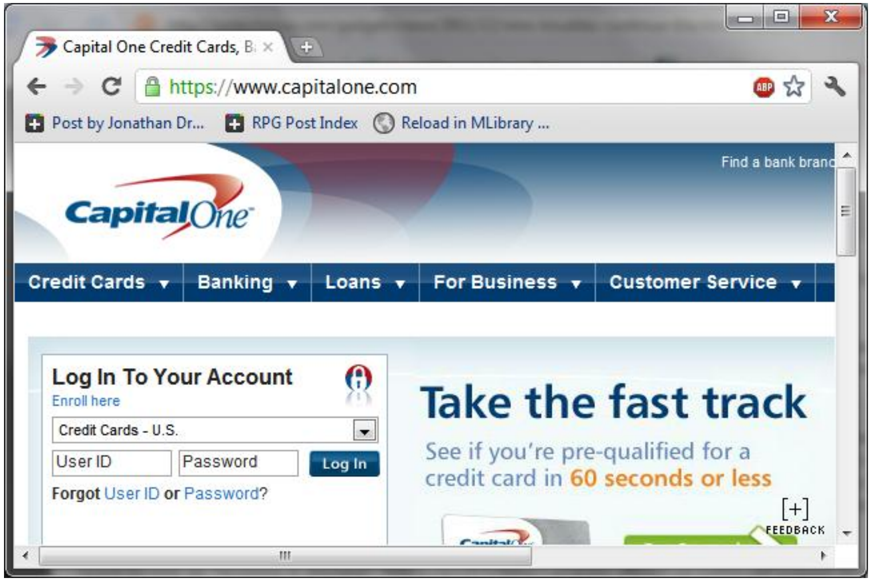
```
if(ptr == NULL) {
   len=thread_local->mylen;
   ptr=malloc(len);
   memcpy(ptr, data, len);
}
```

Example of a Modern Bug

Thread 1
mylen=small



Thread 2
mylen=large



`ptr`

∅

Example of a Modern Bug

TIME	Thread 1 mylen=small	Thread 2 mylen=large
	if(ptr==NULL)	
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		len2=thread_local->mylen;
		ptr=malloc(len2);
	len1=thread_local->mylen;	
	ptr=malloc(len1);	
	memcpy(ptr, data1, len1)	
		memcpy(ptr, data2, len2)

```
ptr
∅
```

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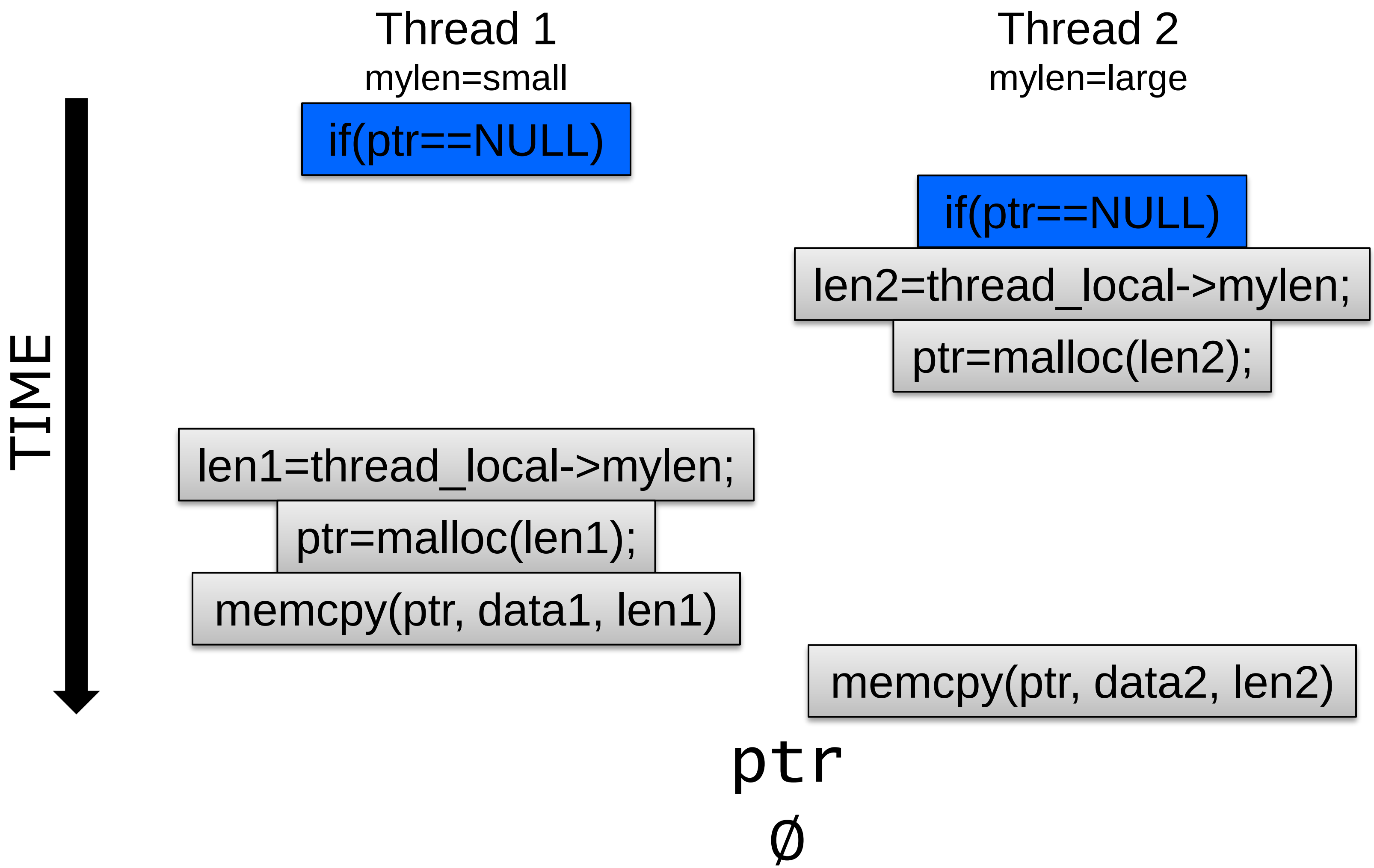

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ptr

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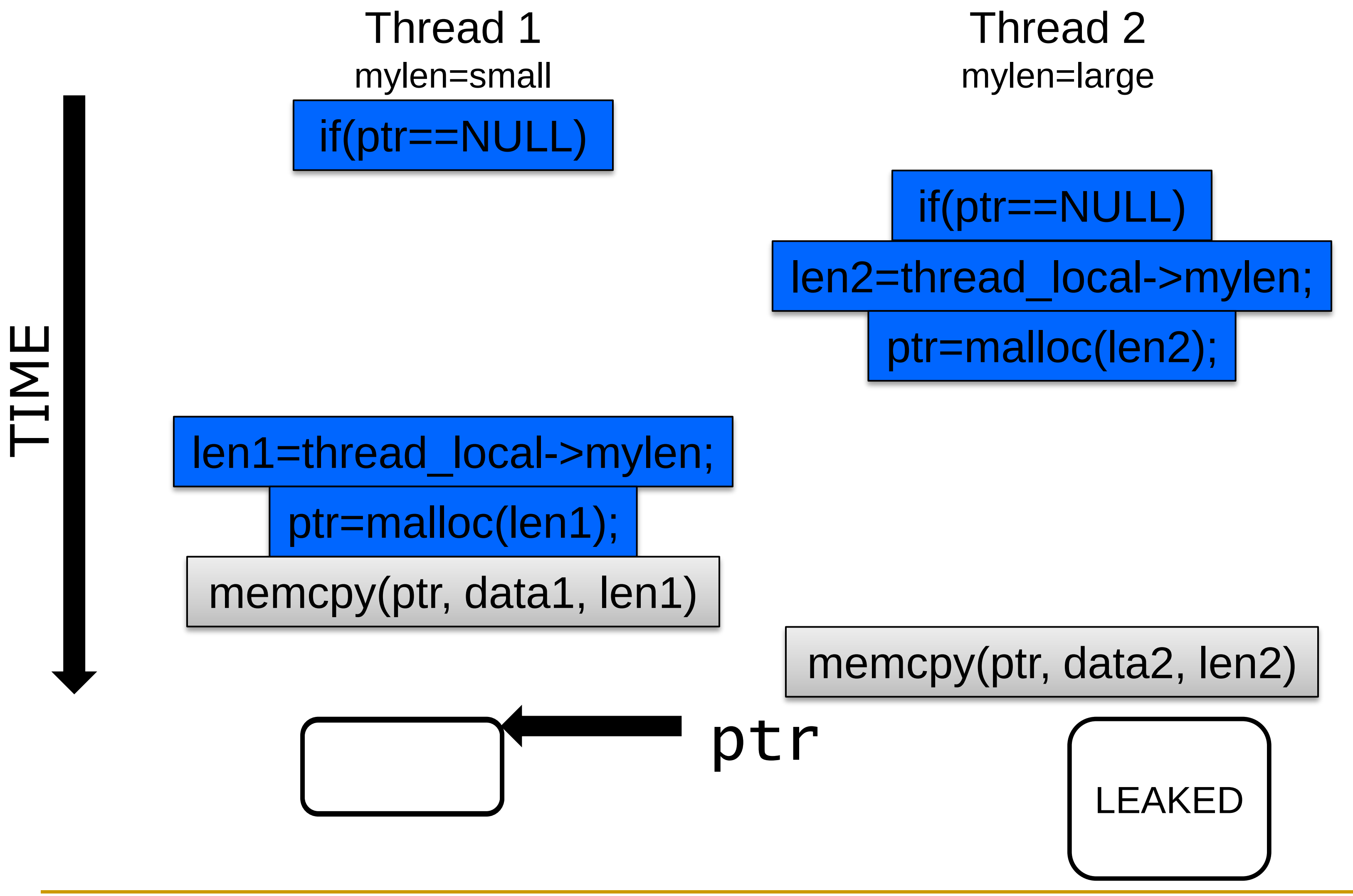

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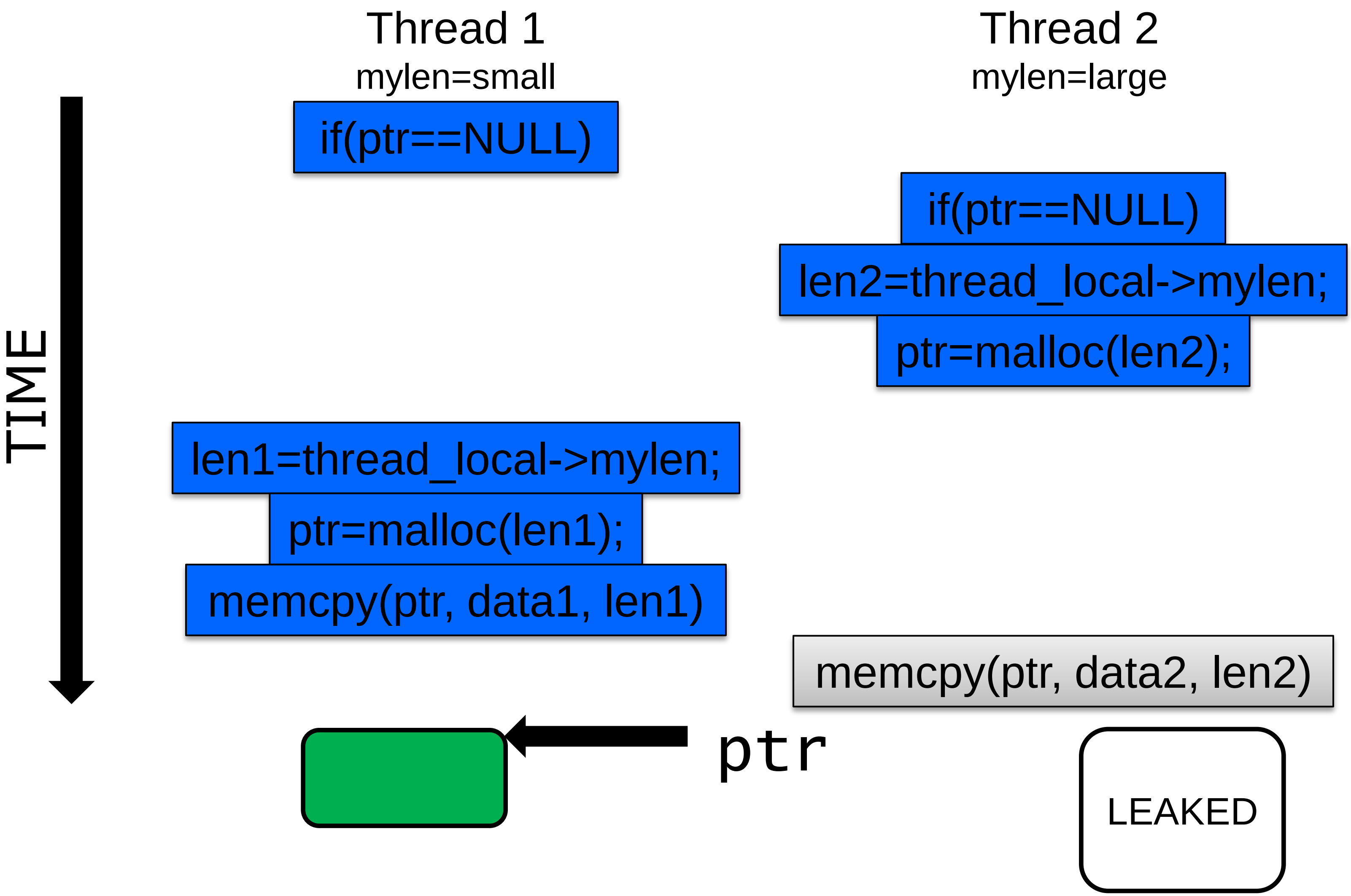

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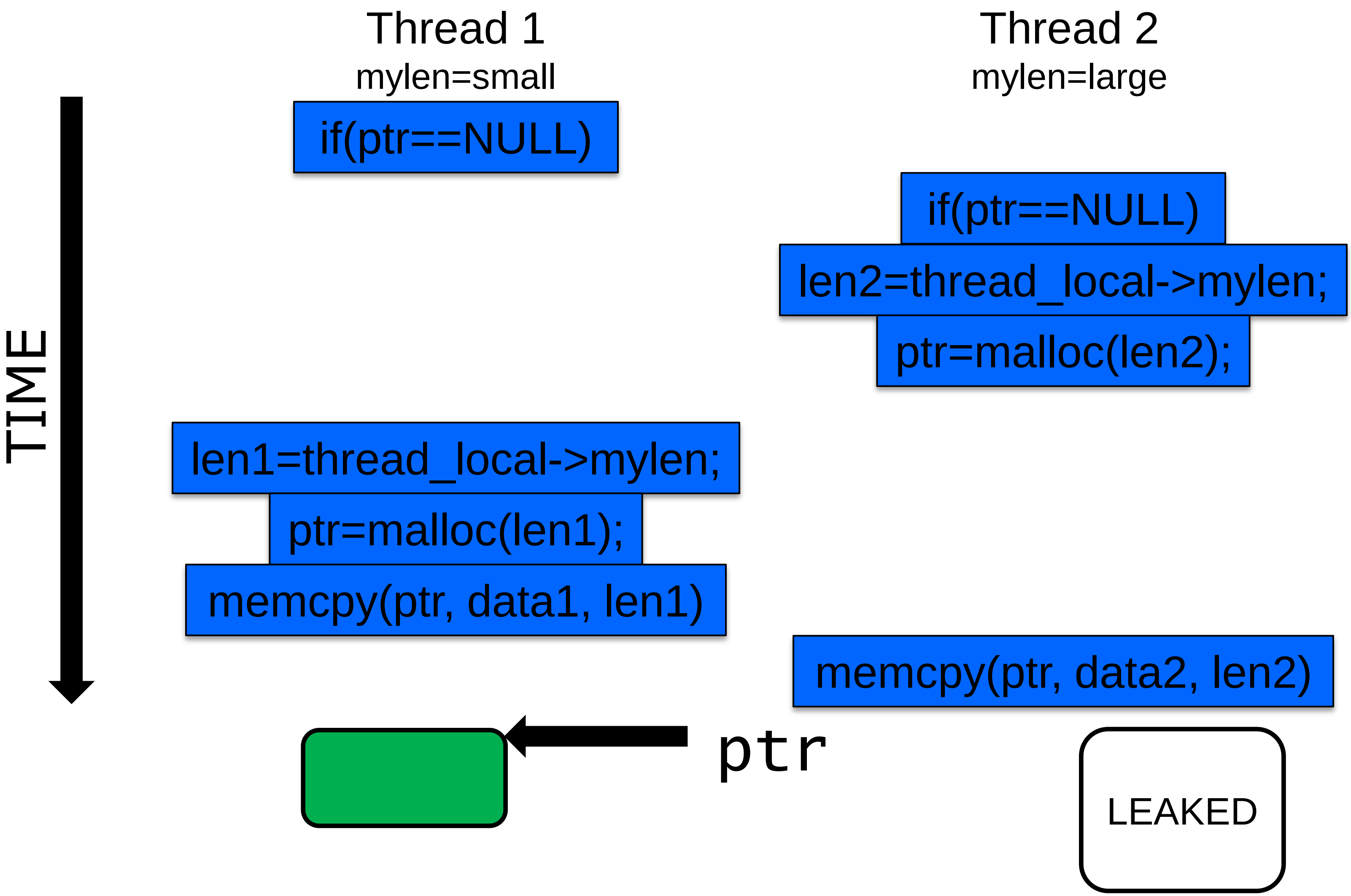

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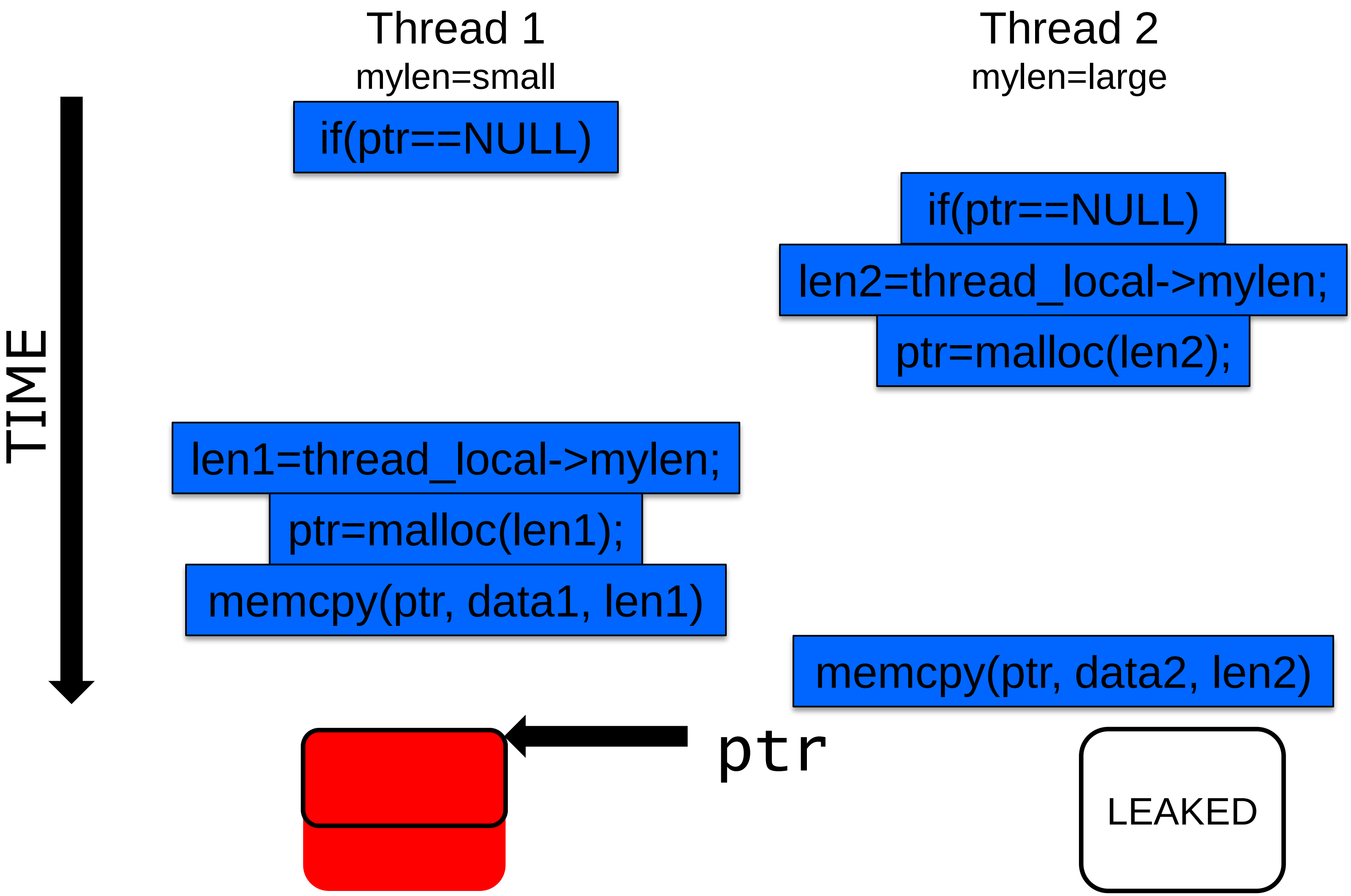
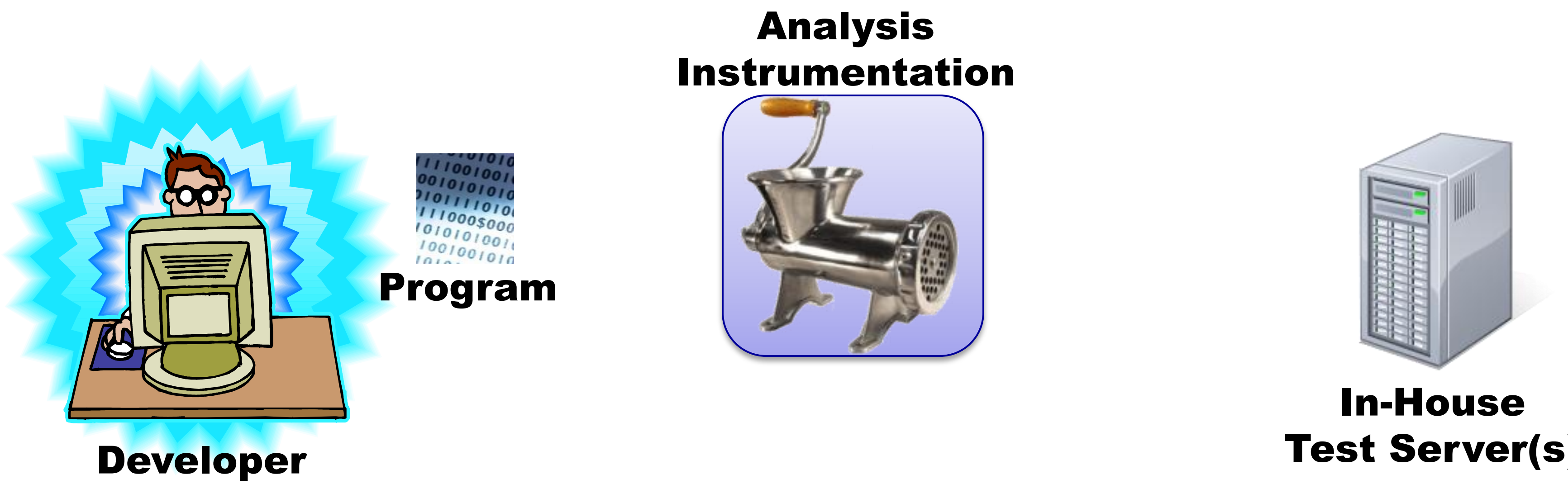


Dynamic Software Analysis

- Analyze the program as it runs
  - \+ System state, find errors on any executed path
  - – LARGE runtime overheads, only test one path



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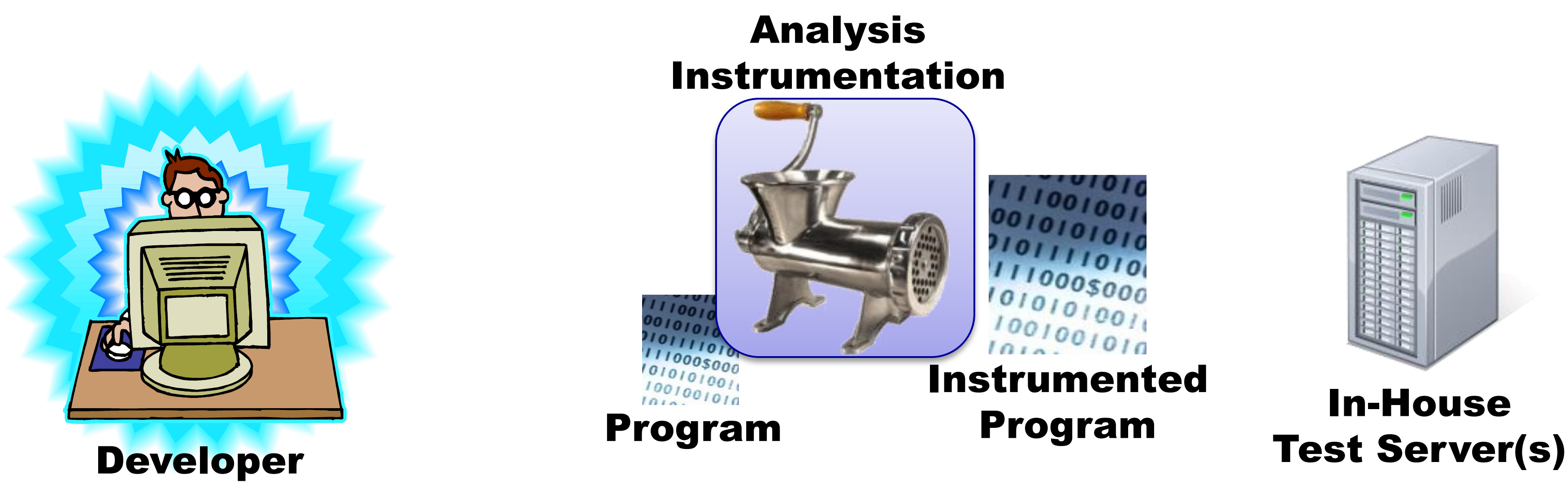

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Developer

Analysis Instrumentation

LONG run time

In-House Test Server(s)

Dynamic Software Analysis

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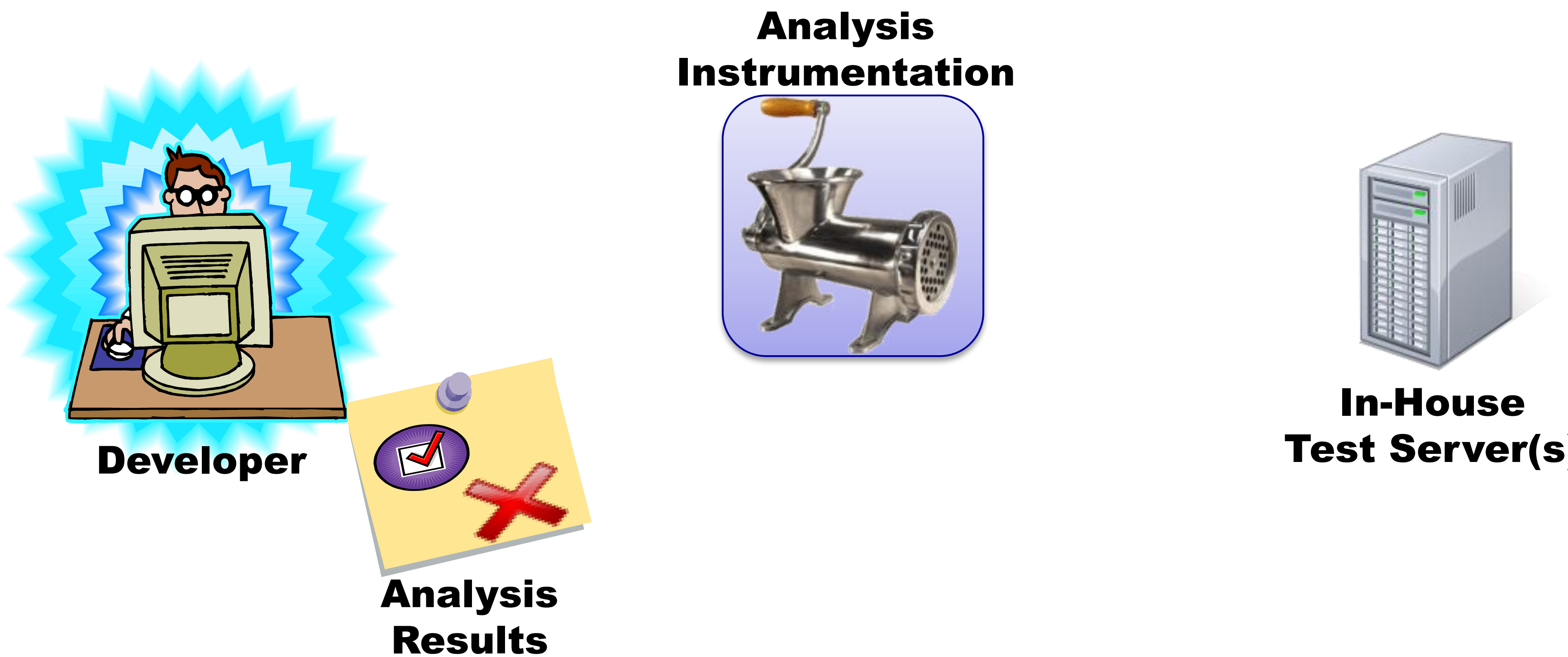


Runtime Overheads: How Large?

- Data Race Detection
  (e.g. Inspector XE)

  2-300x

- Taint Analysis
  (e.g.TaintCheck)

  2-200x

- Memory Checking
  (e.g. MemCheck)

  5-50x

- Dynamic Bounds Checking

  10-80x

- Symbolic Execution

  10-200x

Could use Hardware

- Data Race Detection: HARD, CORD, etc.
- Taint Analysis: Raksha, FlexiTaint, etc.
- Bounds Checking: HardBound

– None Currently Exist; Bugs Are Here Now
– Single-Use Specialization
  – Won't be built due to HW, power, verification costs
  – Unchangeable algorithms locked in HW

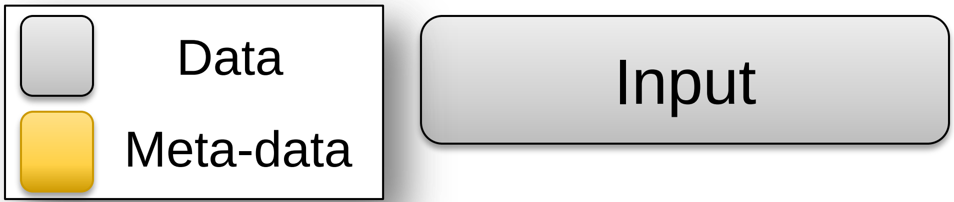
Goals of this Talk

- Accelerate SW Analyses Using Existing HW
- Run Tests **On Demand**: Only When Needed
- Explore Future **Generic HW Additions**

Outline

- Problem Statement
- Background Information
  - Demand-Driven Dynamic Dataflow Analysis
- Proposed Solutions
  - Demand-Driven Data Race Detection
  - Unlimited Hardware Watchpoints

Example Dynamic Dataflow Analysis



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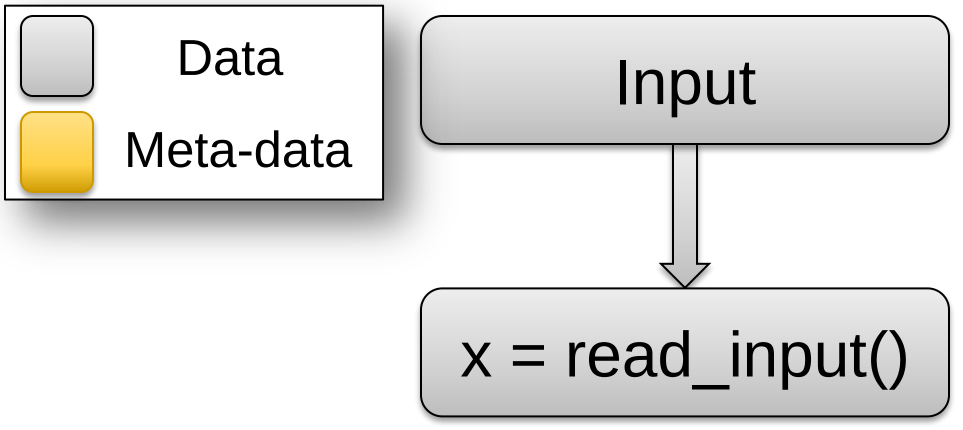

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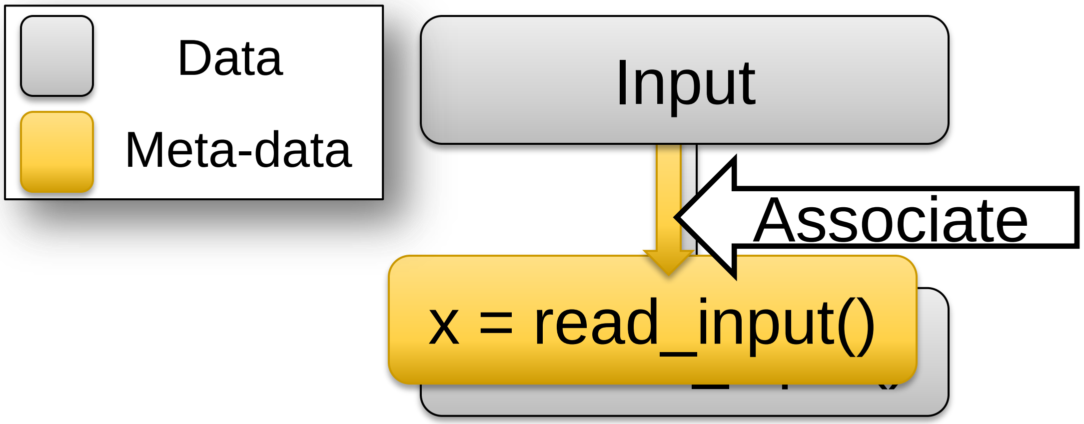

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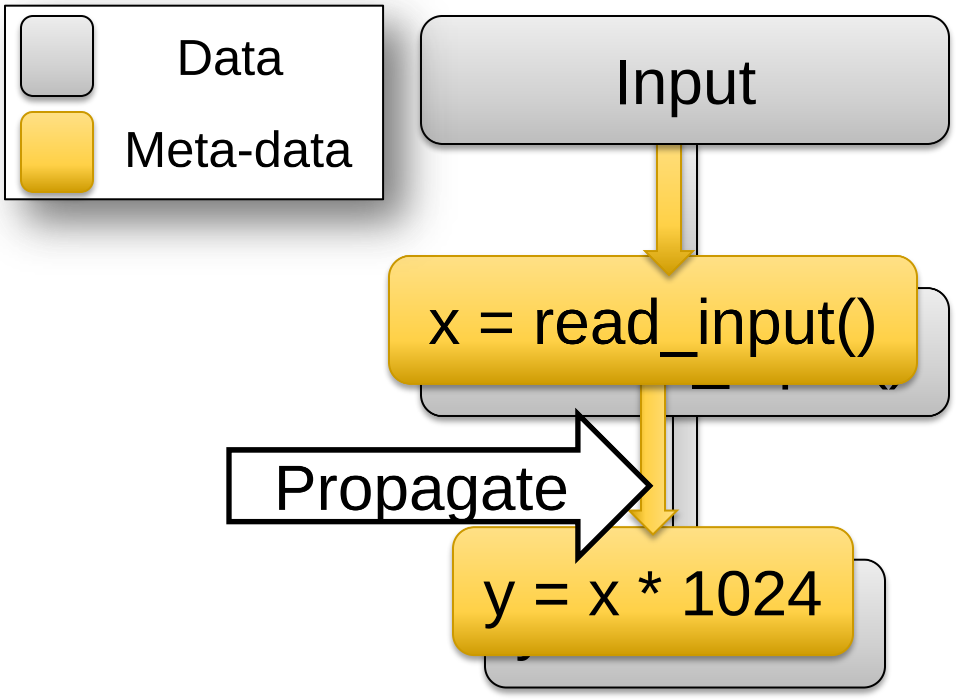

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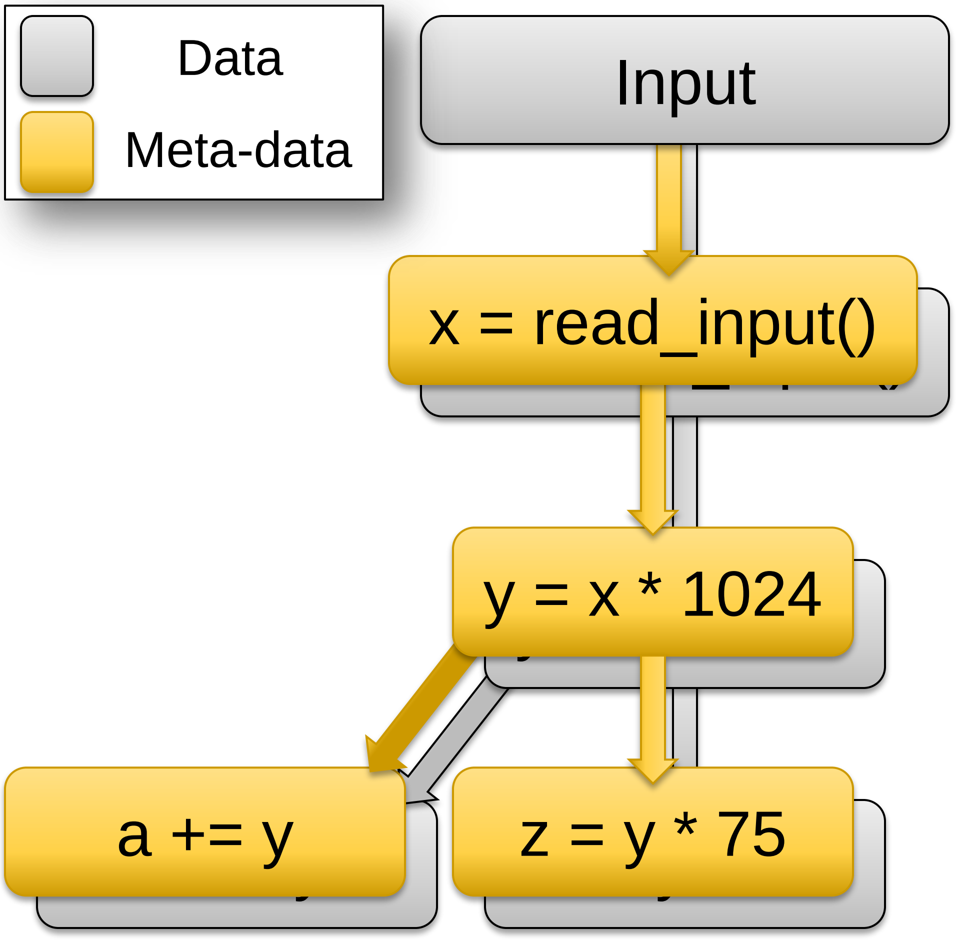

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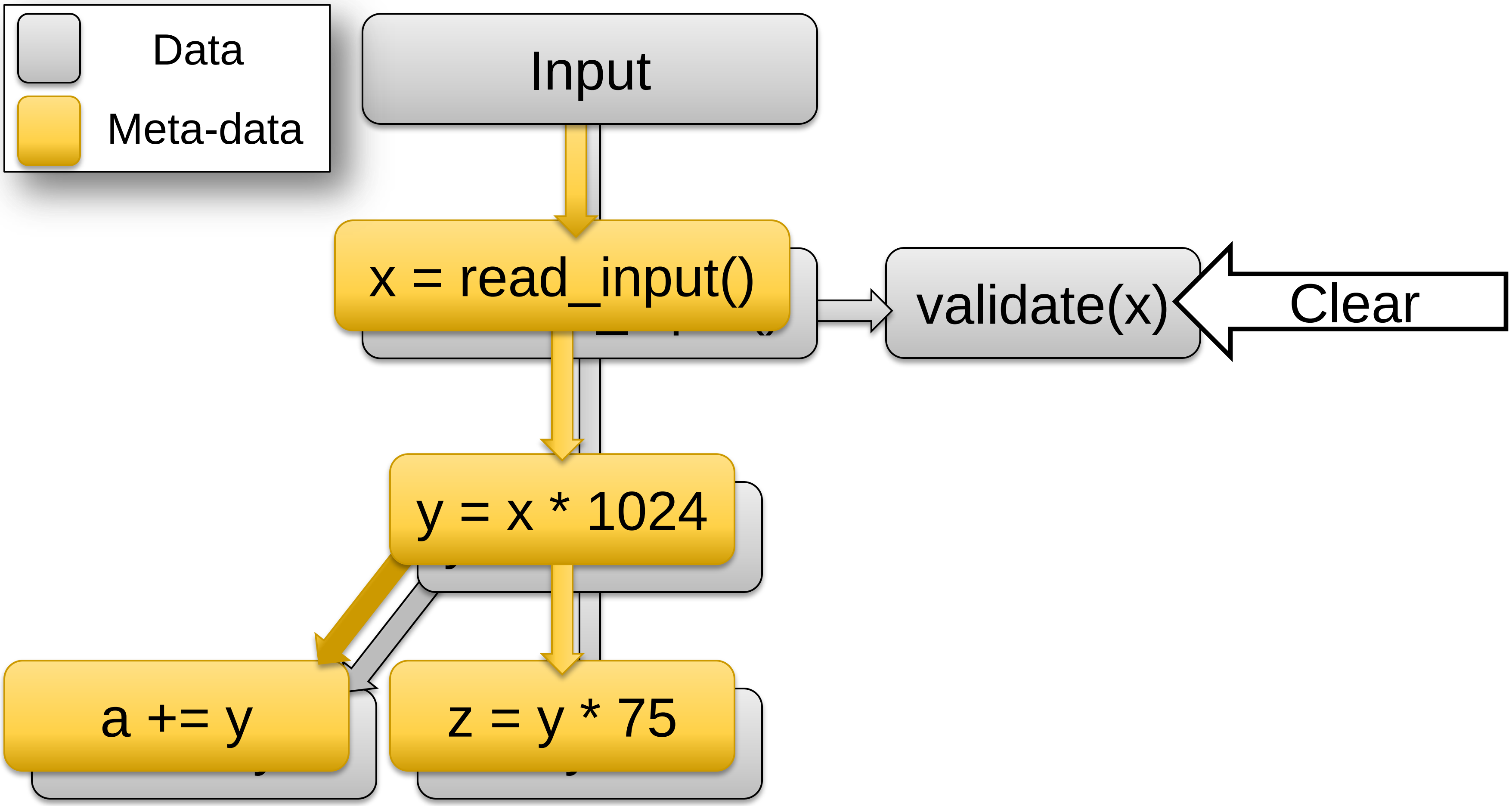

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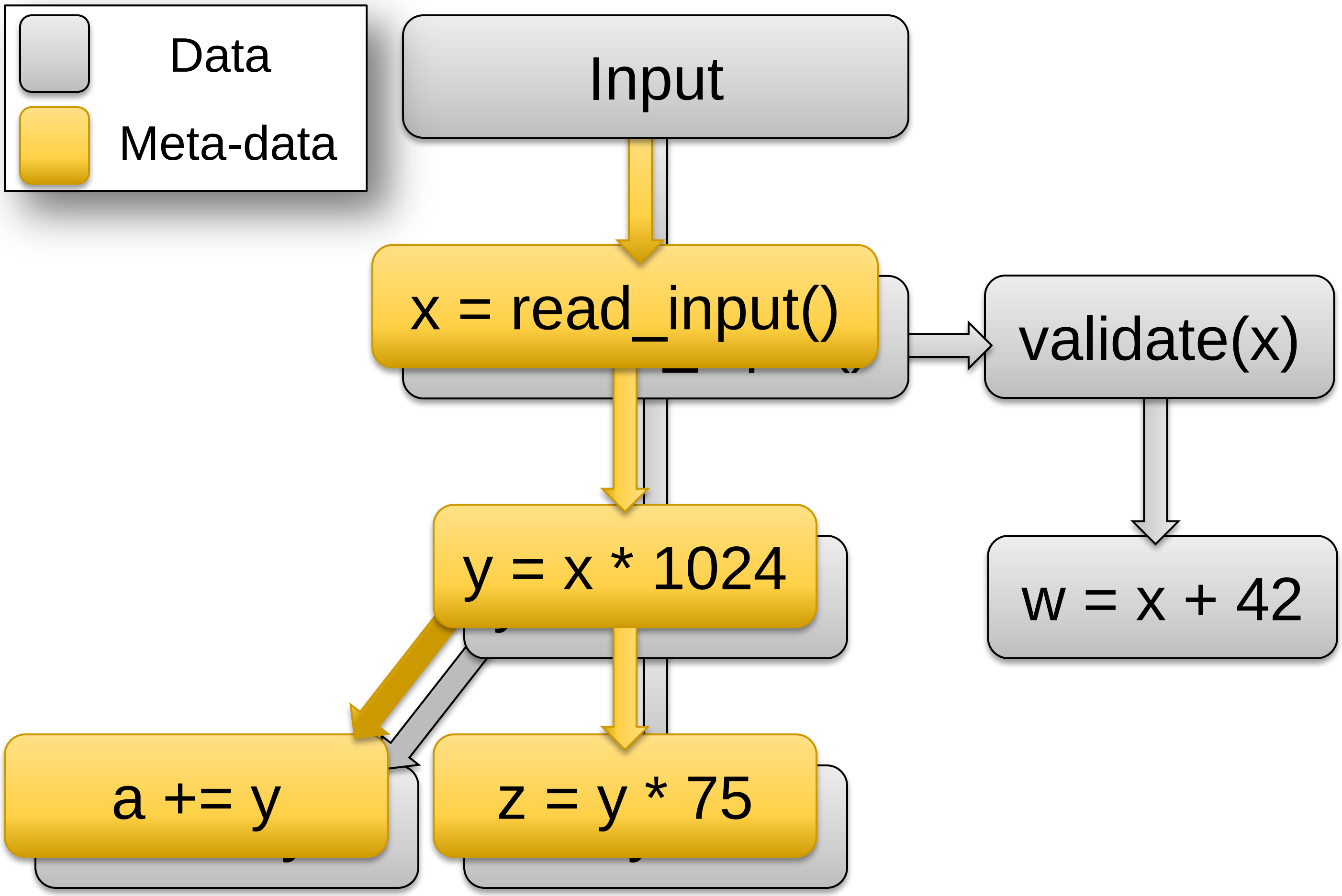

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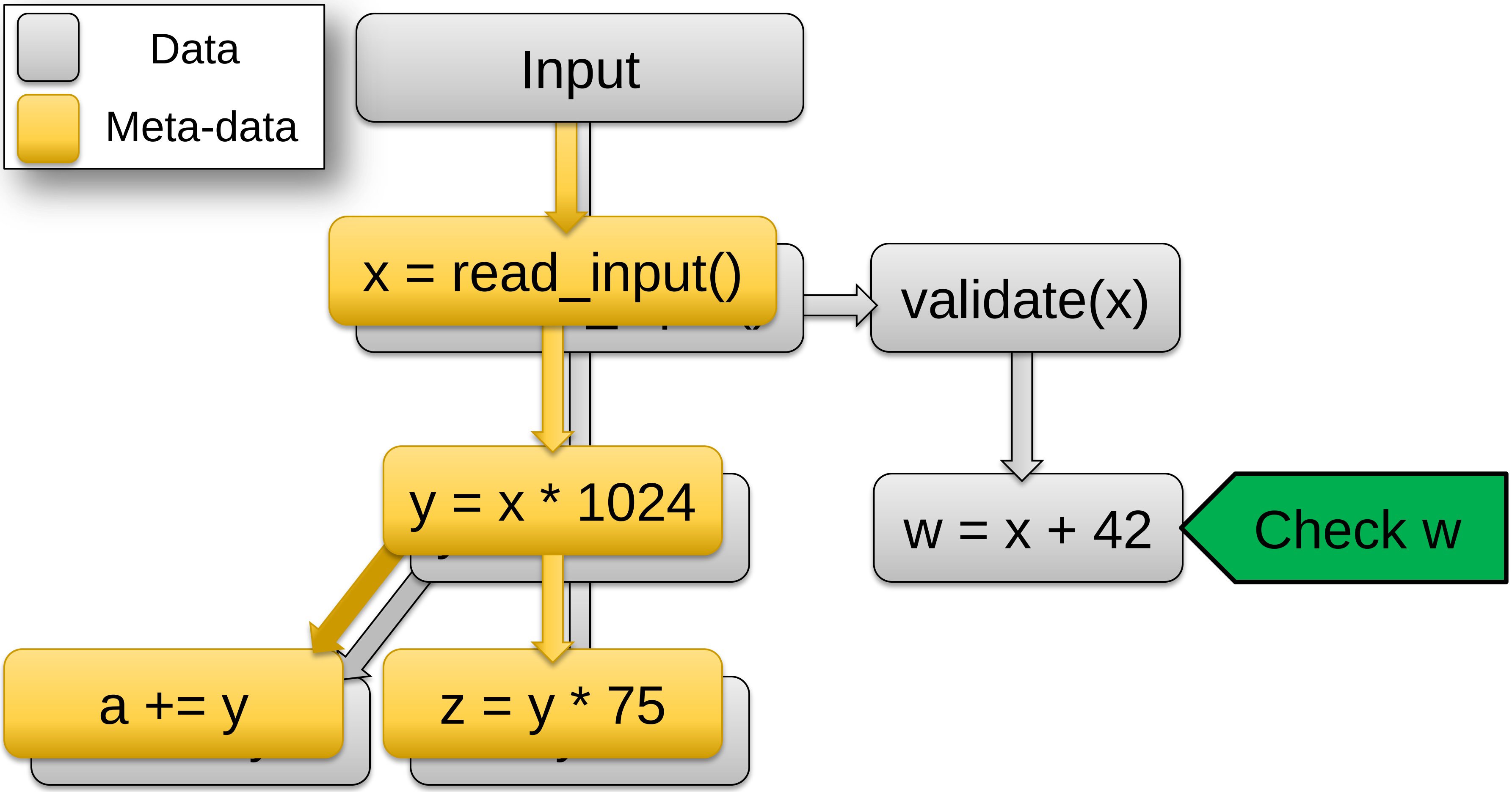

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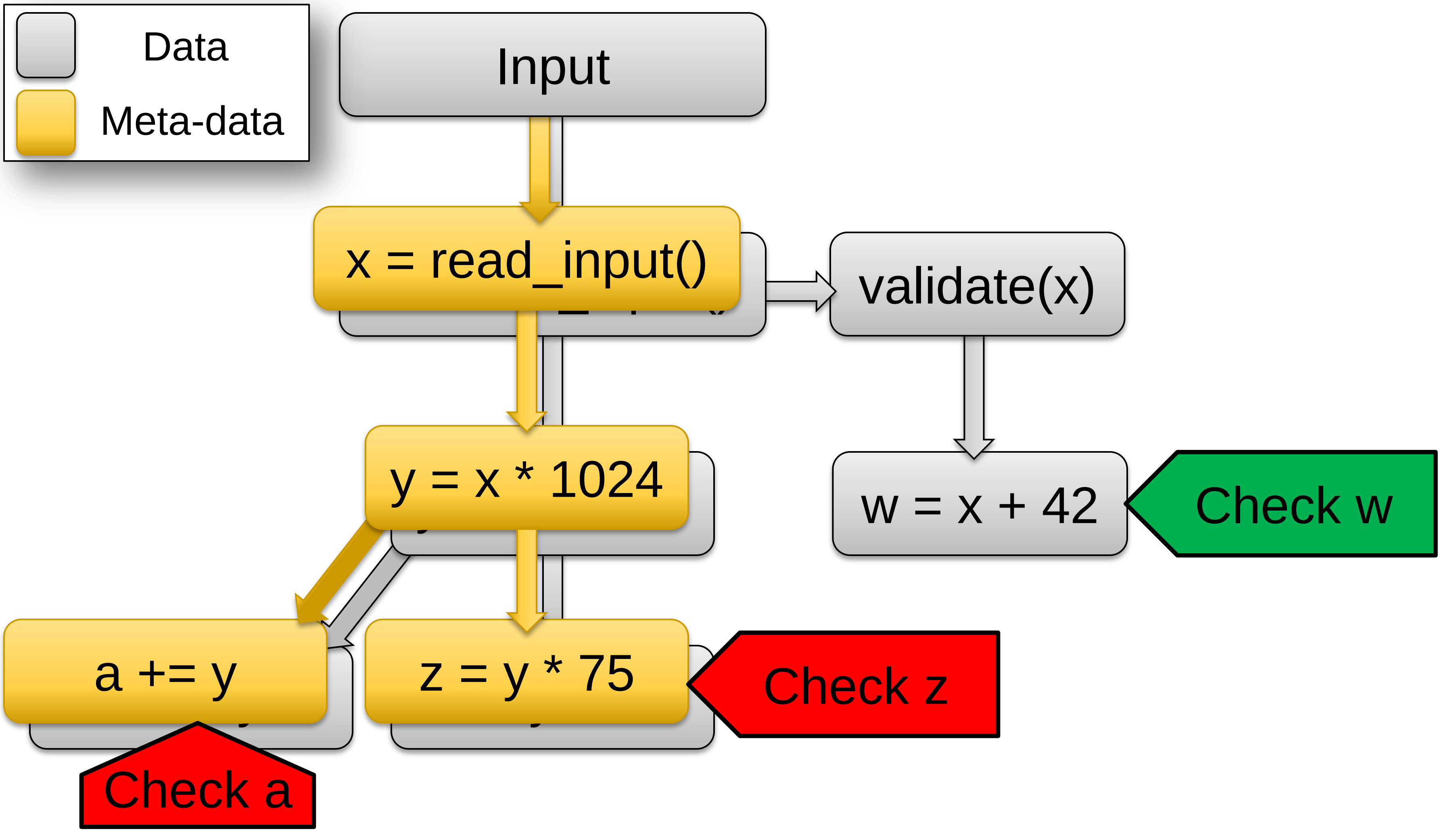
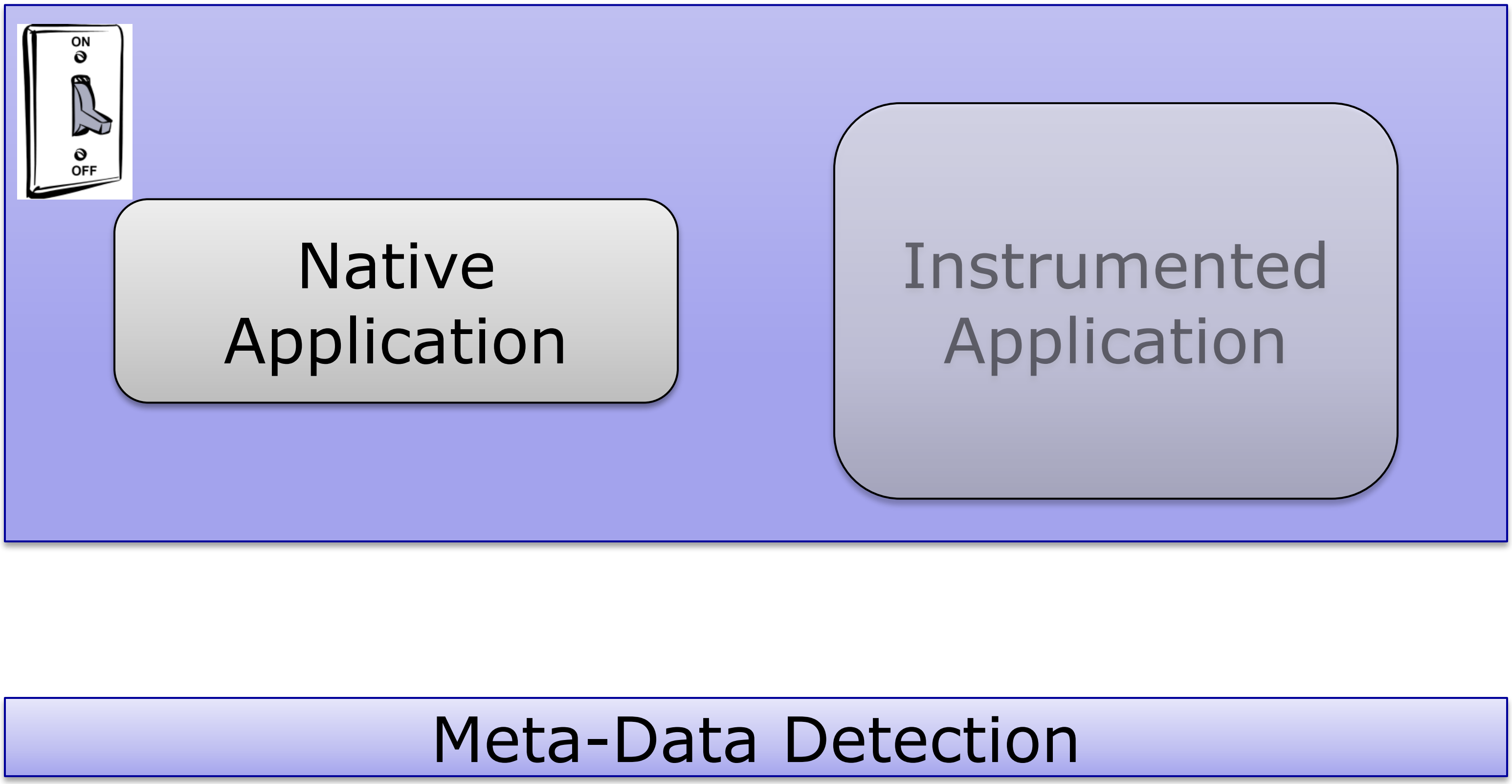


Demand-Driven Dataflow Analysis

- Only Analyze Shadowed Data



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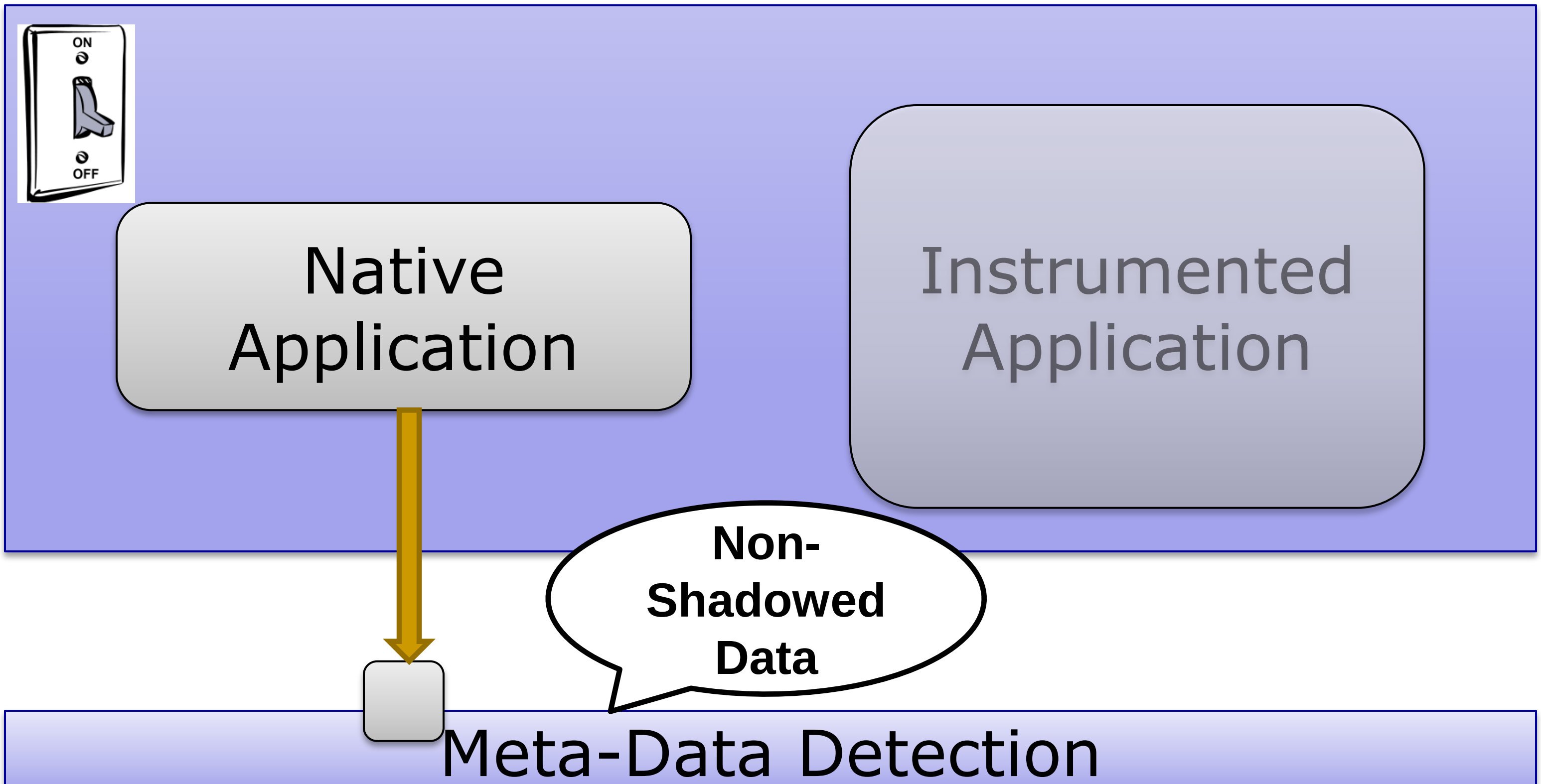

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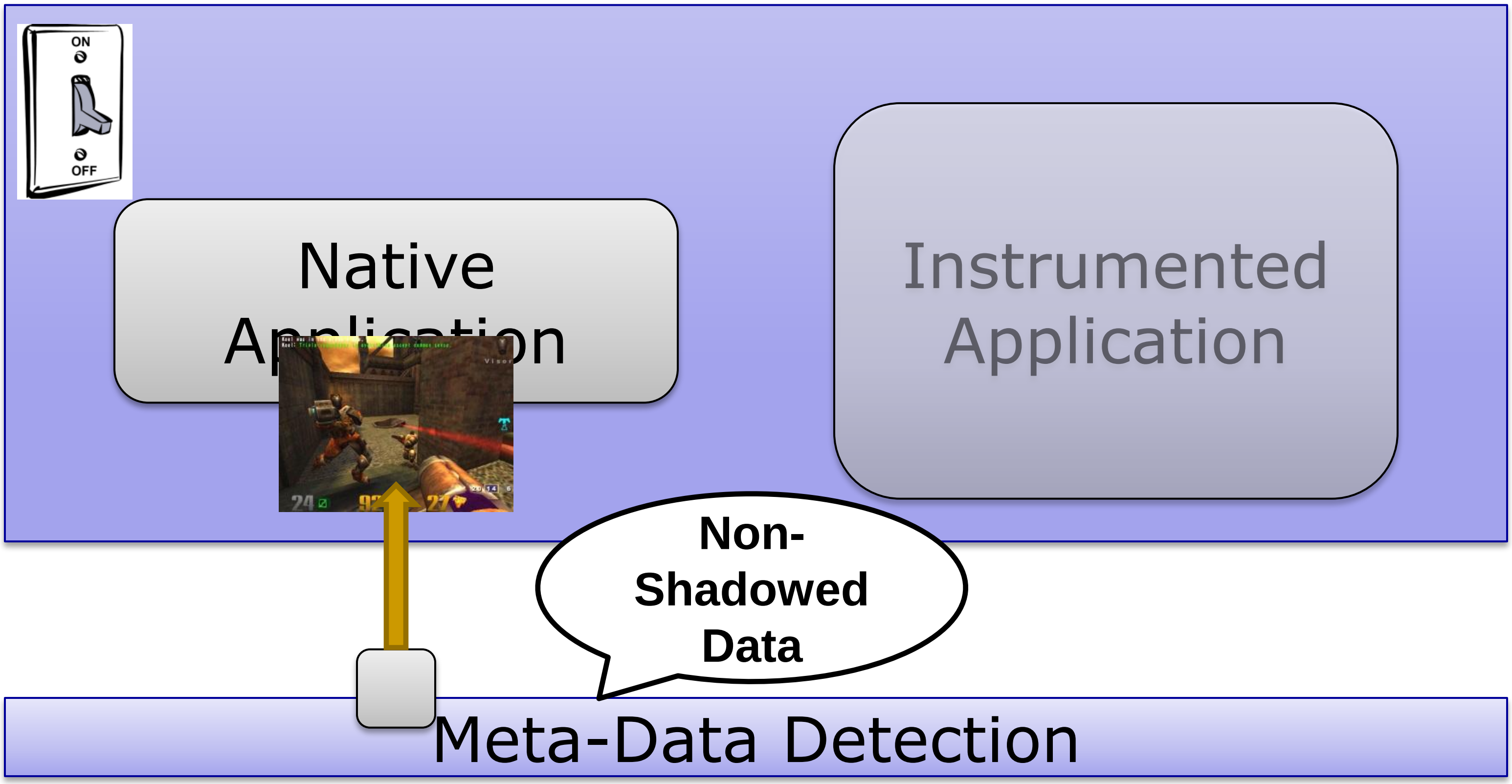

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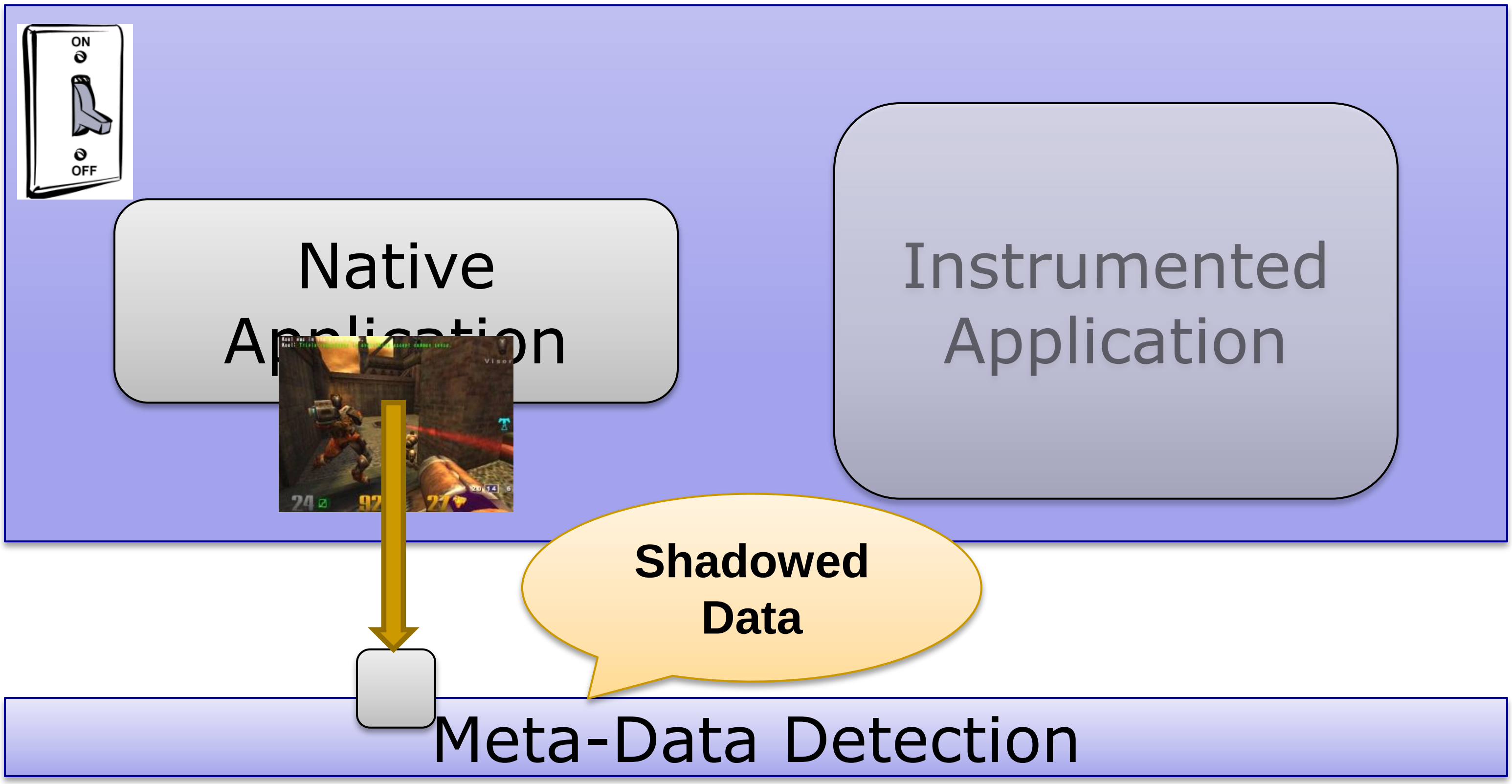

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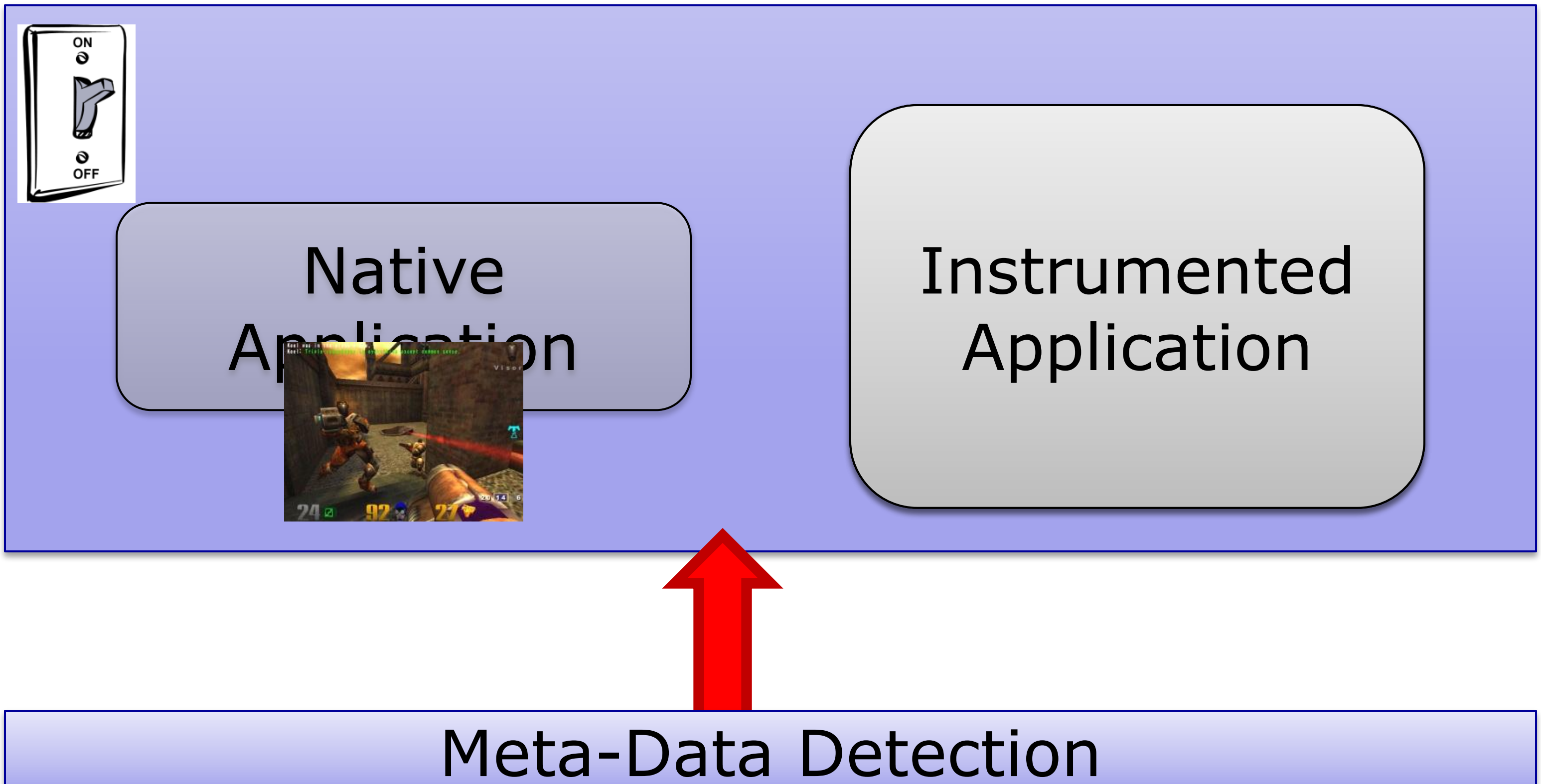

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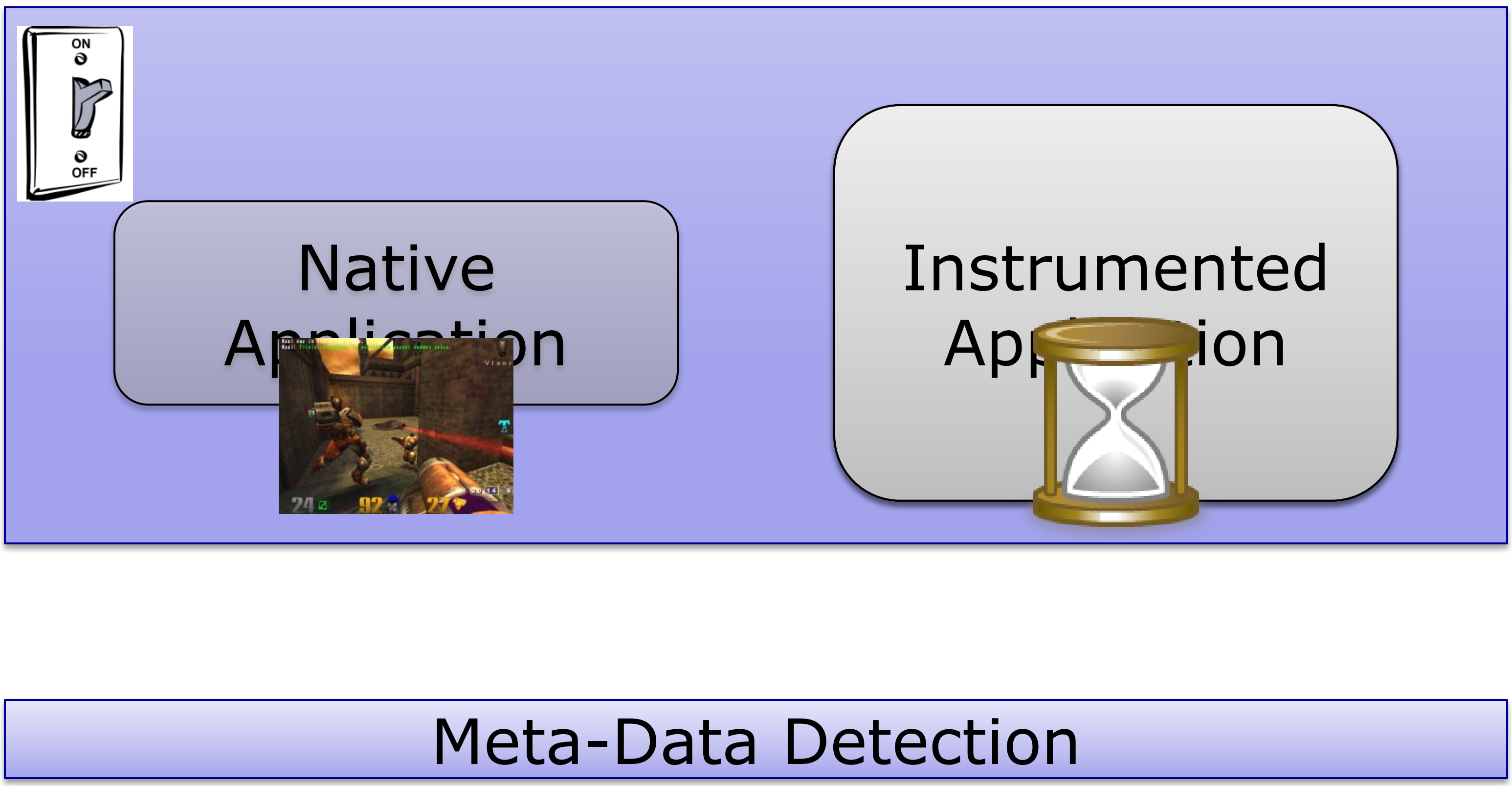

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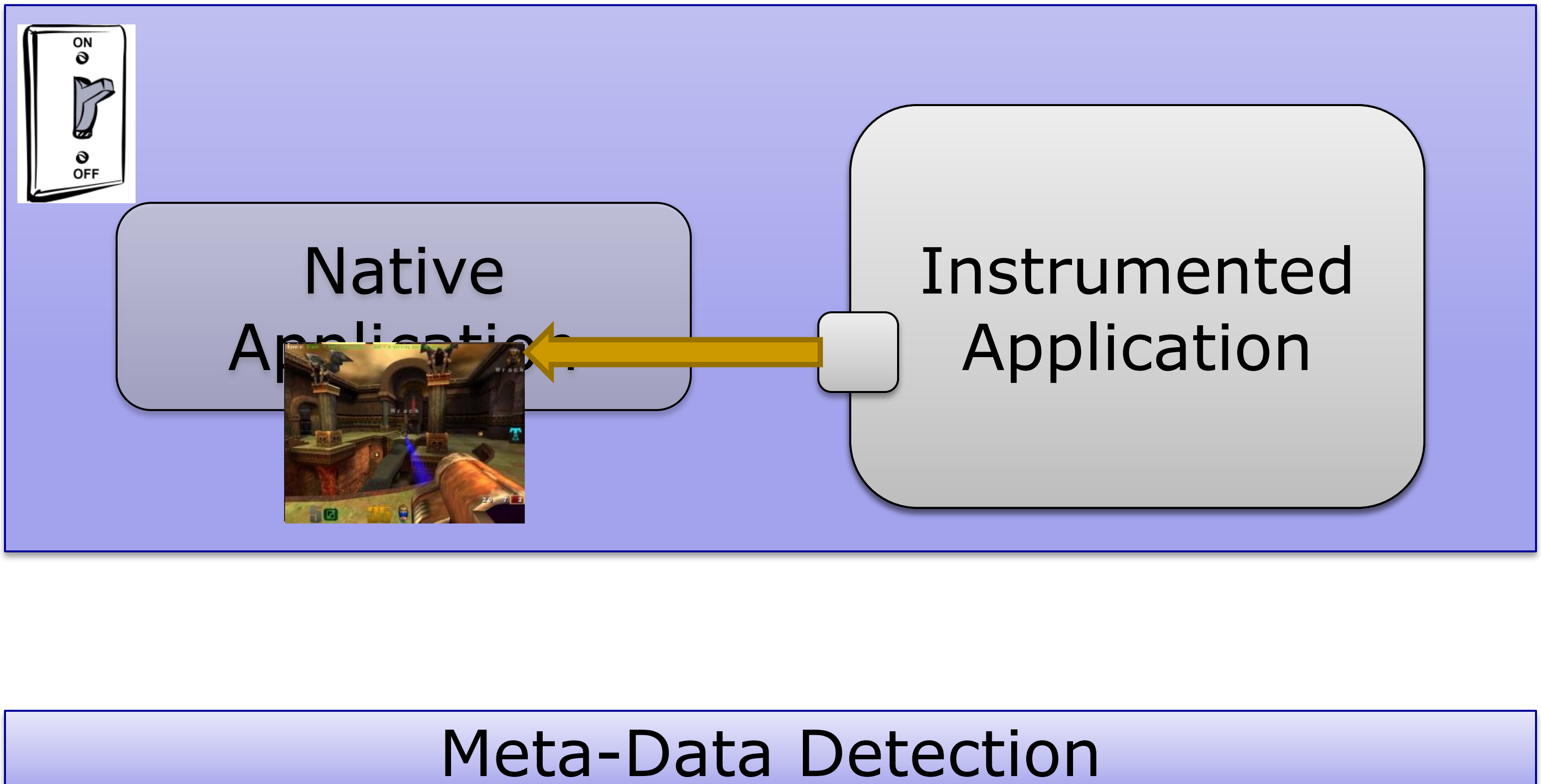

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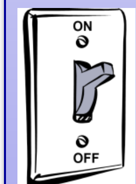


Native Application

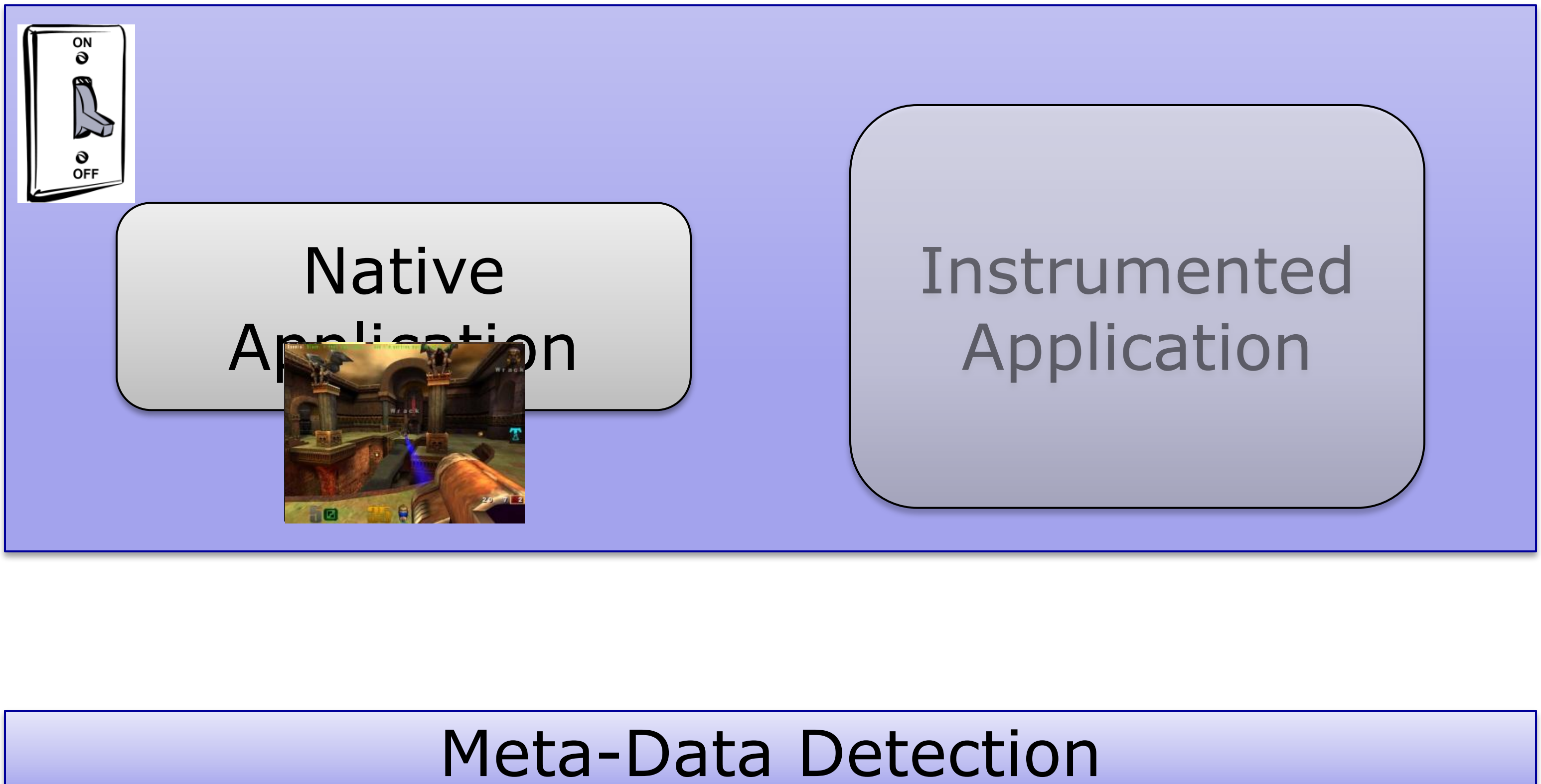
Instrumented Application

No meta-data

Meta-Data Detection

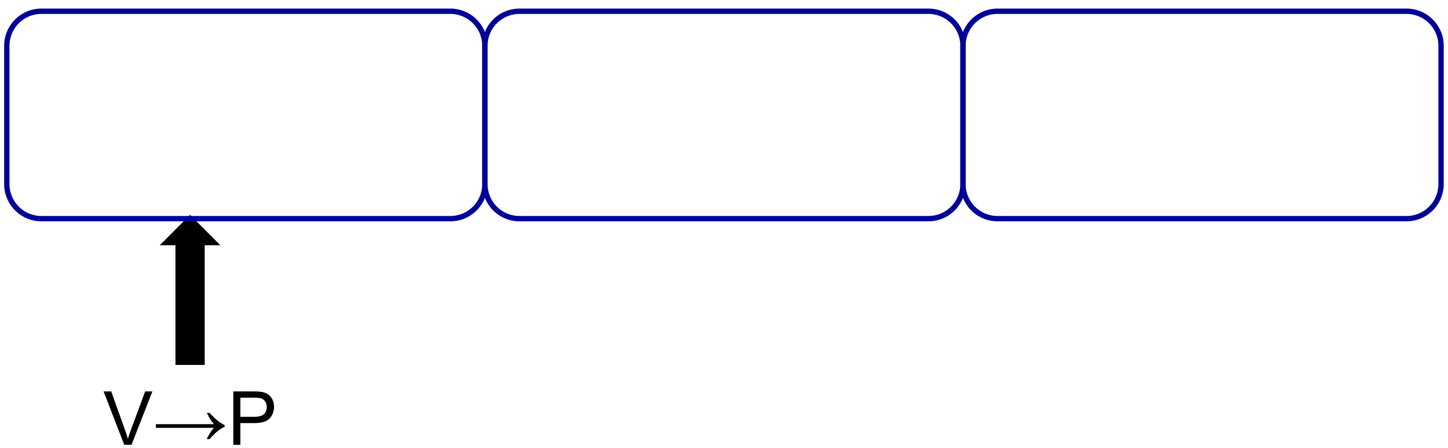
Demand-Driven Dataflow Analysis

- Only Analyze Shadowed Data



Finding Meta-Data

- No additional overhead when no meta-data
  - Needs hardware support
- Take a fault when touching shadowed data
- Solution: Virtual Memory Watchpoints



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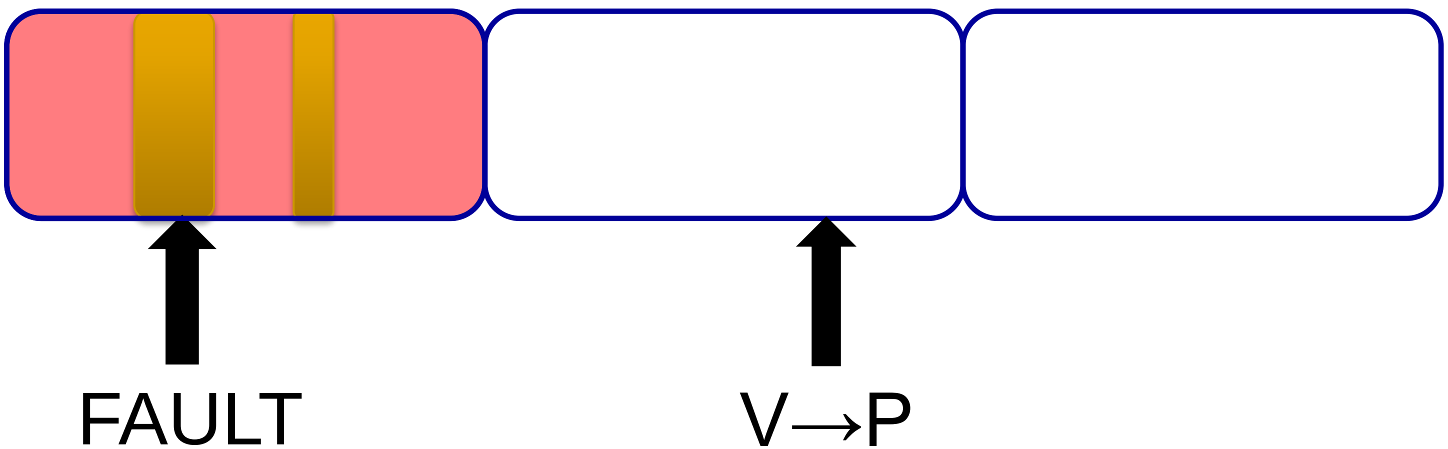

Results by Ho et al.

- From “Practical Taint-Based Protection using Demand Emulation”

System	Slowdown (normalized)
Taint Analysis	101.7x
On-Demand Taint Analysis	1.98x

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Software Data Race Detection

- Add checks around every memory access
- Find inter-thread sharing events
- Synchronization between write-shared accesses?
  - No? Data race.

Data Race Detection

TIME

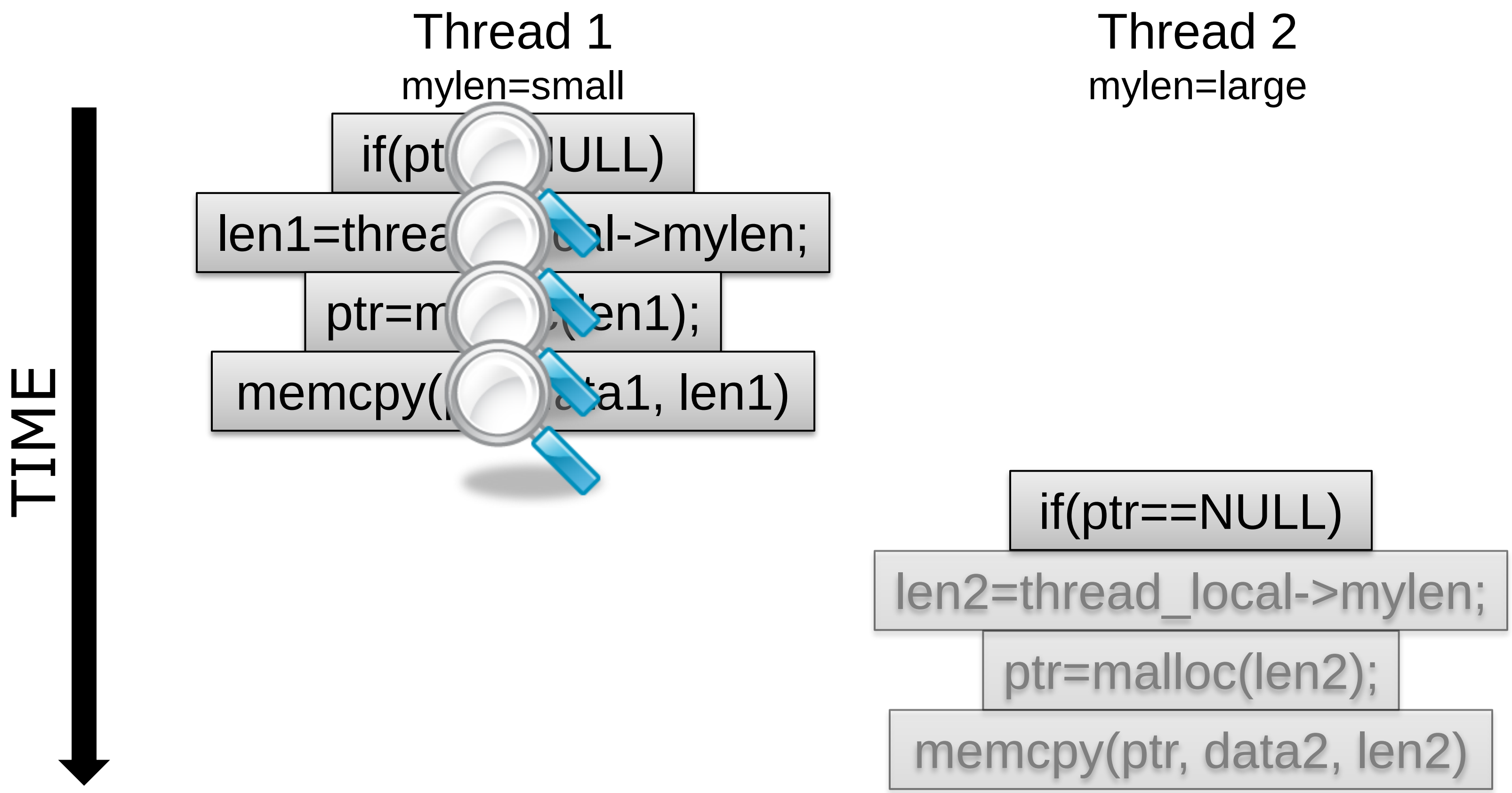
Thread 1
mylen=small

```
if(ptr==NULL)
len1=thread_local->mylen;
ptr=malloc(len1);
memcpy(ptr, data1, len1)
```

Thread 2
mylen=large

```
if(ptr==NULL)
len2=thread_local->mylen;
ptr=malloc(len2);
memcpy(ptr, data2, len2)
```

Data Race Detection



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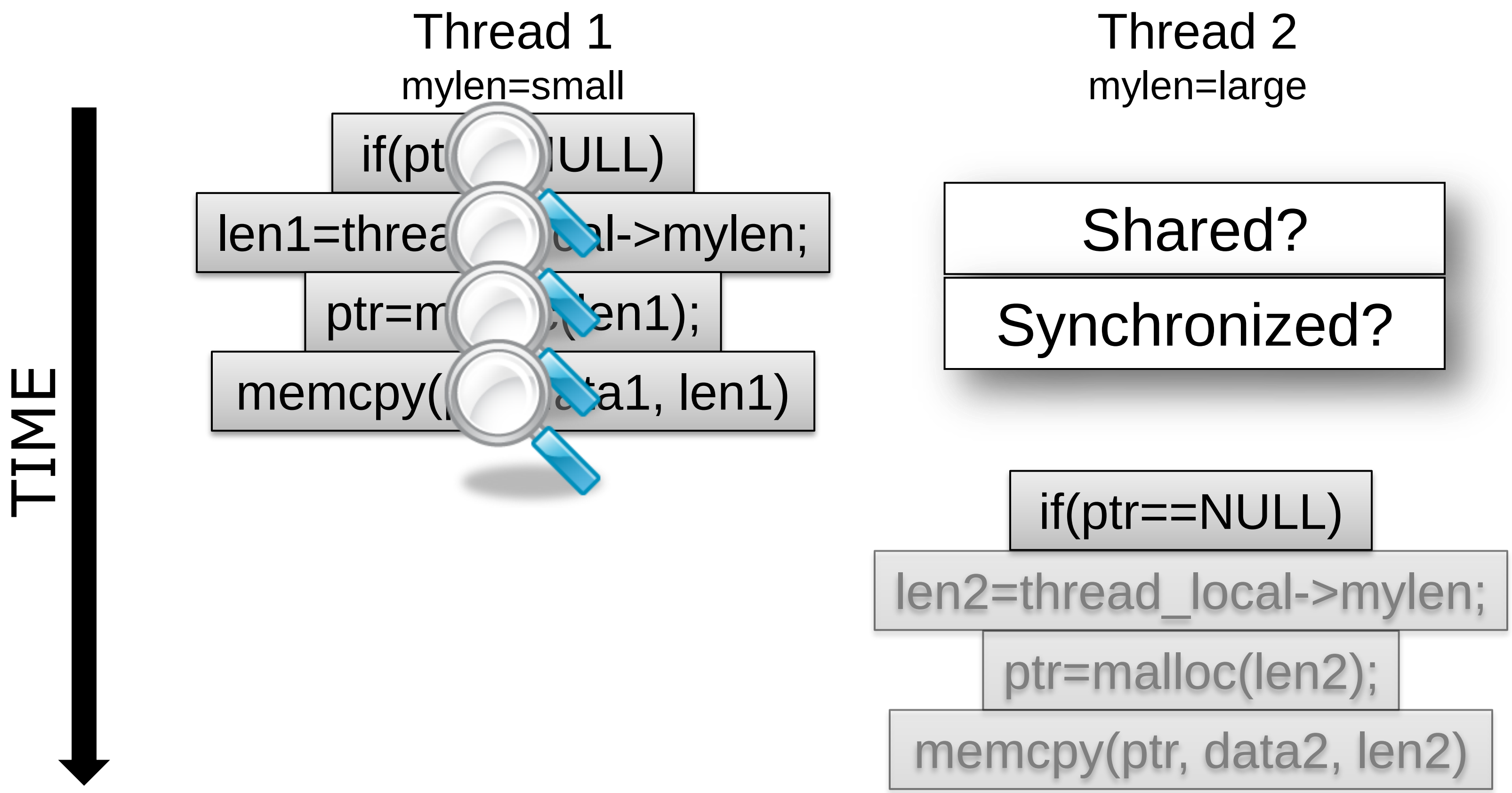

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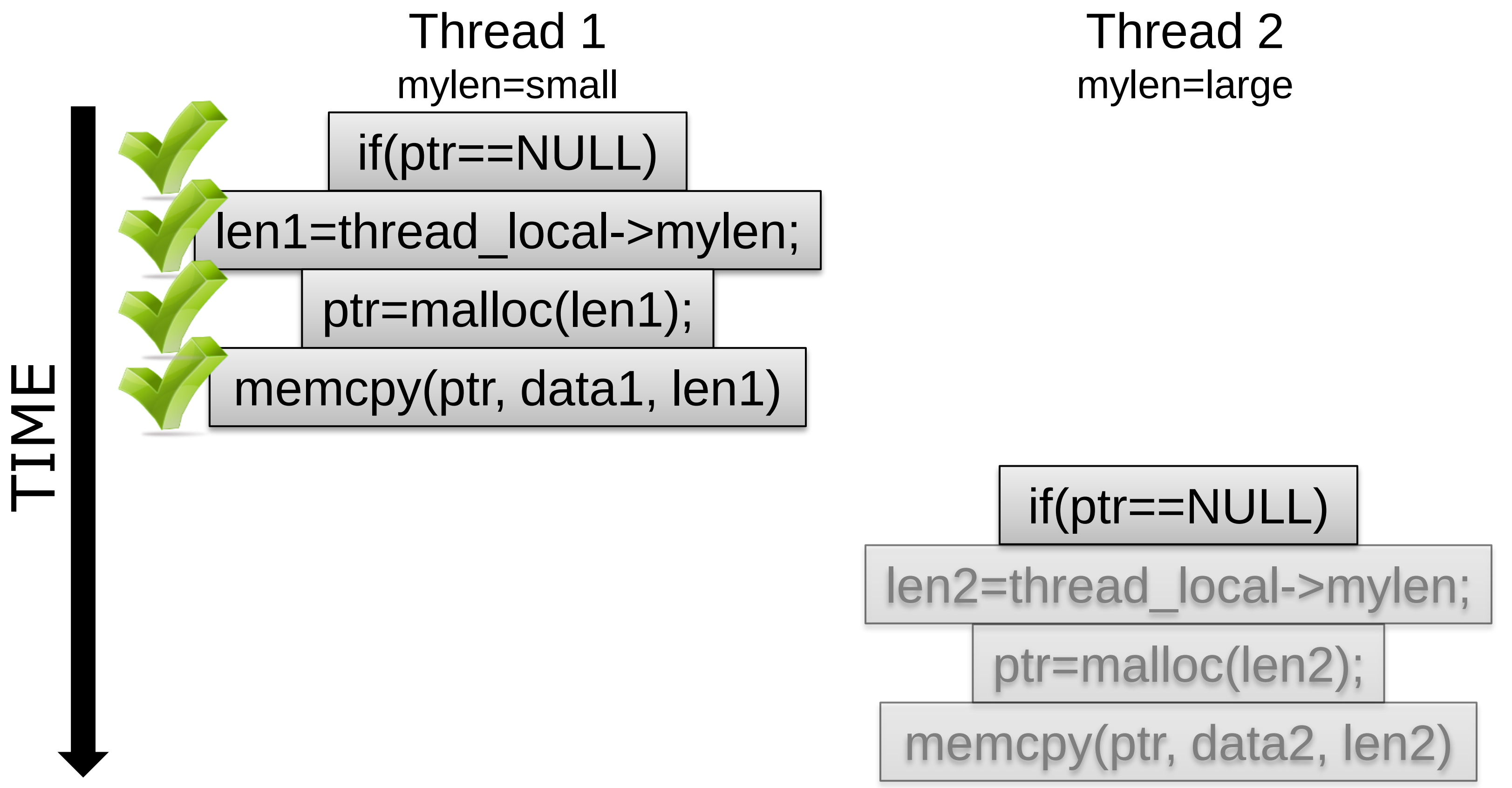

Example of Data Race Detection

TIME

Thread 1 mylen=small	Thread 2 mylen=large
if(ptr==NULL)	
len1=thread_local->mylen;	Shared?
ptr=malloc(len1);	
memcpy(ptr, data1, len1)	
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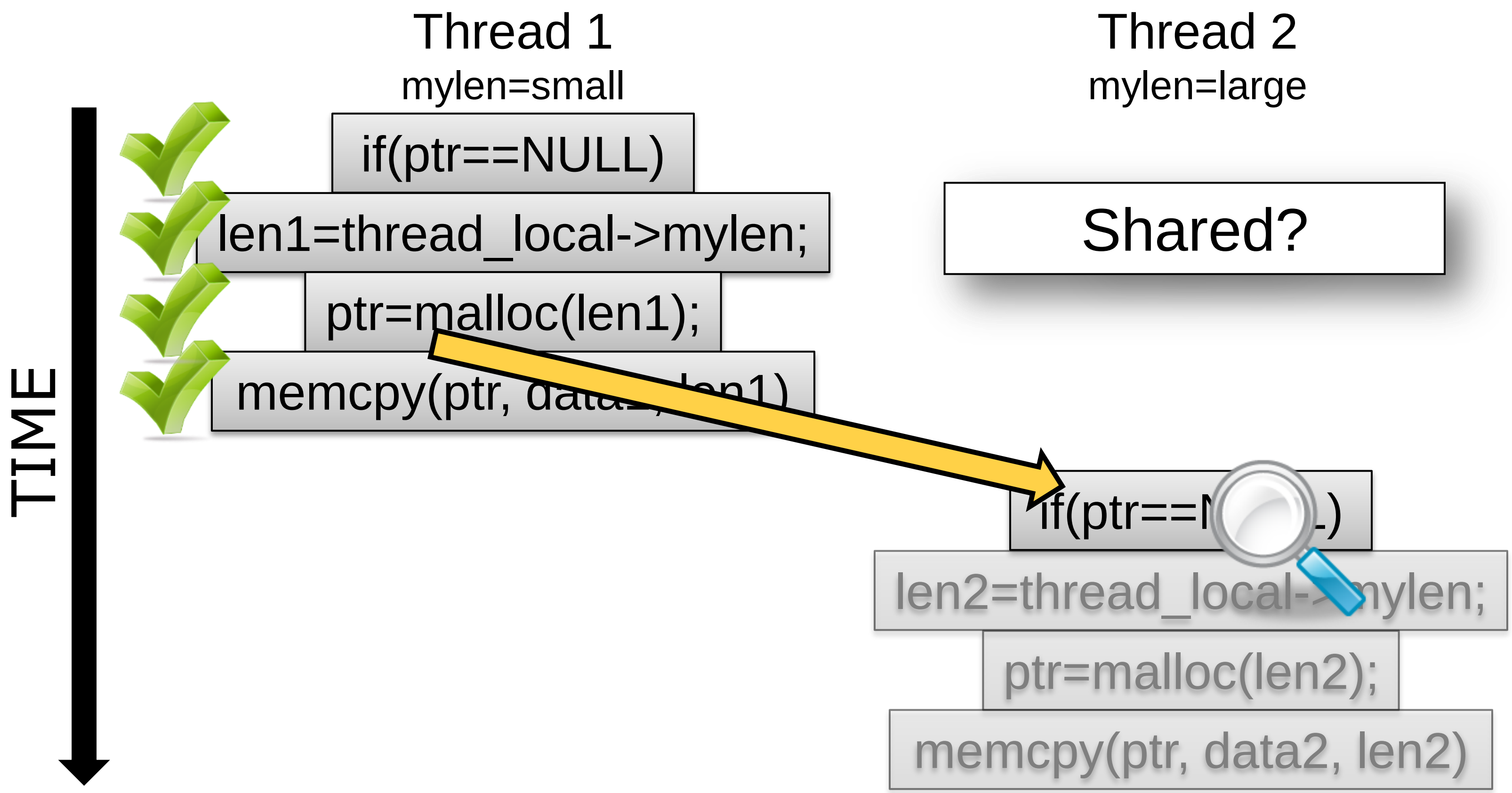

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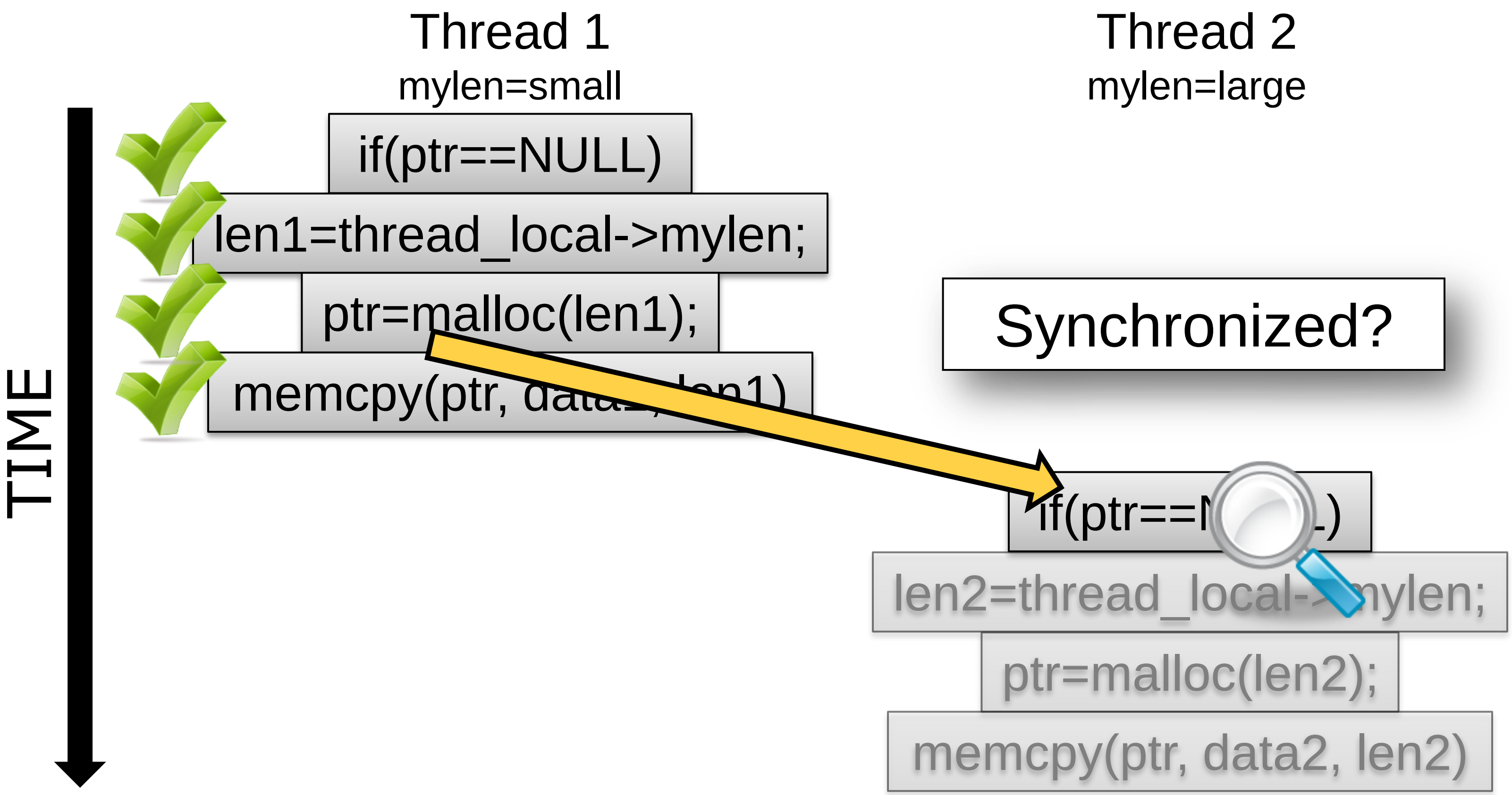

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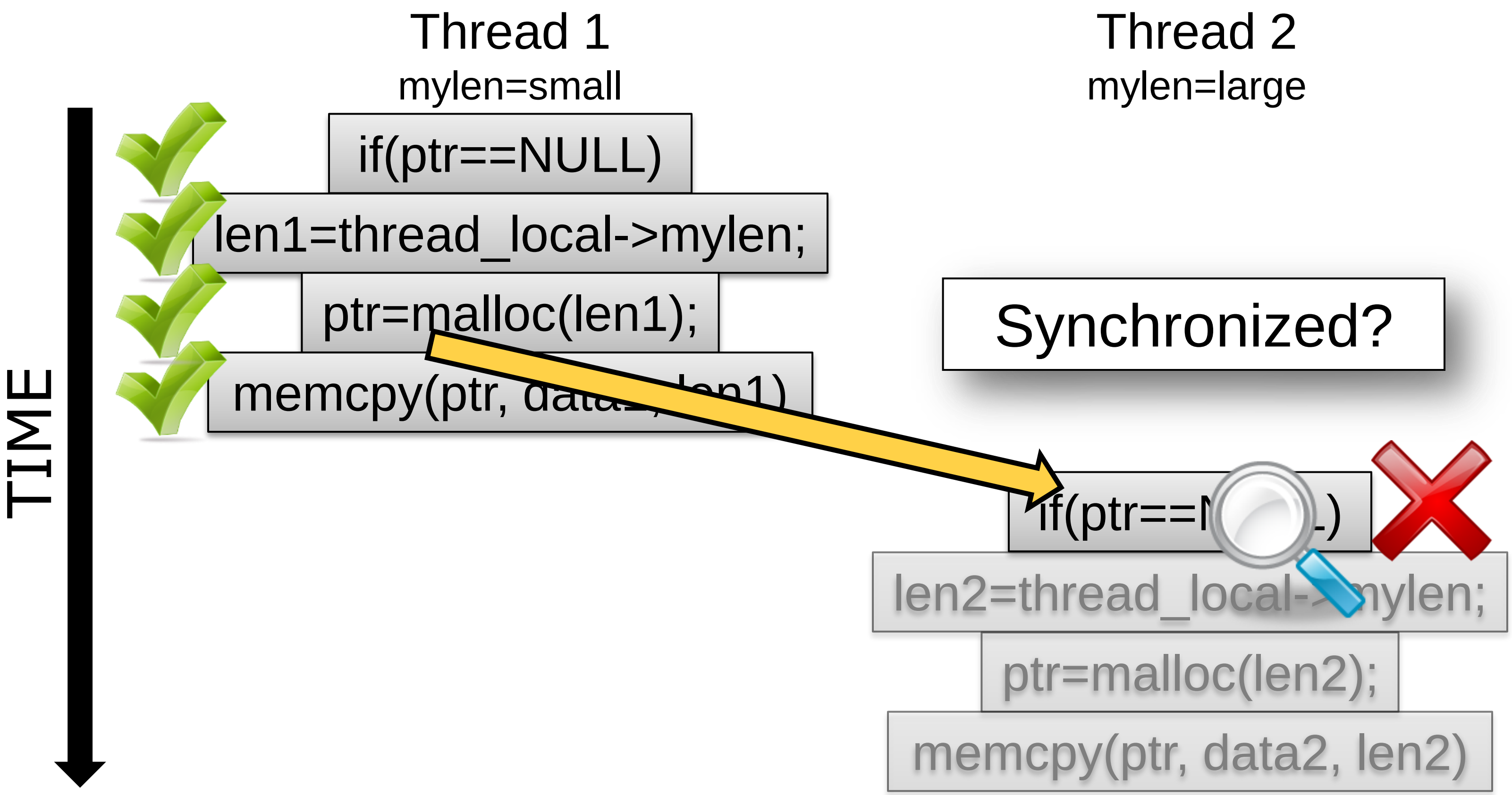
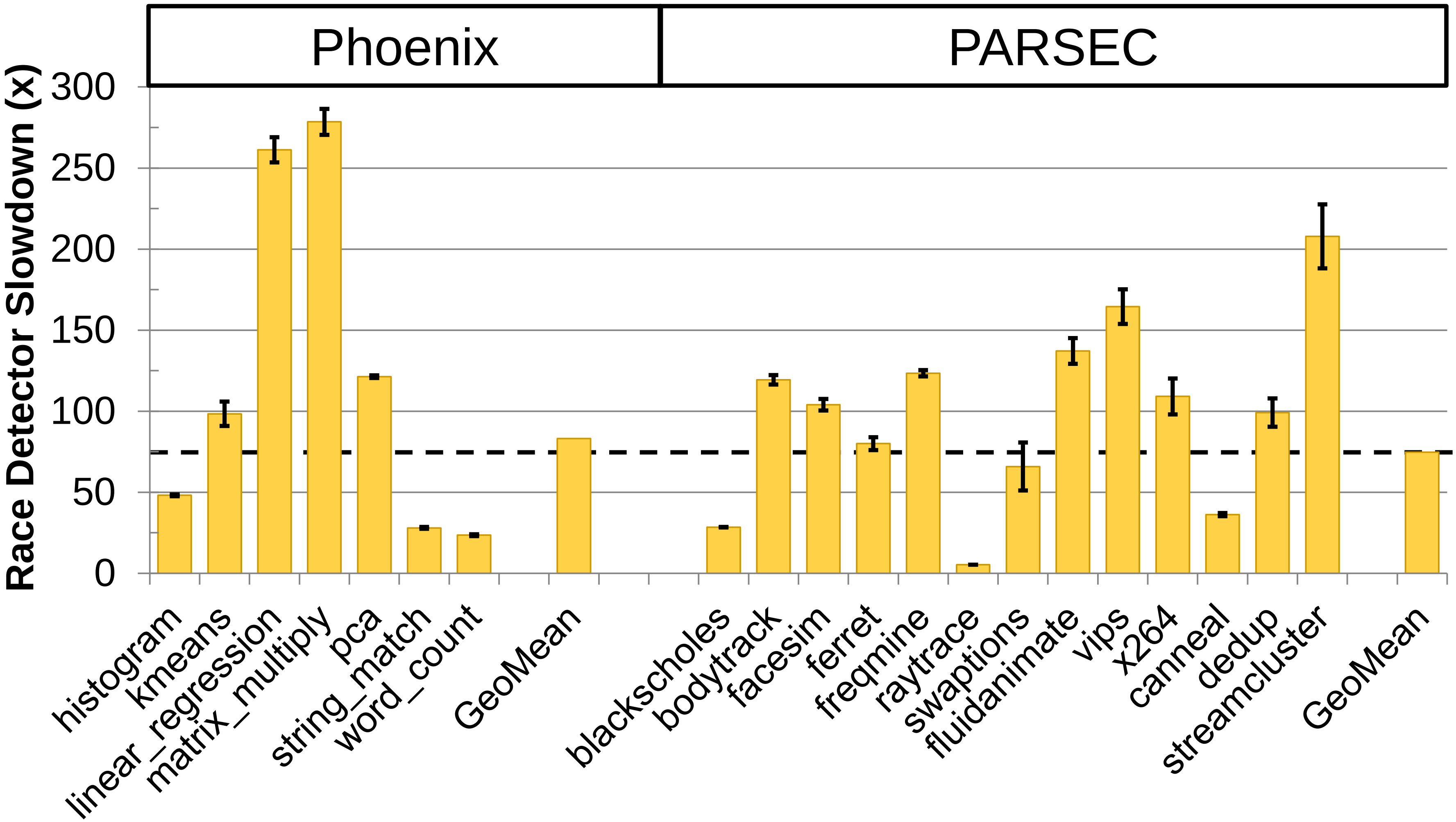
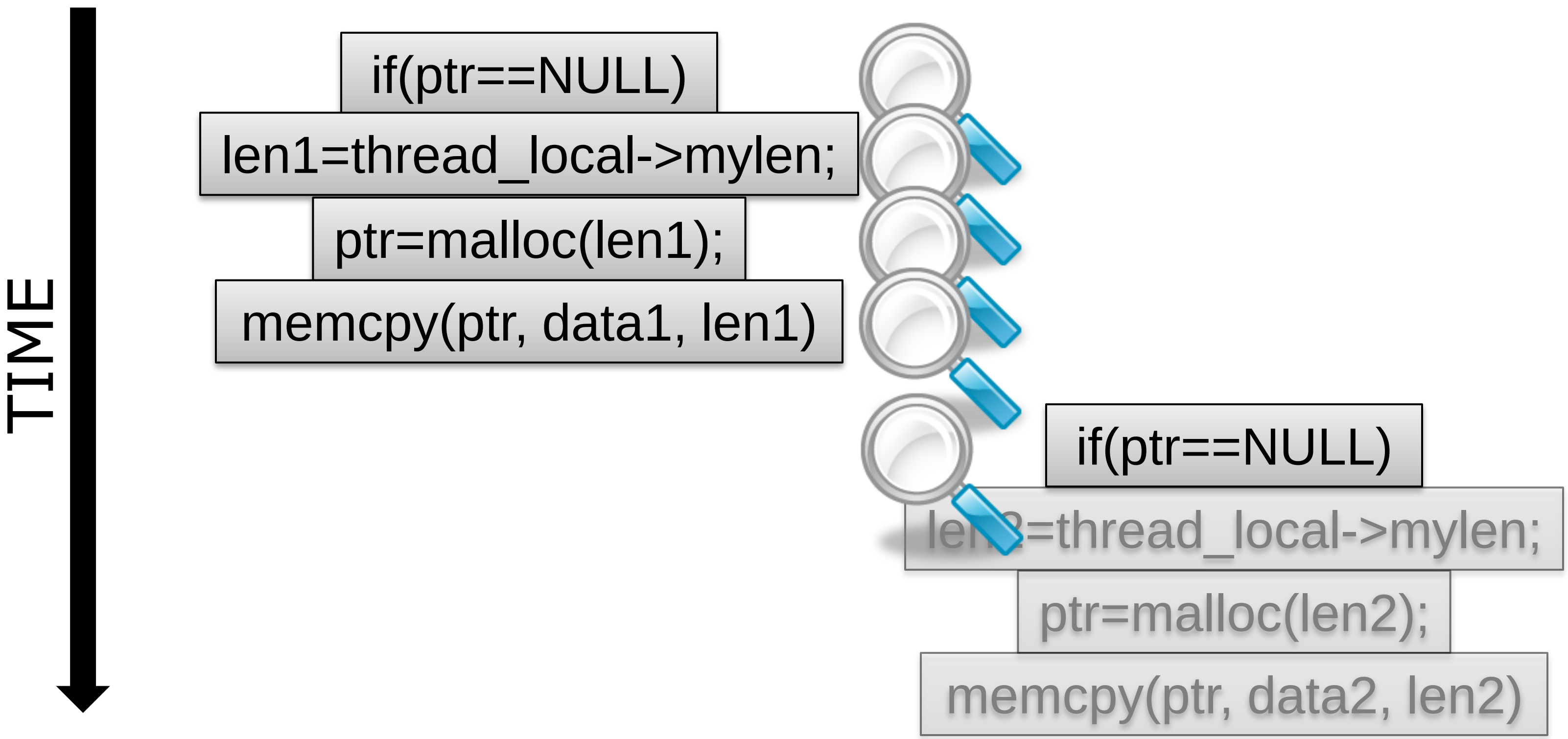


SW Race Detection is Slow



Inter-thread Sharing is What's Important

"Data races ... are failures in programs that **access and update shared data** in critical sections" – Netzer & Miller, 1992



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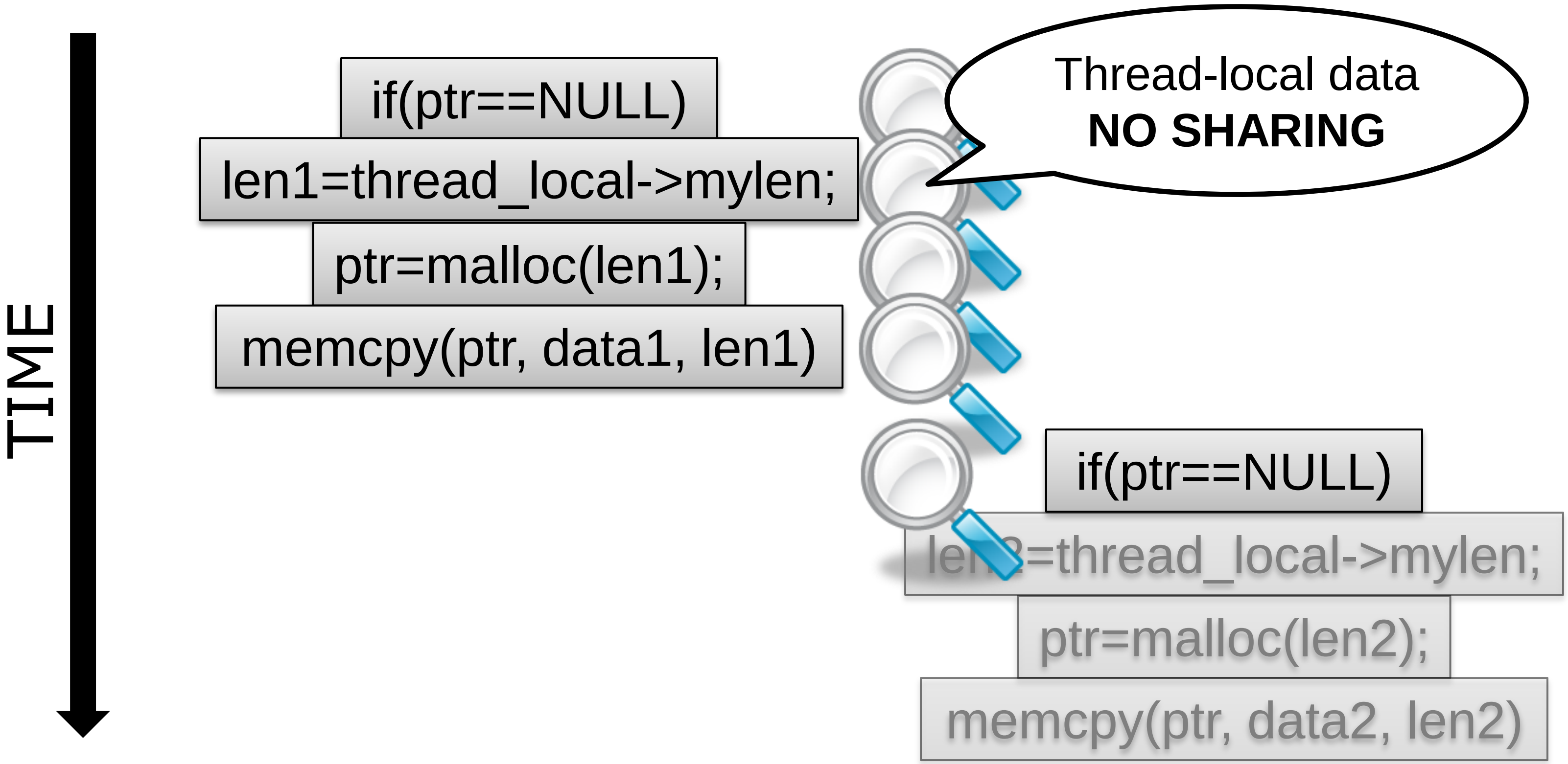

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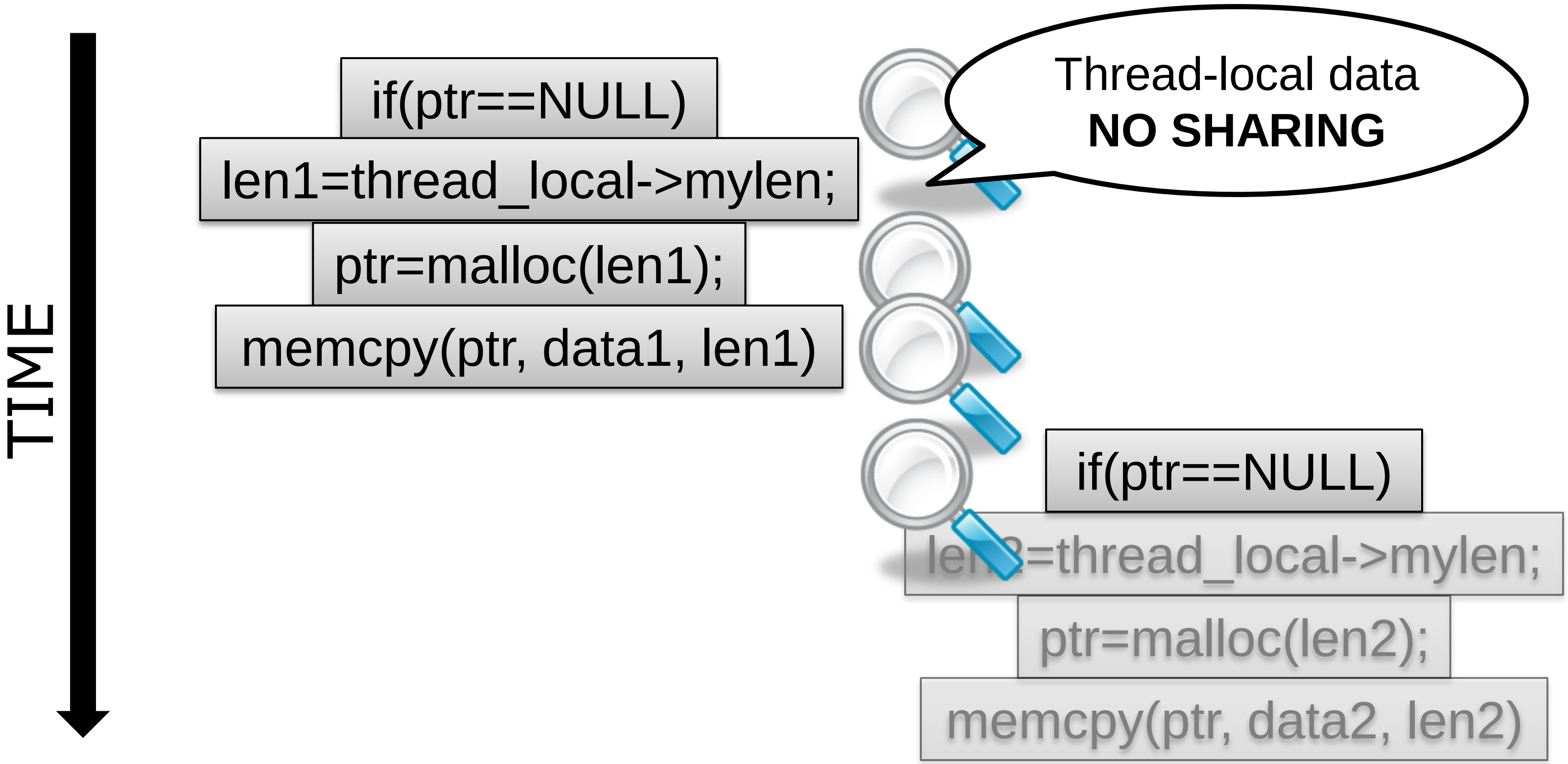

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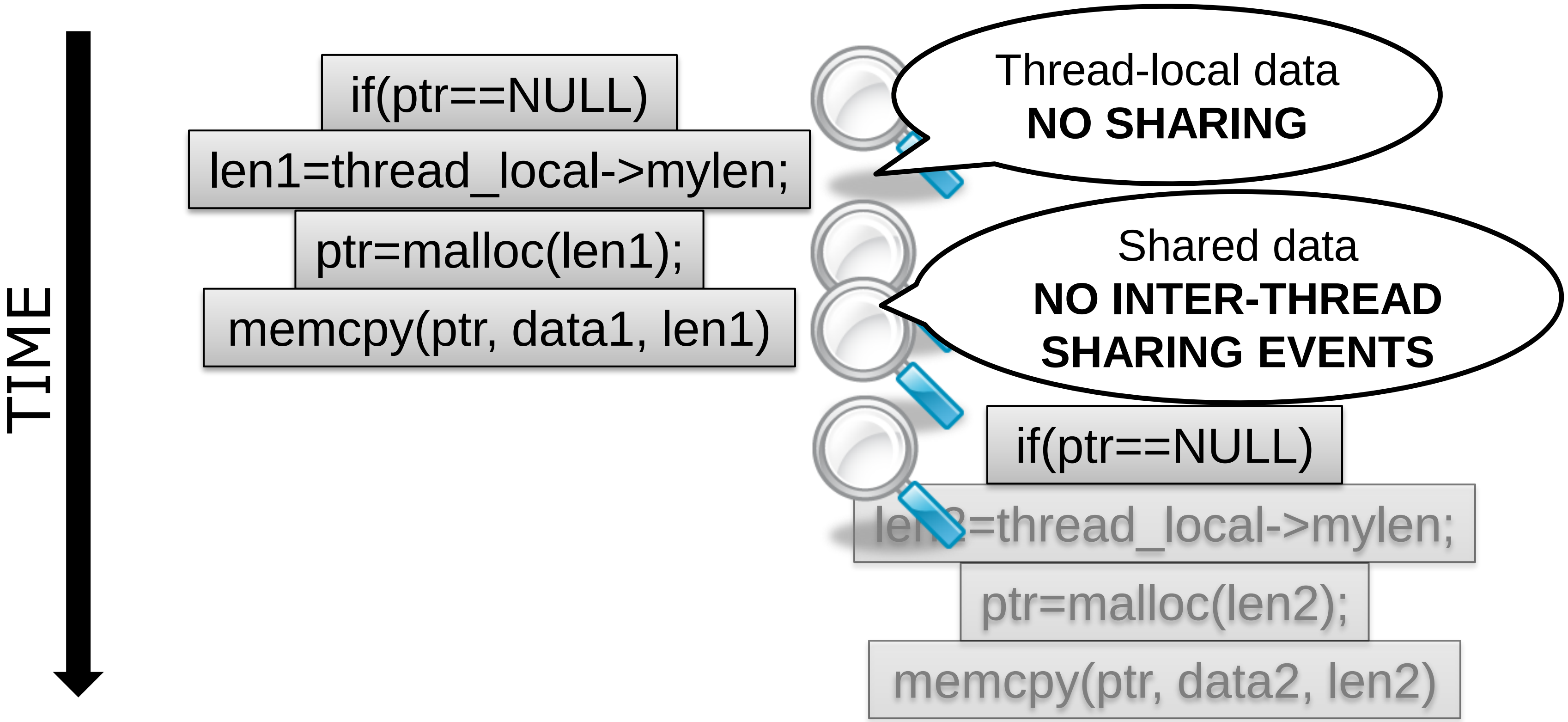

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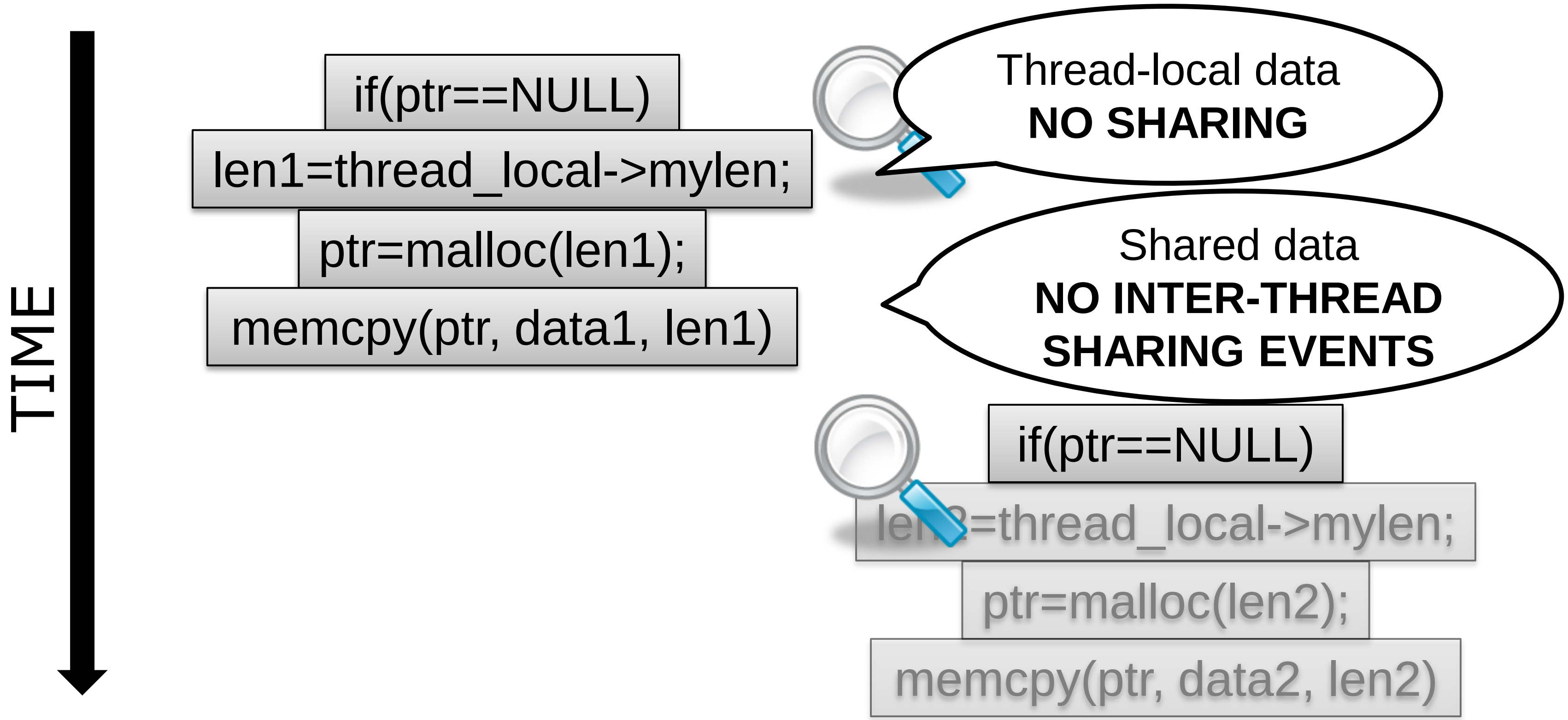


Inter-thread Sharing is What's Important

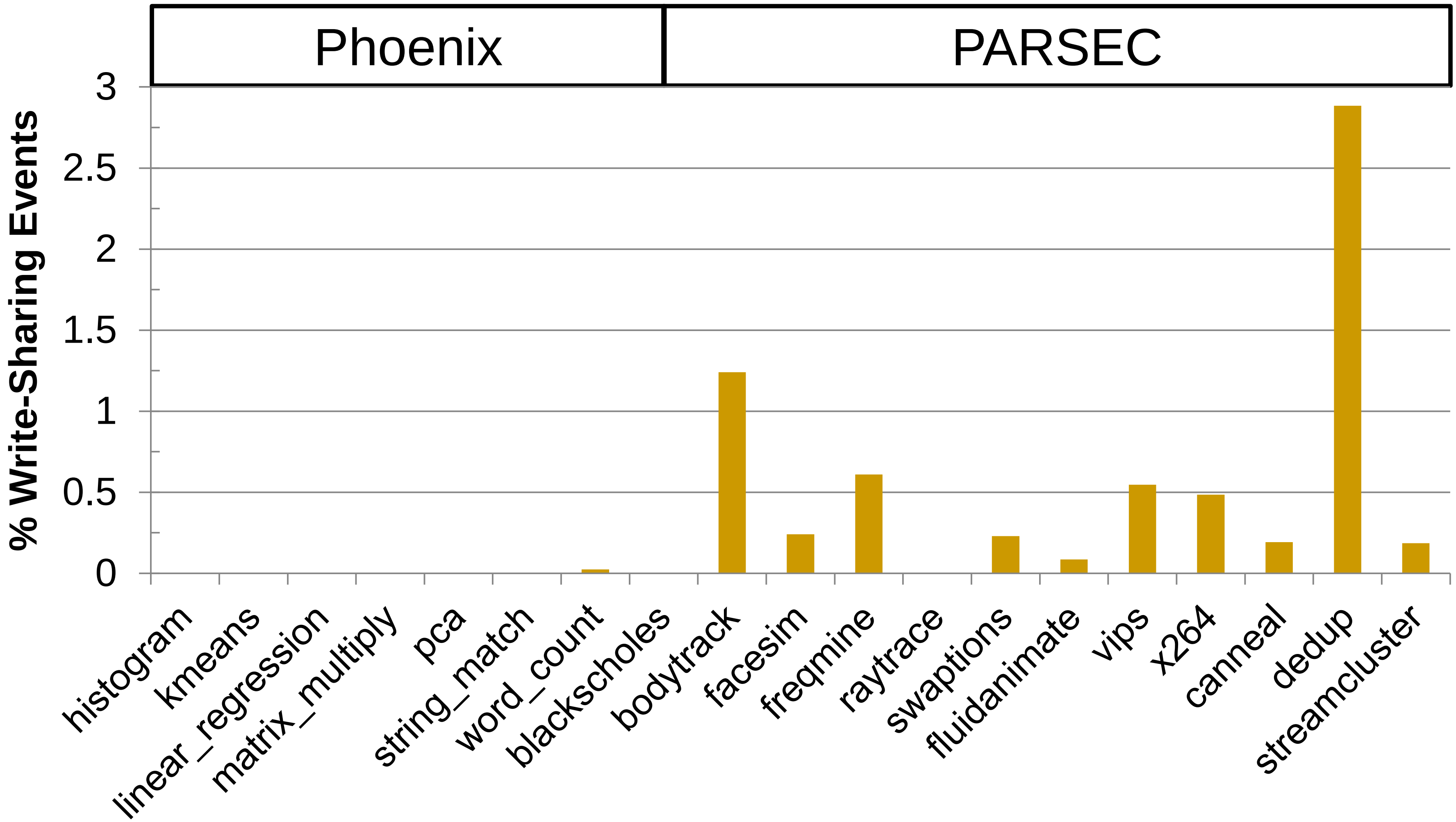
"Data races ... are failures in programs that **access and update shared data** in critical sections" – Netzer & Miller, 1992

TIME

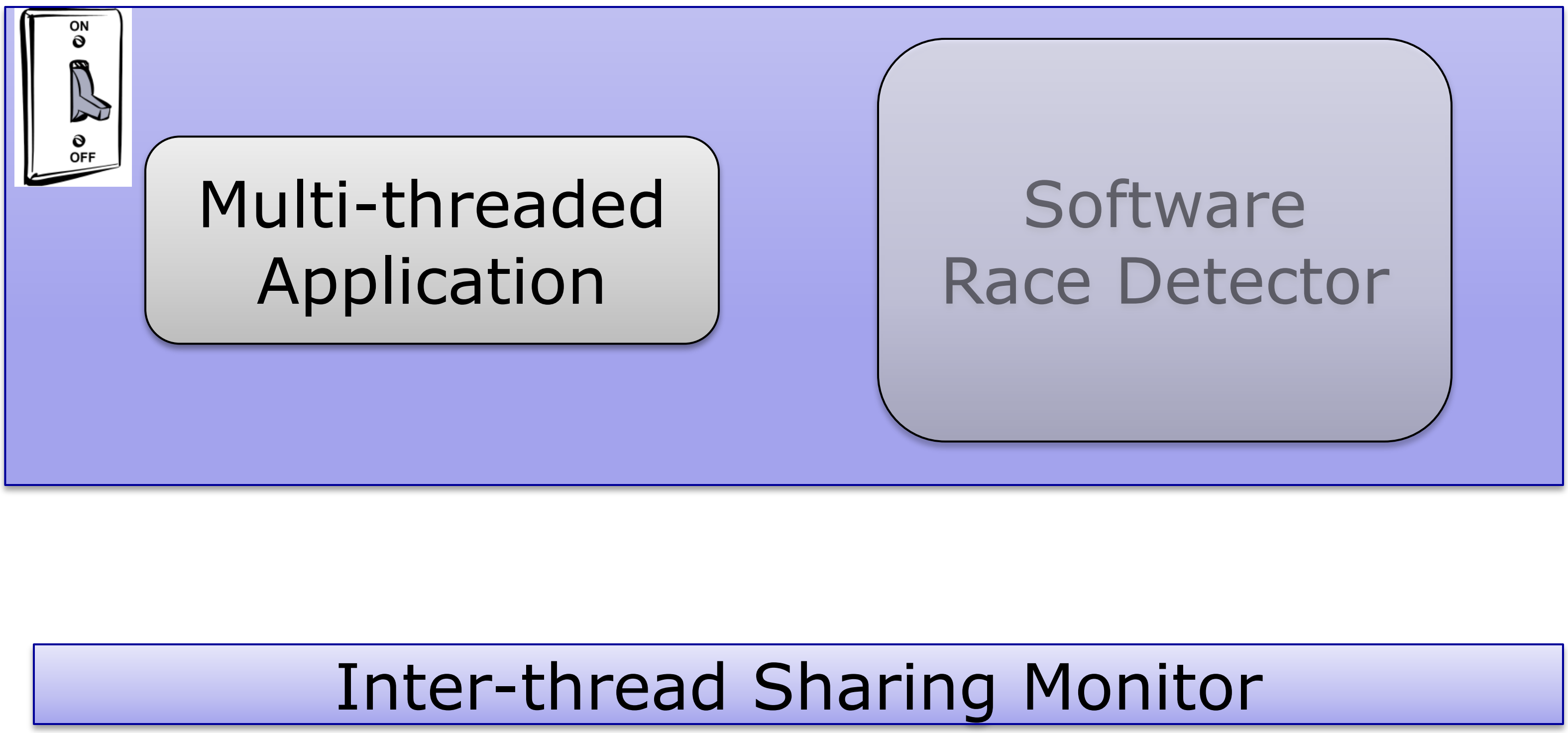
```
if(ptr==NULL)
len1=thread_local->mylen;
ptr=malloc(len1);
memcpy(ptr, data1, len1)
```

```
if(ptr==NULL)
len2=thread_local->mylen;
ptr=malloc(len2);
memcpy(ptr, data2, len2)
```

Very Little Inter-Thread Sharing



Use Demand-Driven Analysis!



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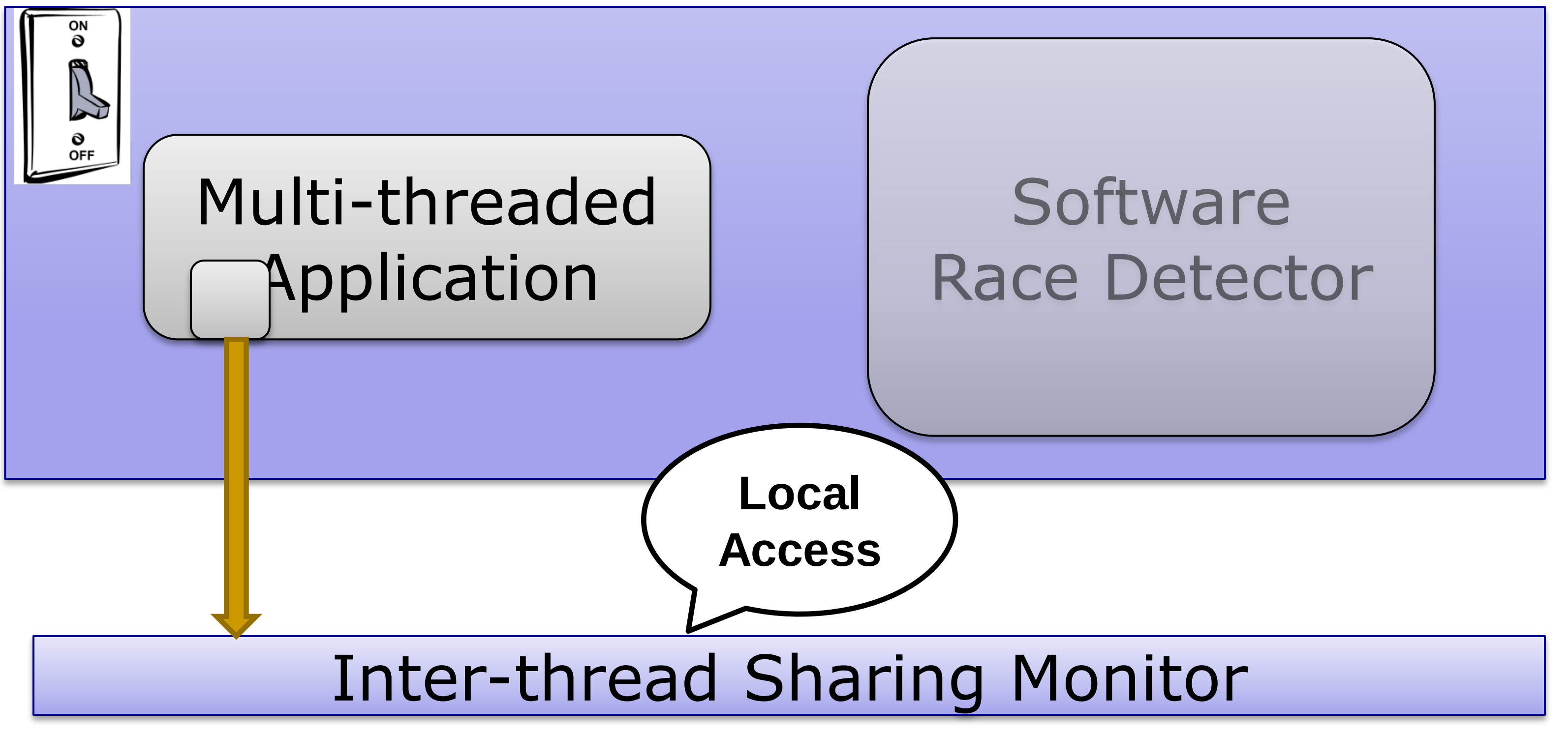

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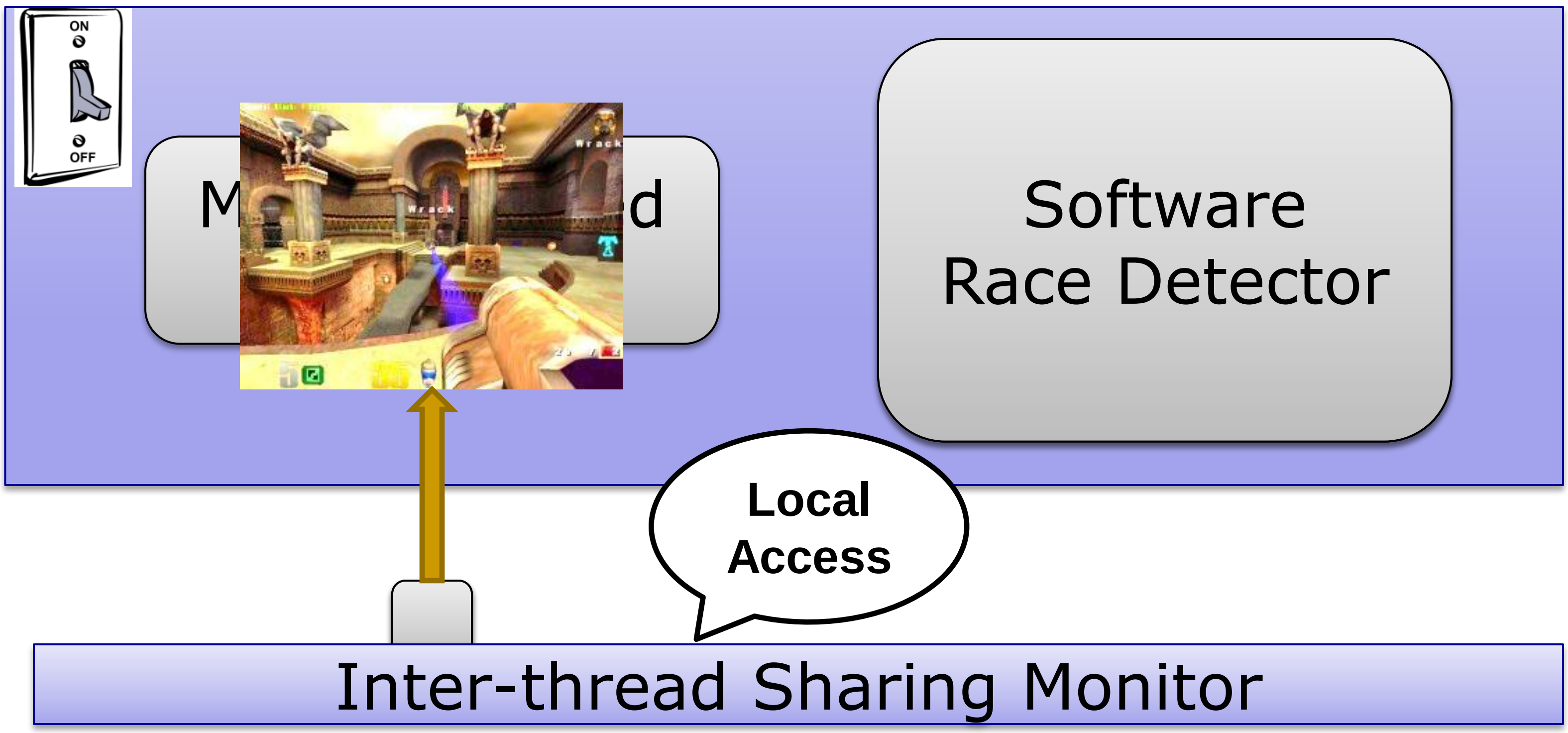

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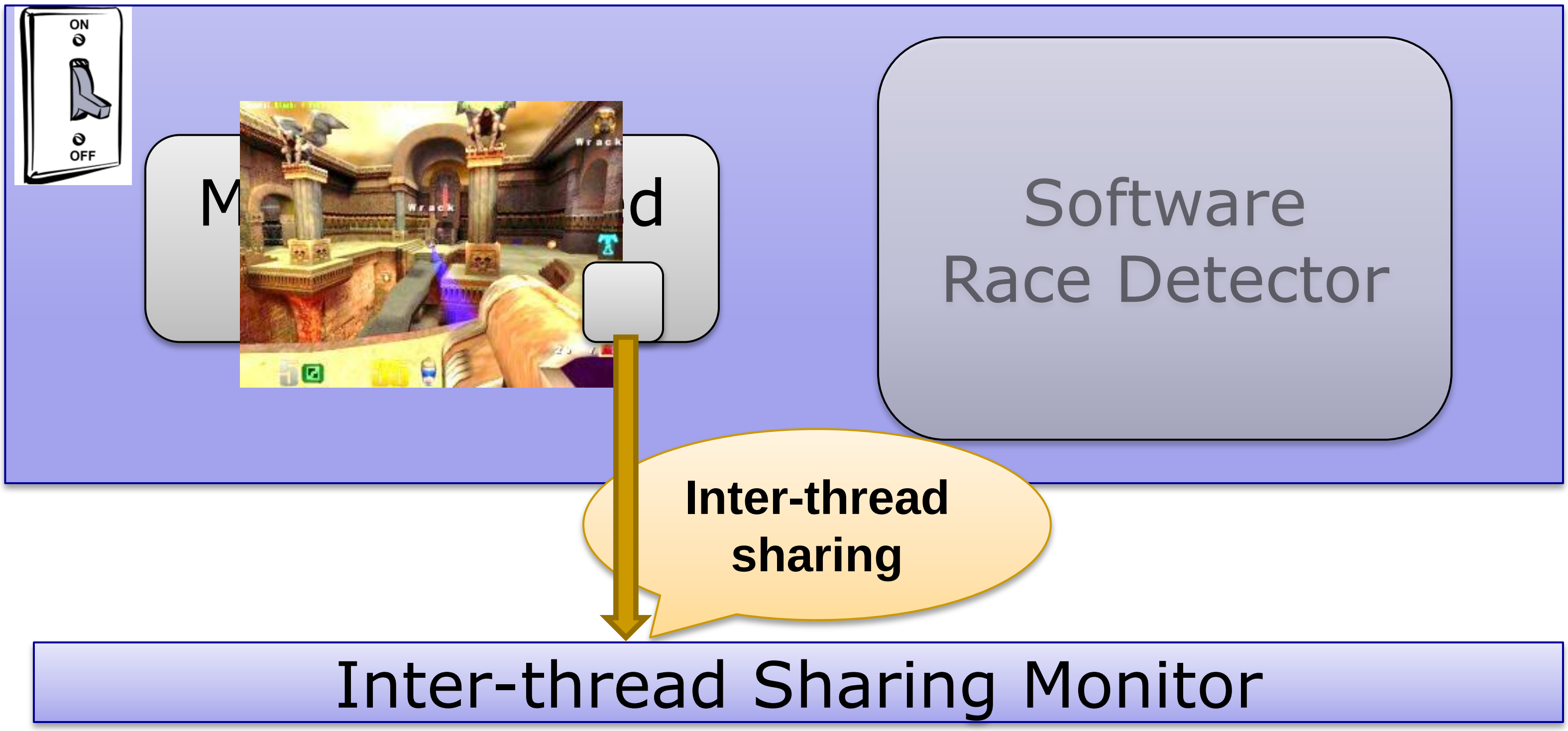

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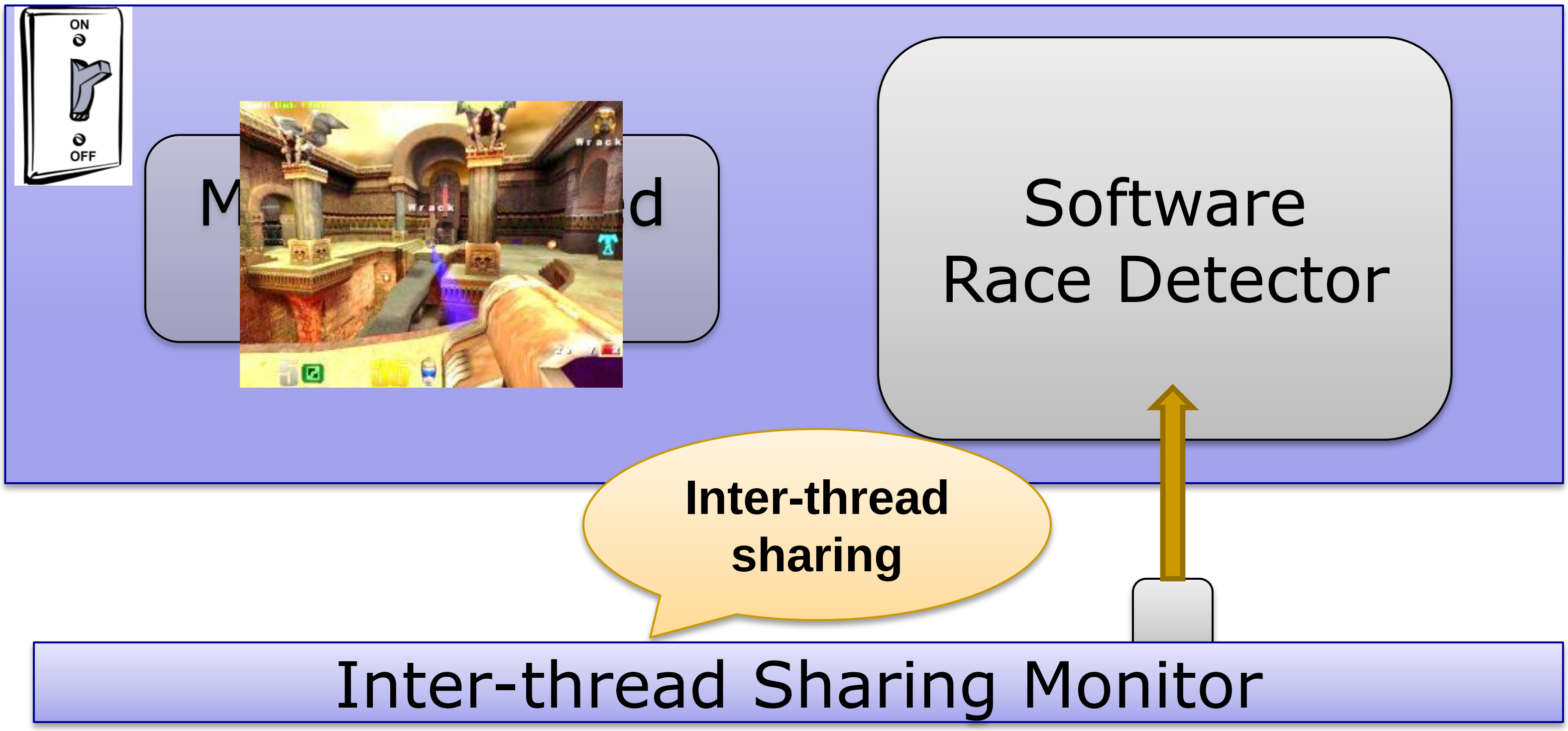

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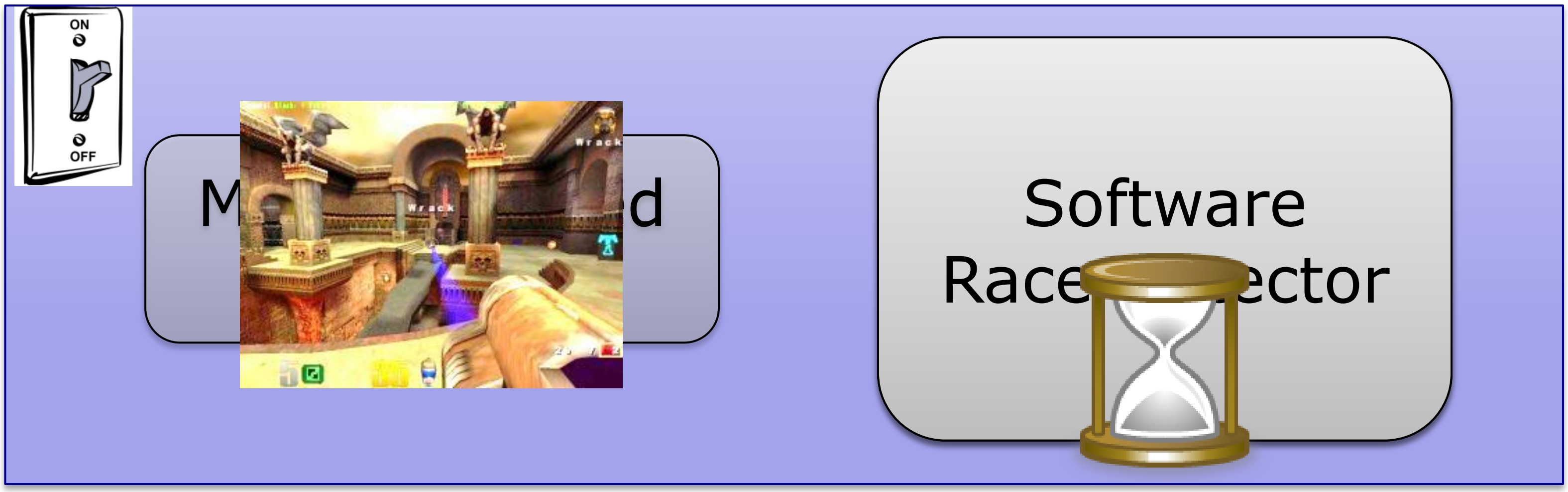
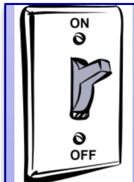


Inter-thread Sharing Monitor

Use Demand-Driven Analysis!

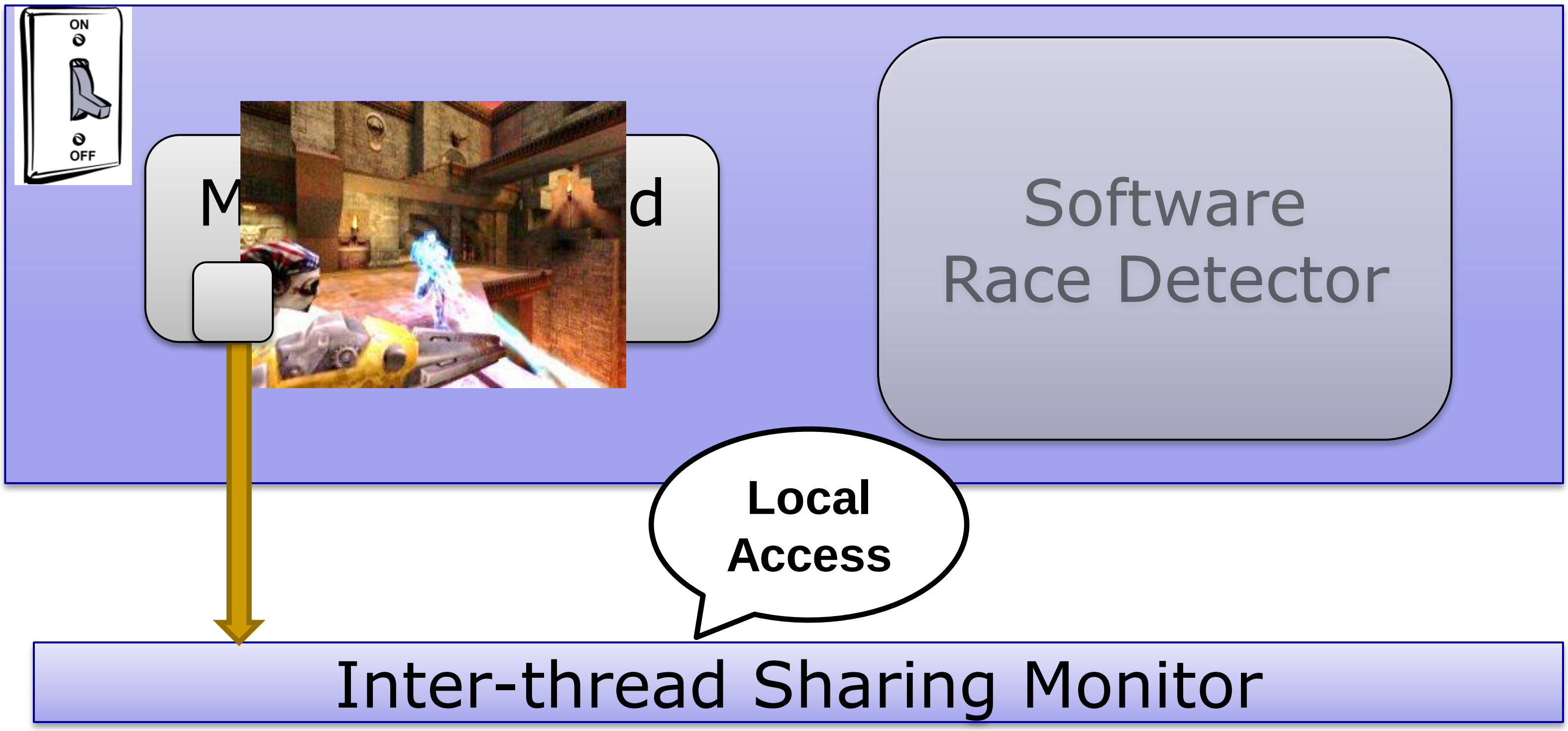


M d

Software
Race Detector

Inter-thread Sharing Monitor

Use Demand-Driven Analysis!



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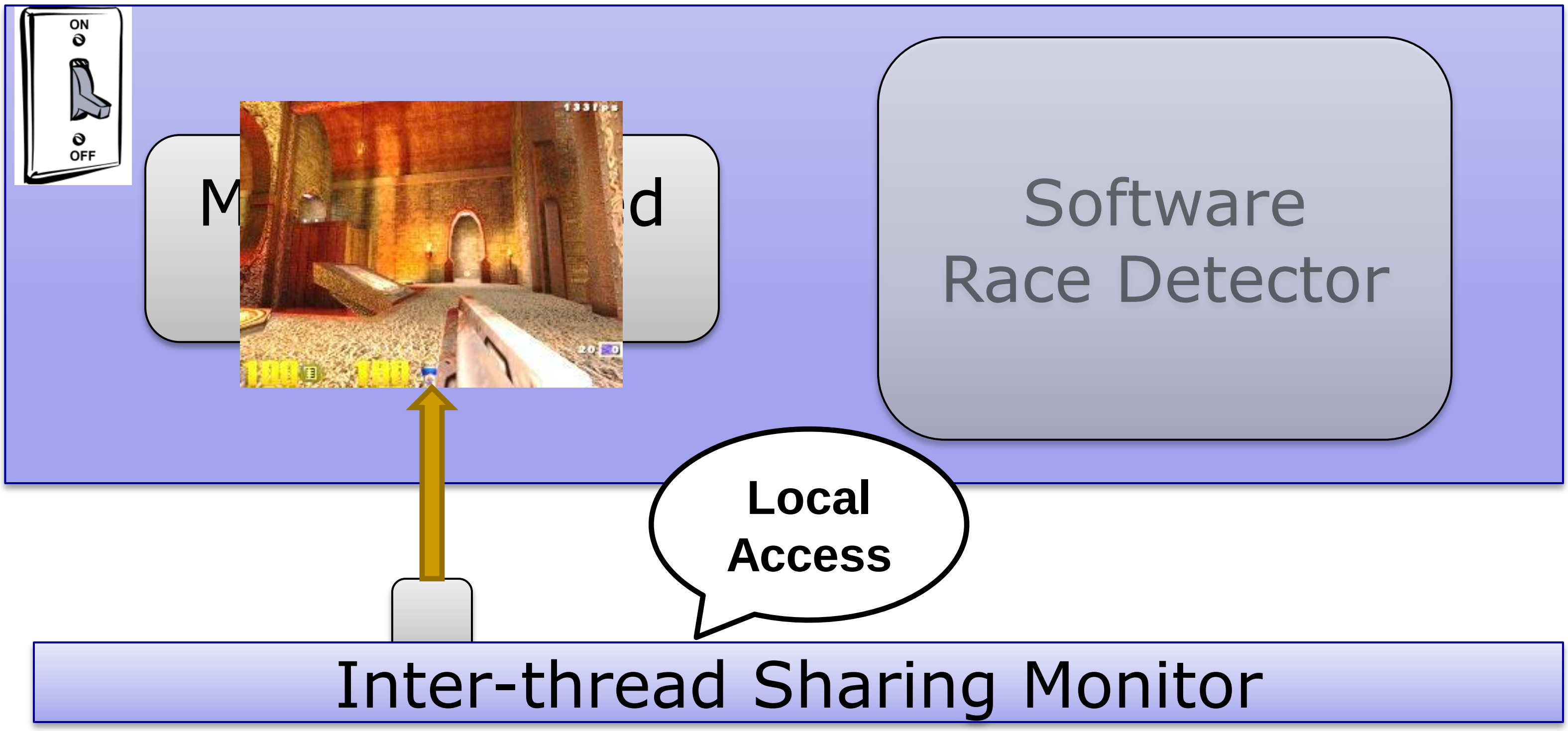

Finding Inter-thread Sharing

- Virtual Memory Watchpoints?

Finding Inter-thread Sharing

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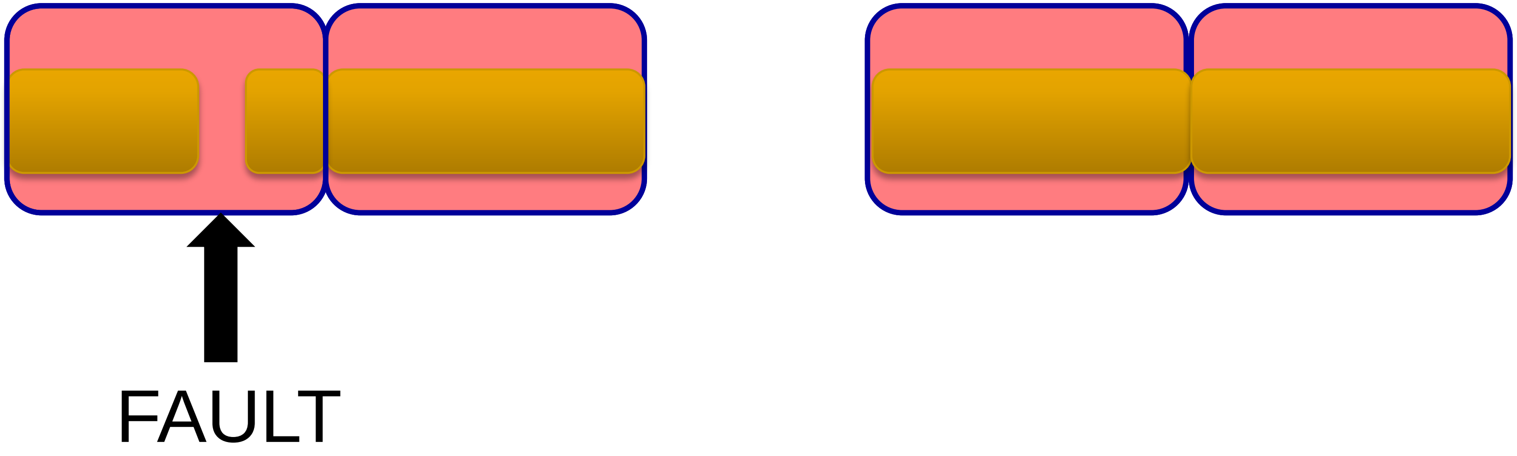

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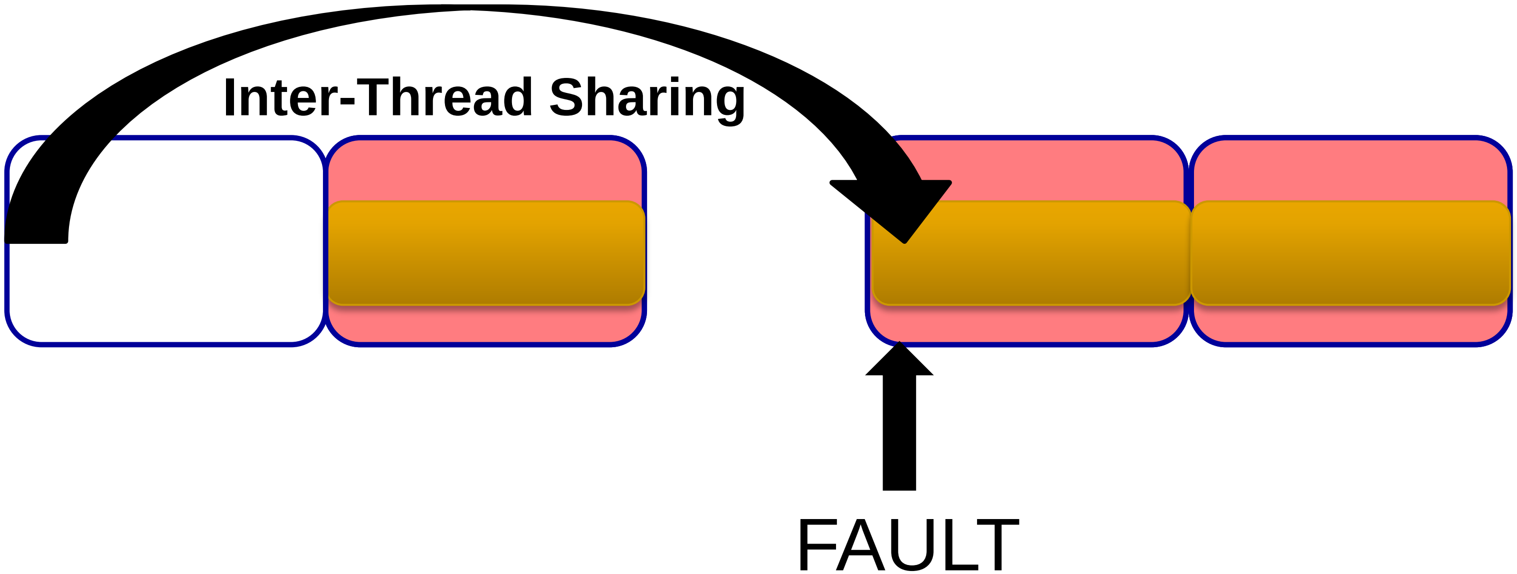

Finding Inter-thread Sharing

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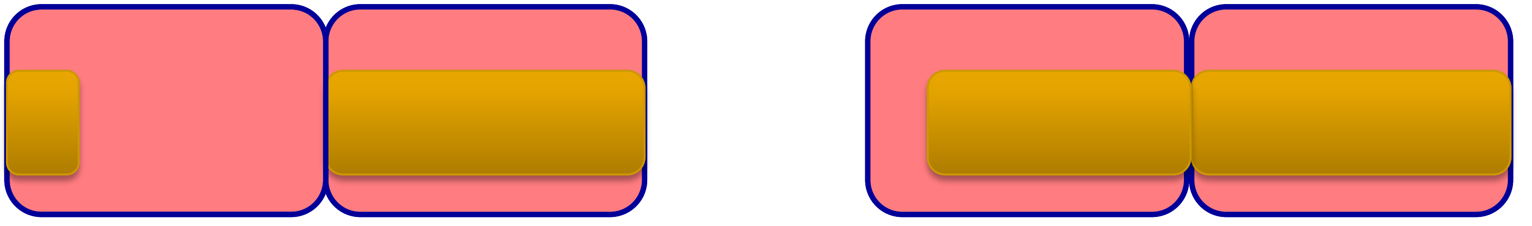
  – ~100% of accesses cause page faults

Finding Inter-thread Sharing

- Virtual Memory Watchpoints?



  – ~100% of accesses cause page faults
- Granularity Gap

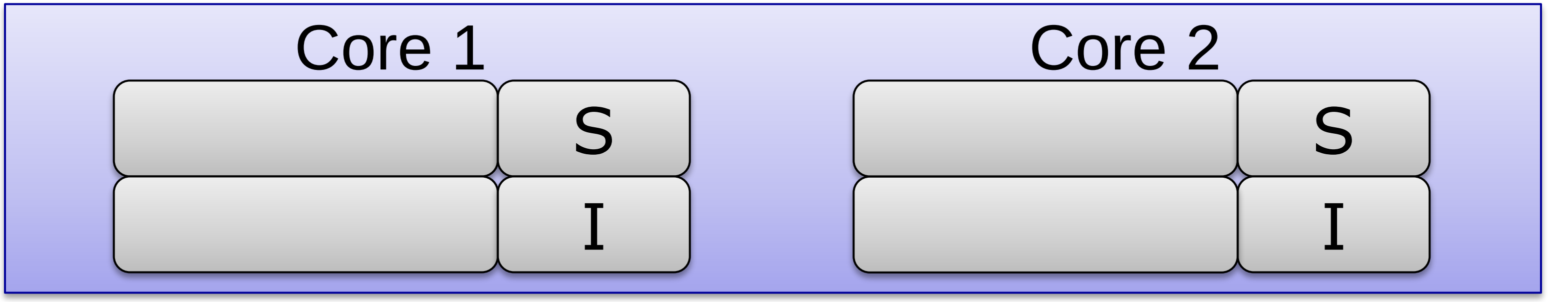
Finding Inter-thread Sharing

- Virtual Memory Watchpoints?

  - ~100% of accesses cause page faults
- Granularity Gap
- Per-process not per-thread
- Must go through the kernel on faults
- Syscalls for setting/removing meta-data

Hardware Sharing Detector

- HITM in Cache: W→R Data Sharing



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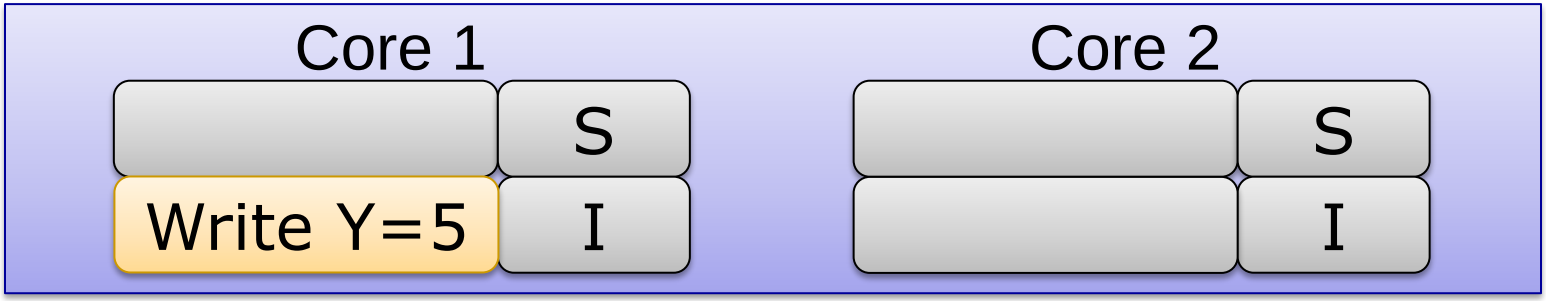

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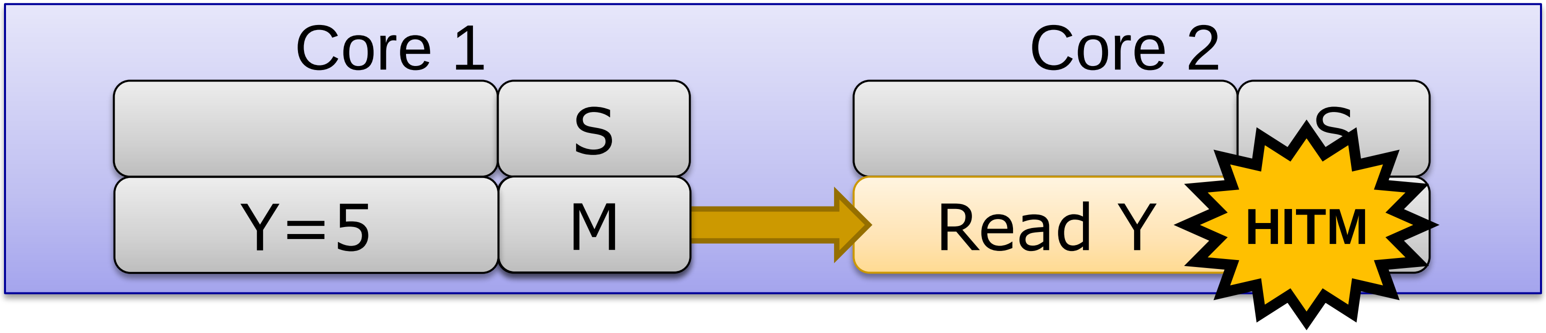

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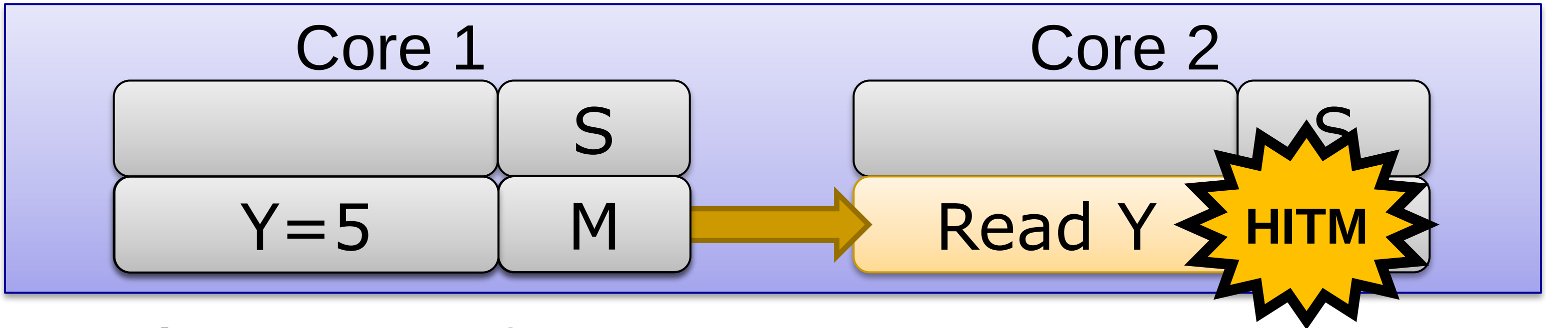
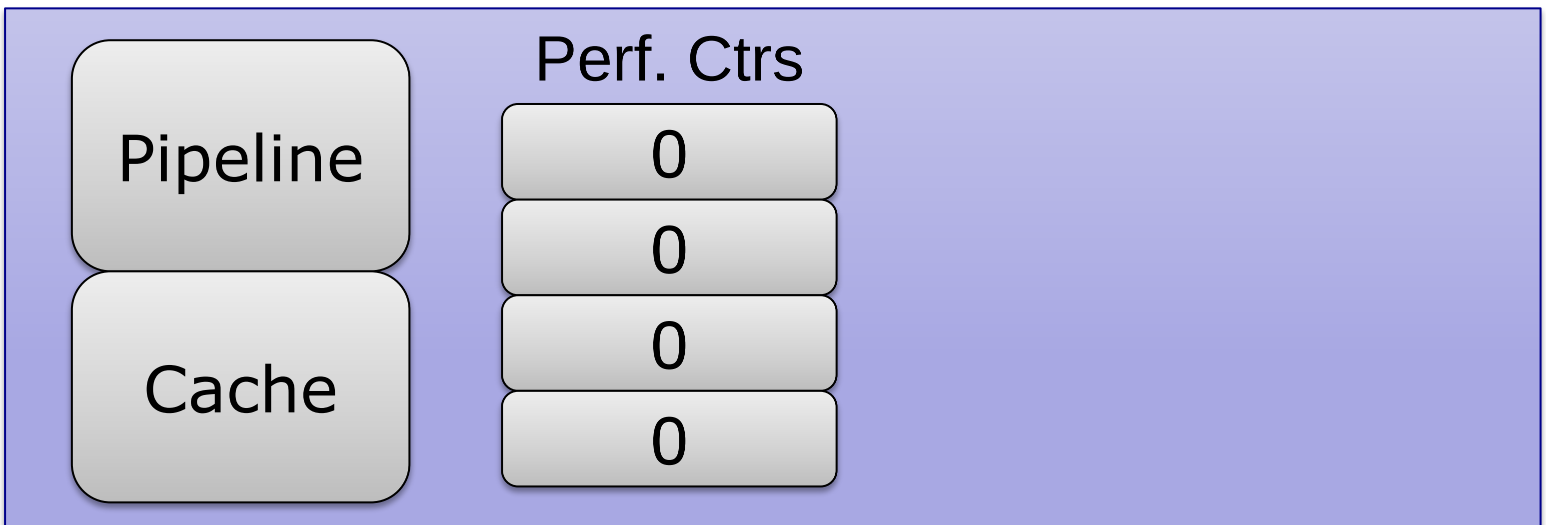


- Hardware Performance Counters



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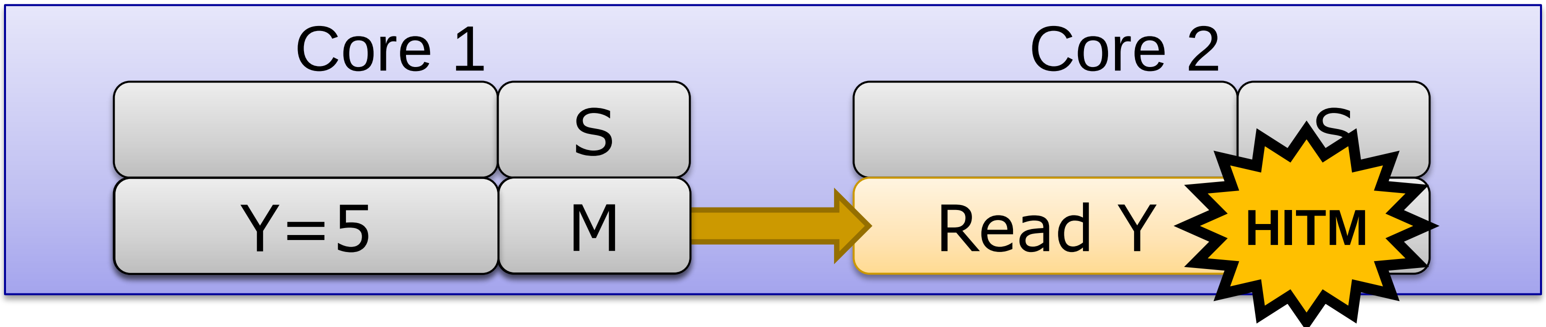

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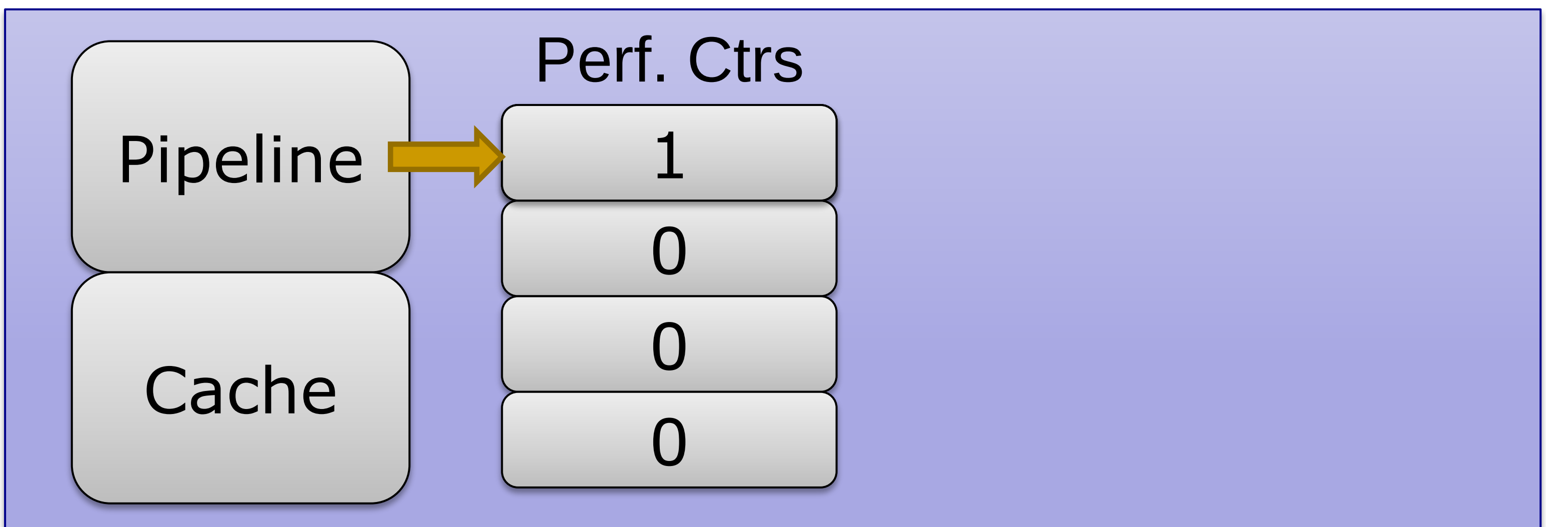

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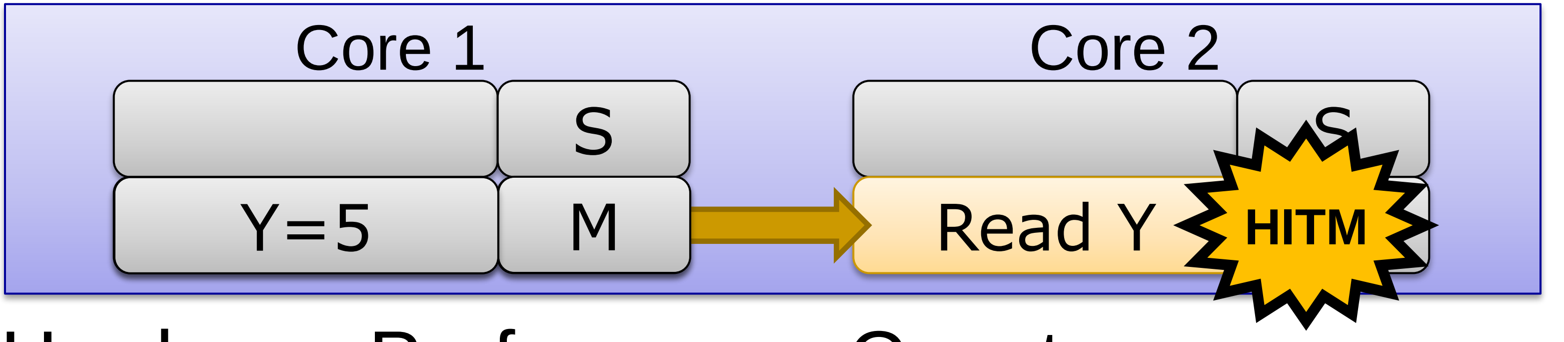

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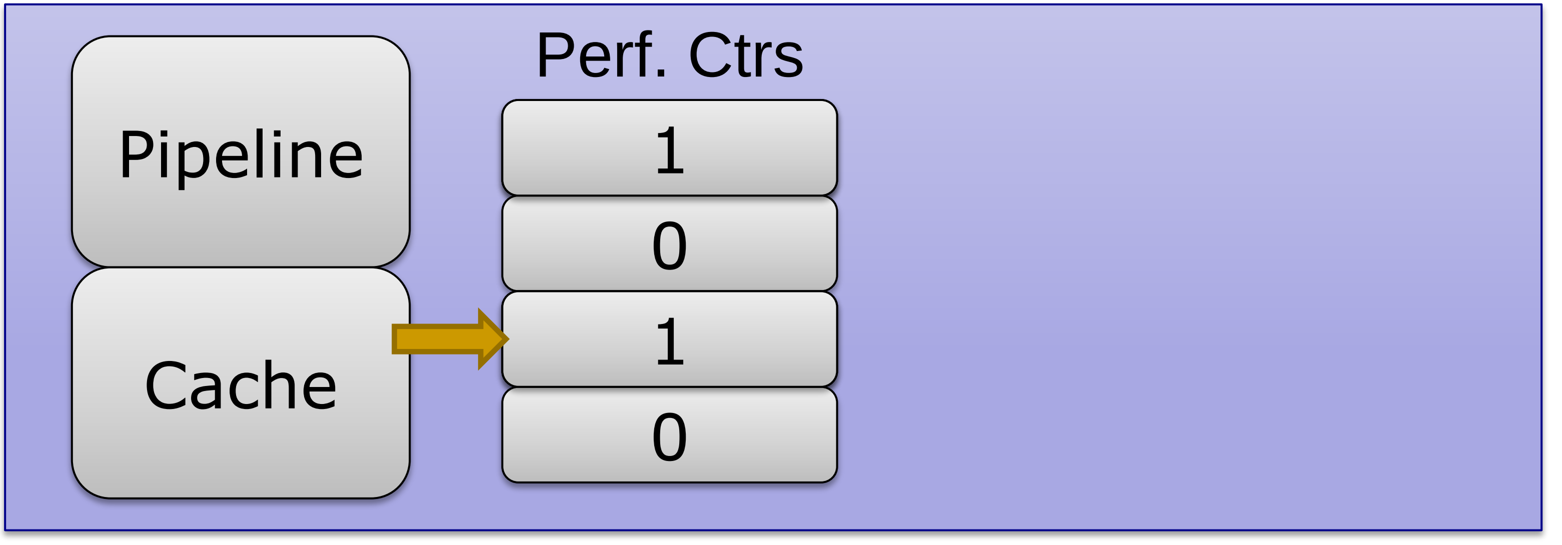

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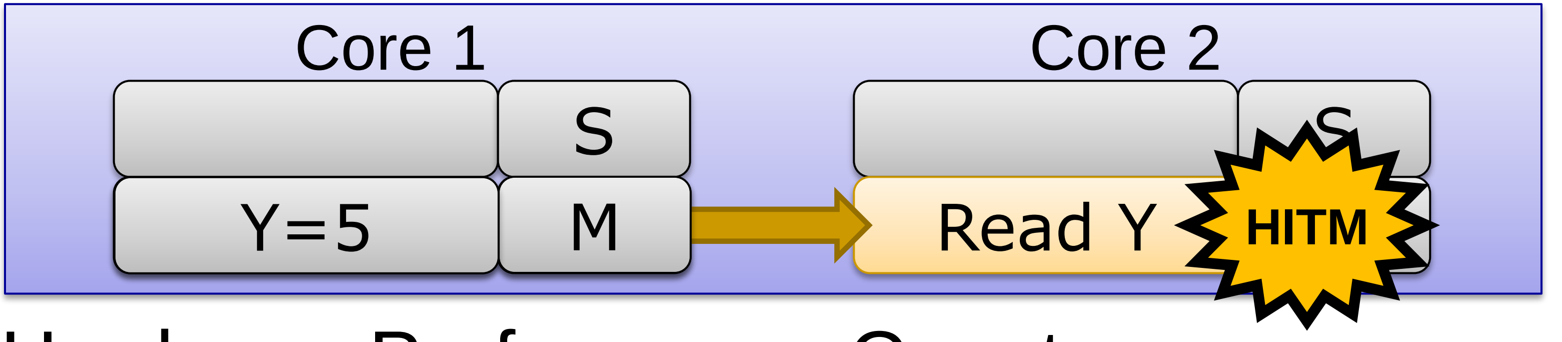

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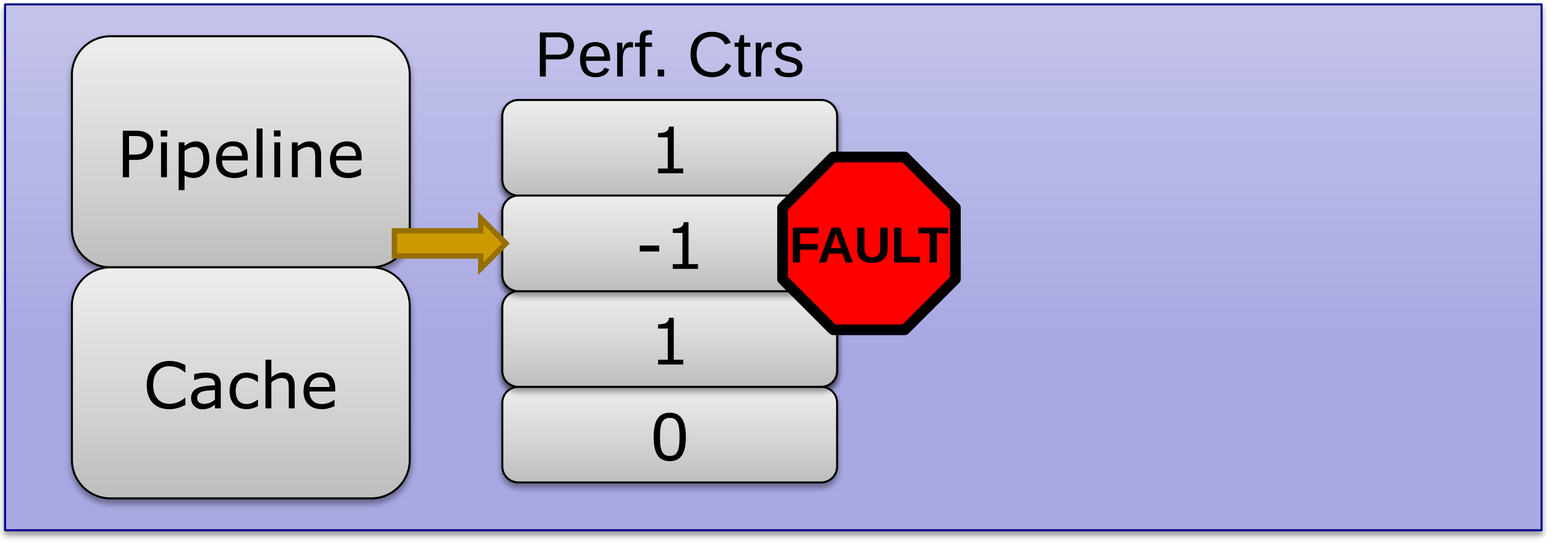

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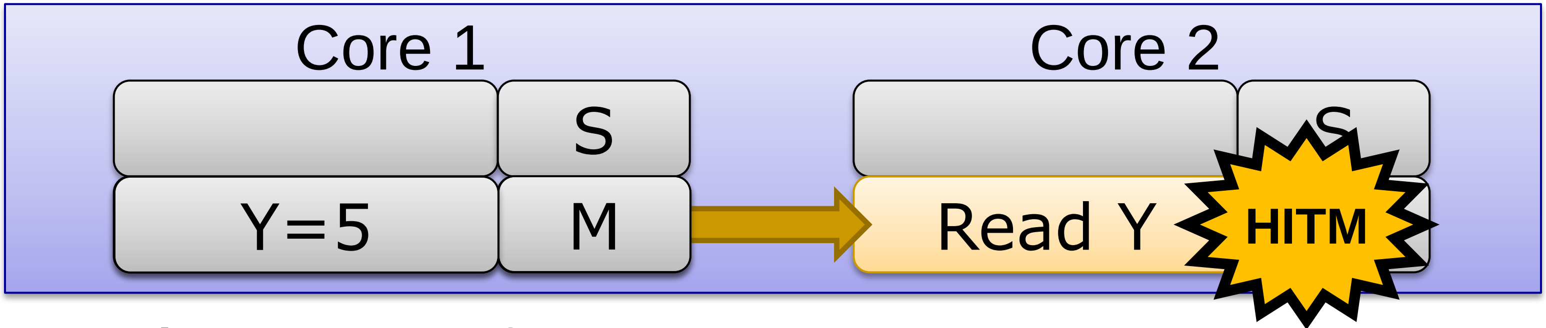

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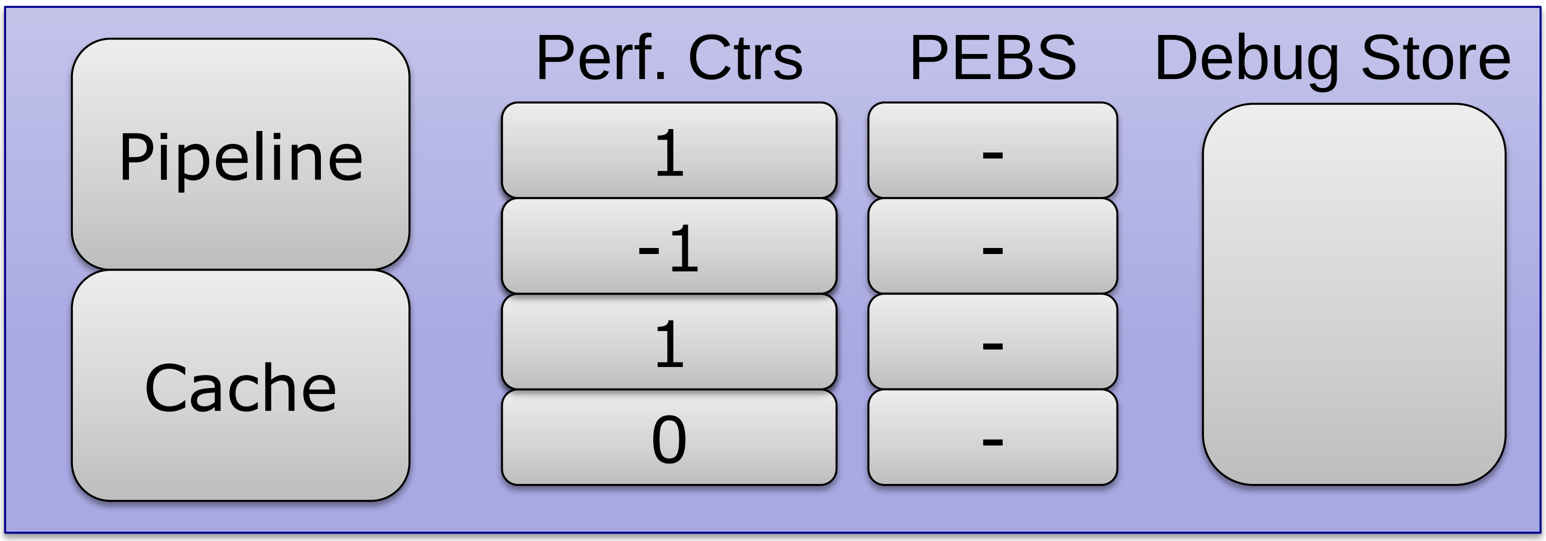

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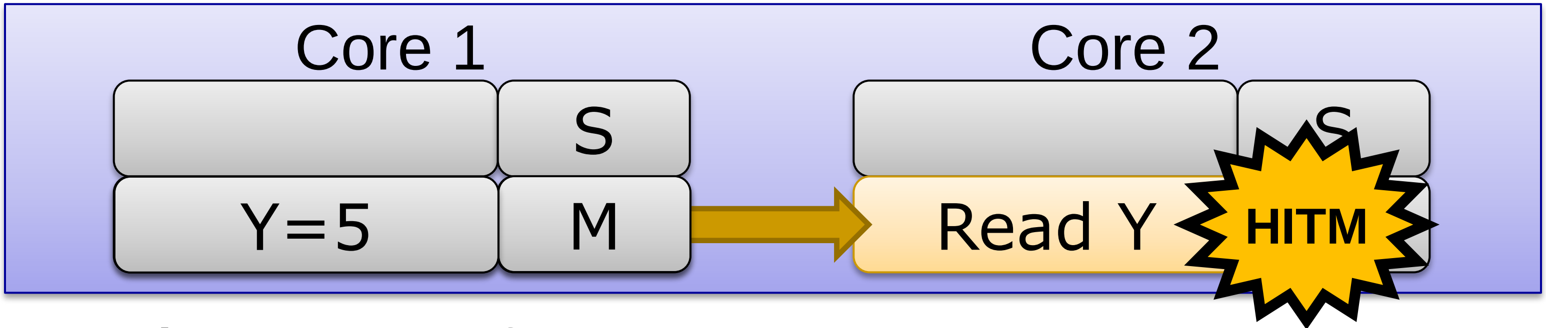

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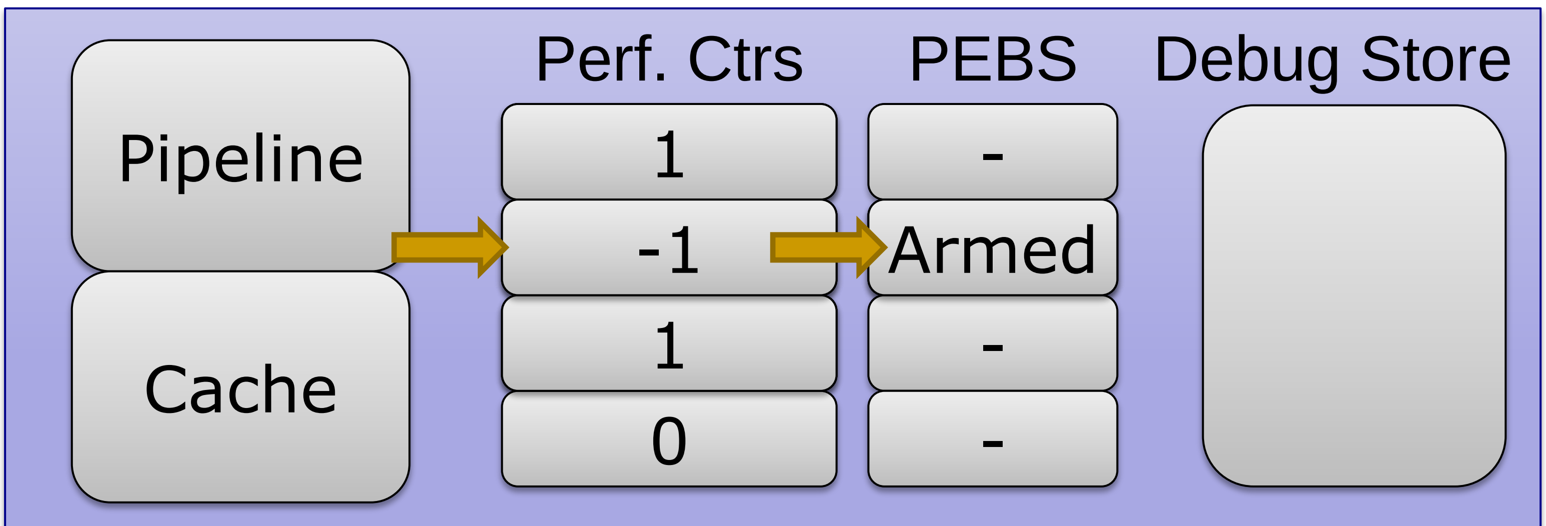

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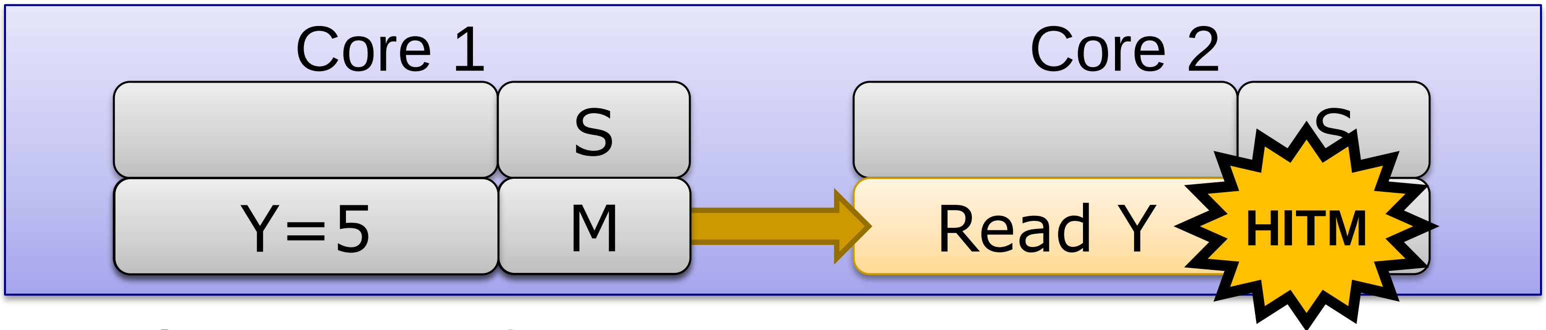

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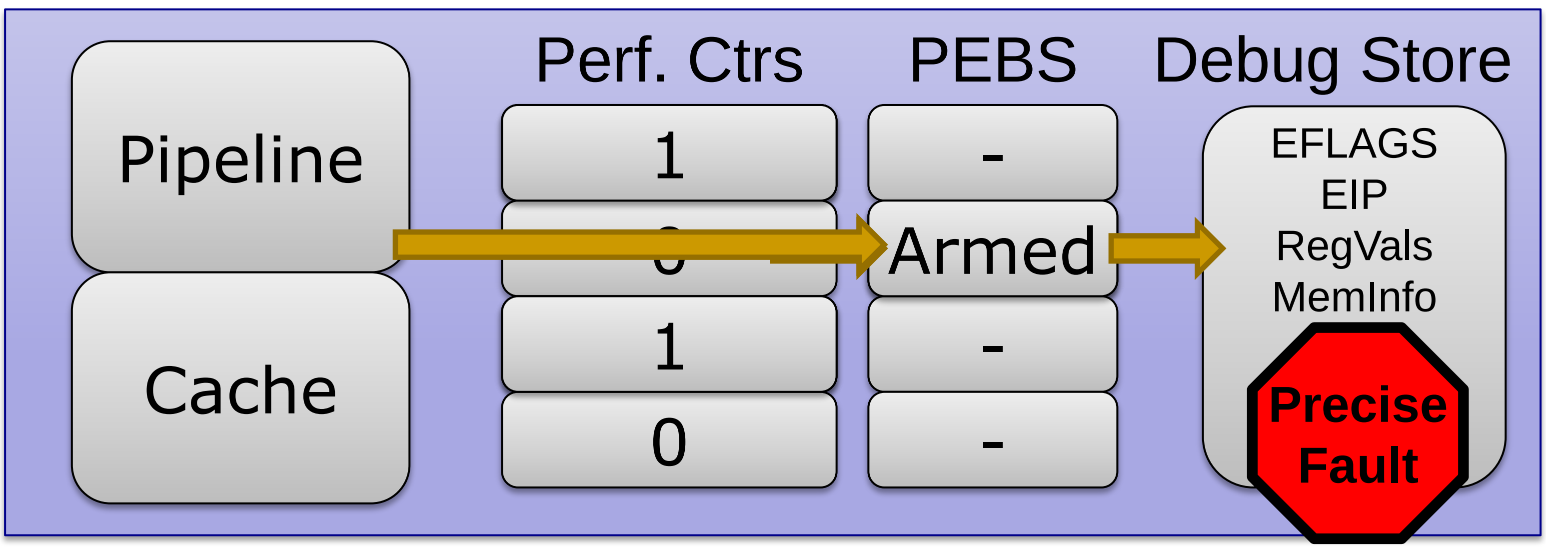
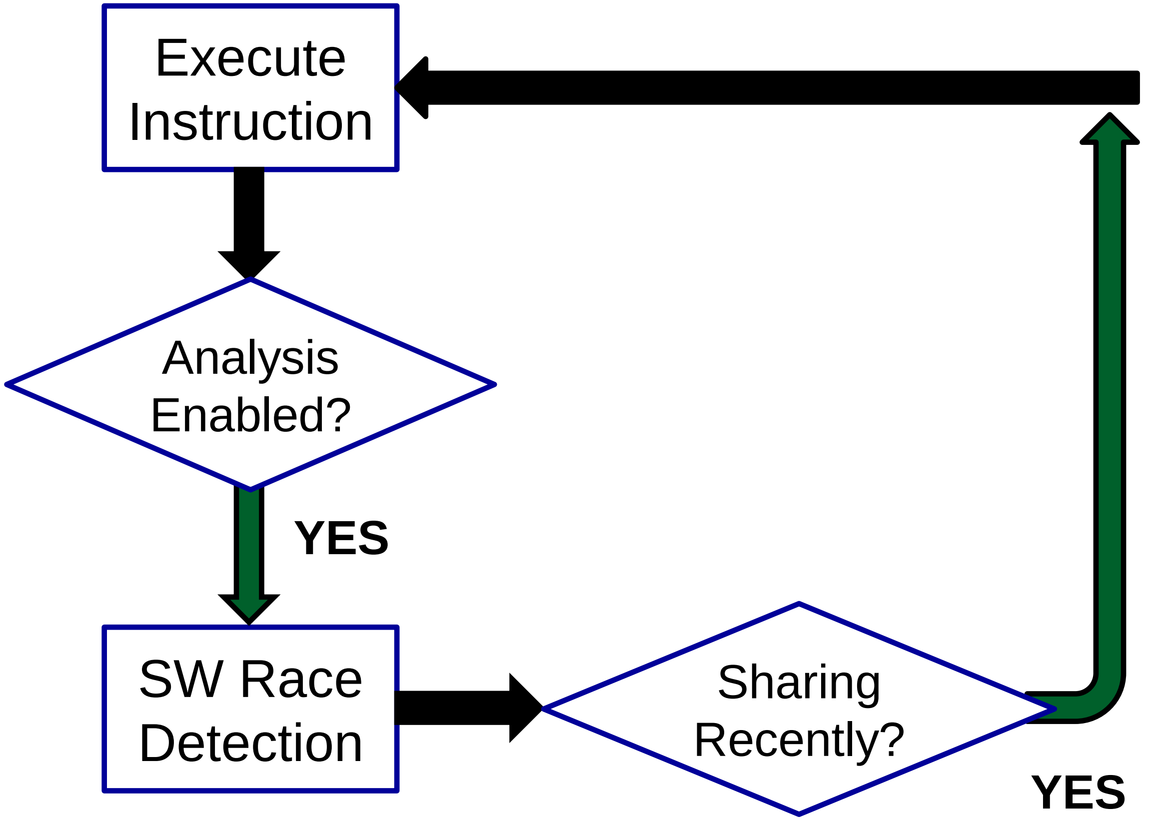


Potential Accuracy & Perf. Problems

- Limitations of Performance Counters
  - HITM only finds W→R Data Sharing
  - Hardware prefetcher events aren’t counted
- Limitations of Cache Events
  - SMT sharing can’t be counted
  - Cache eviction causes missed events
  - False sharing, etc…
- PEBS events still go through the kernel

On-Demand Analysis on Real HW



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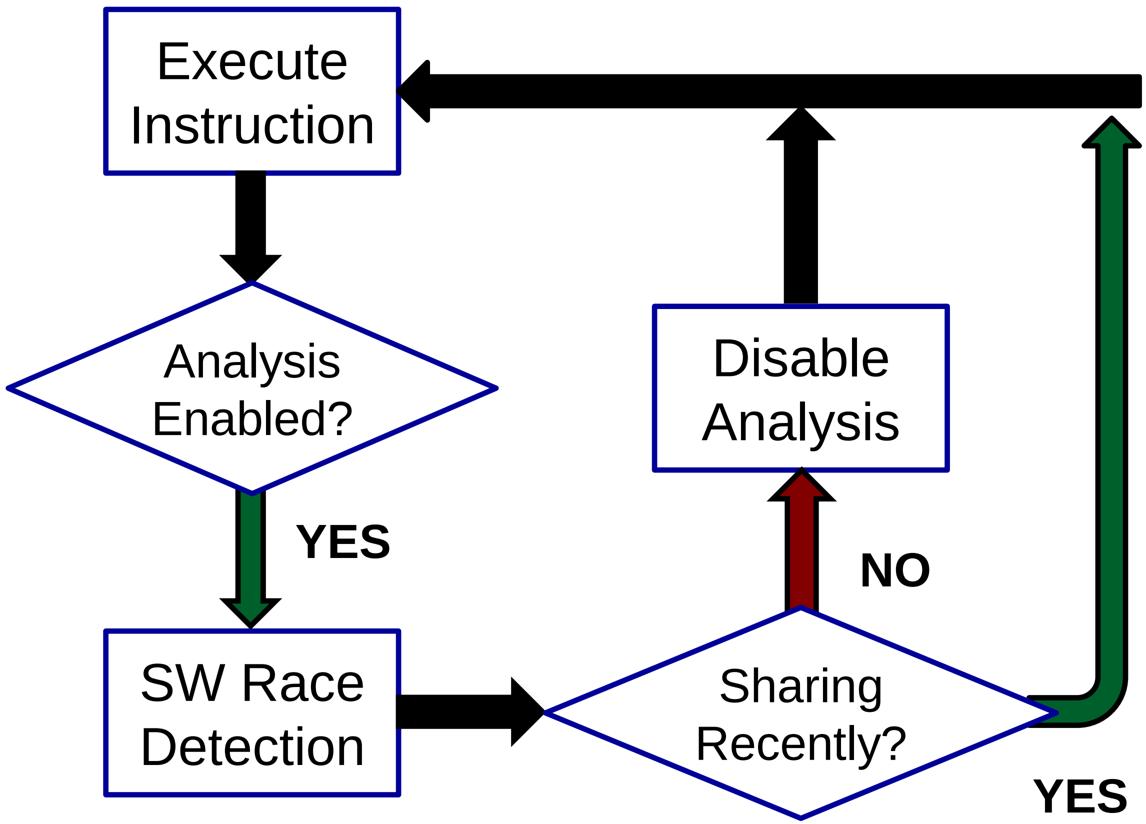

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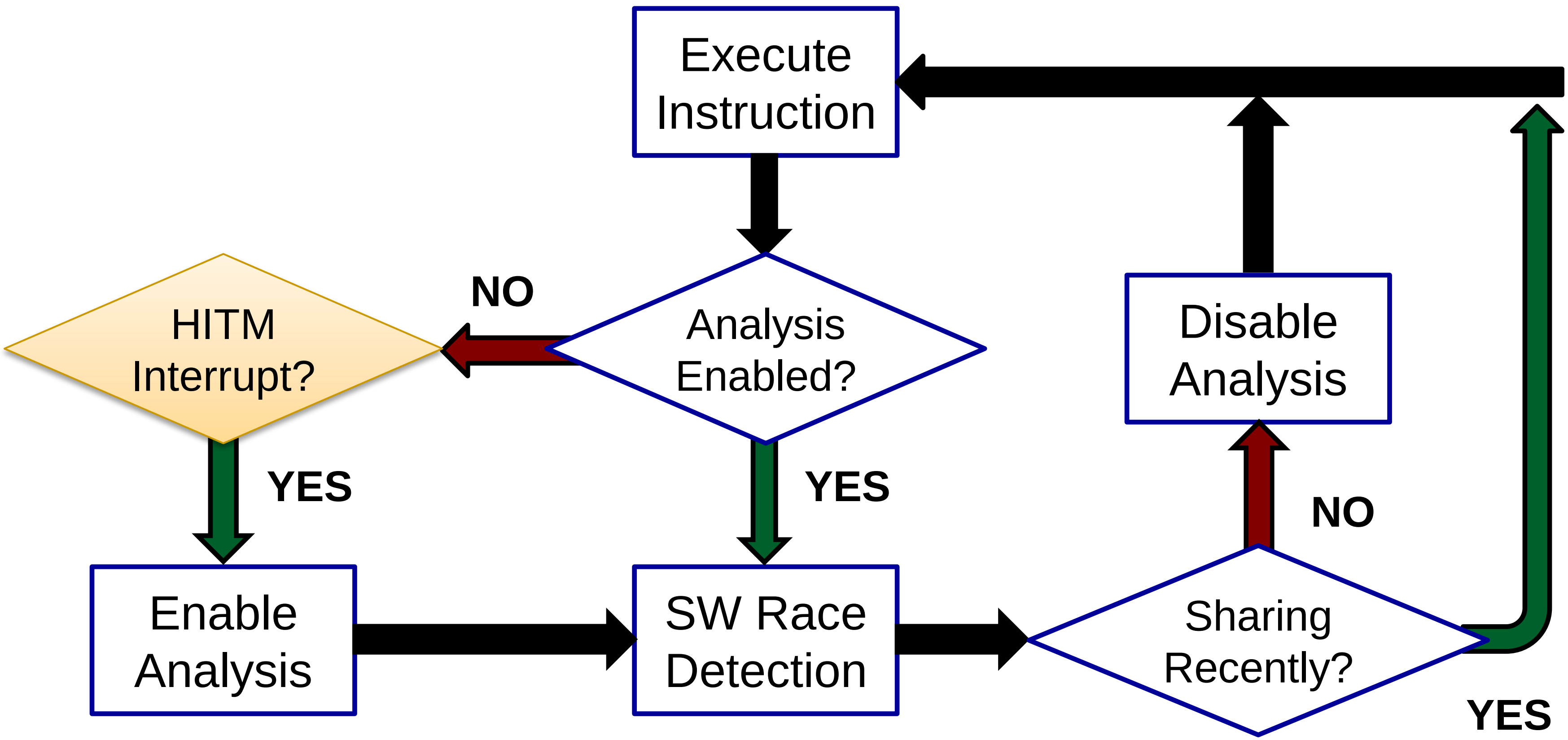

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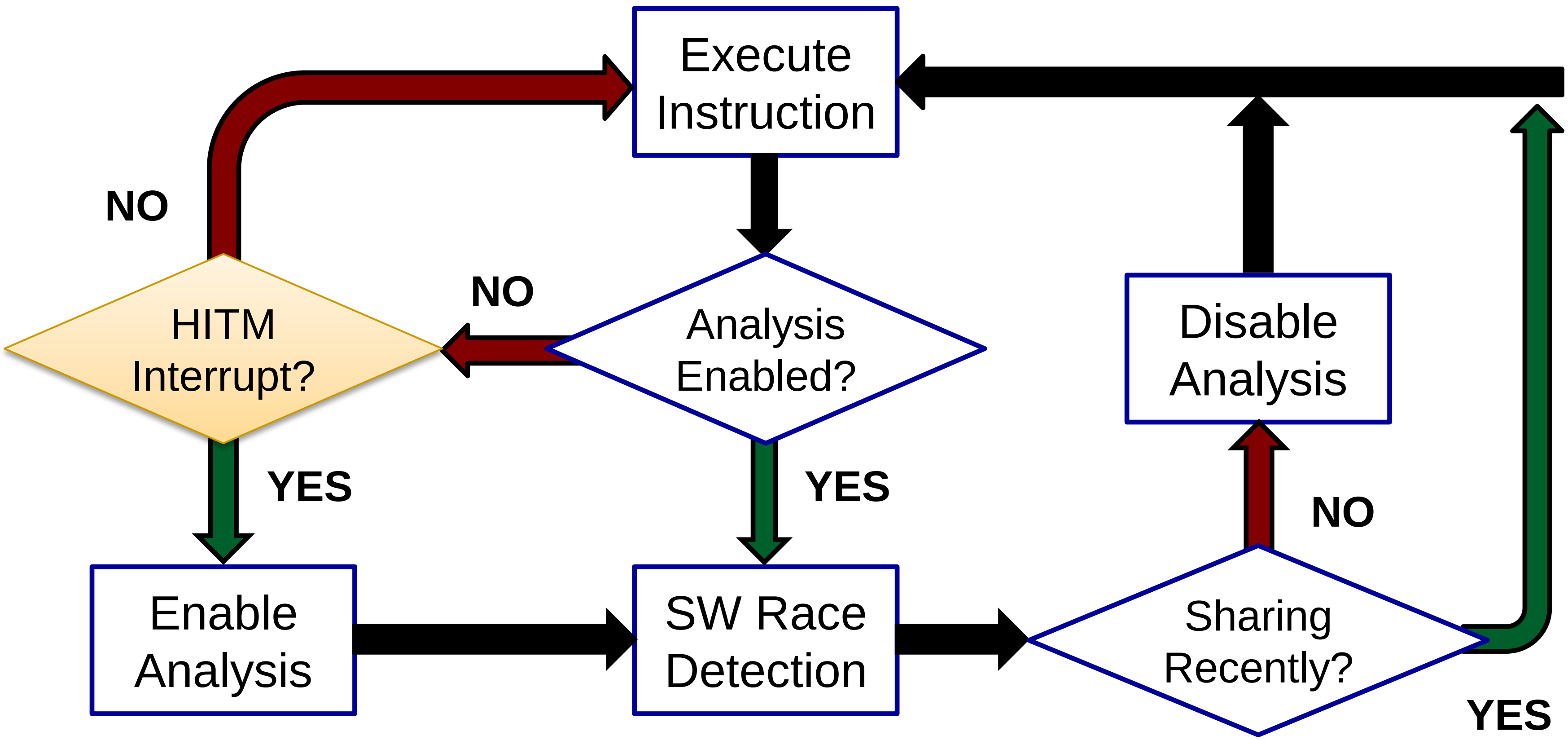

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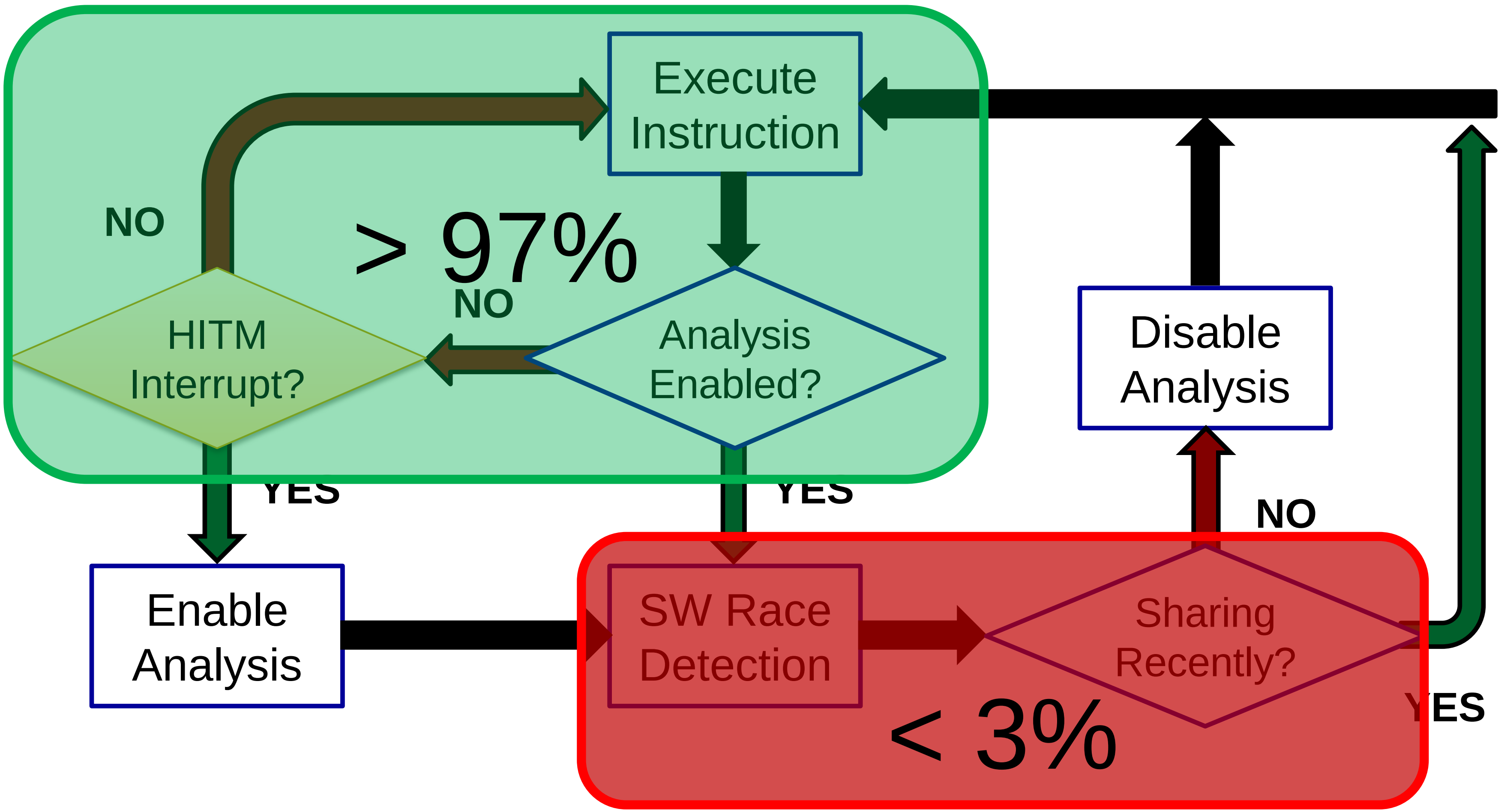
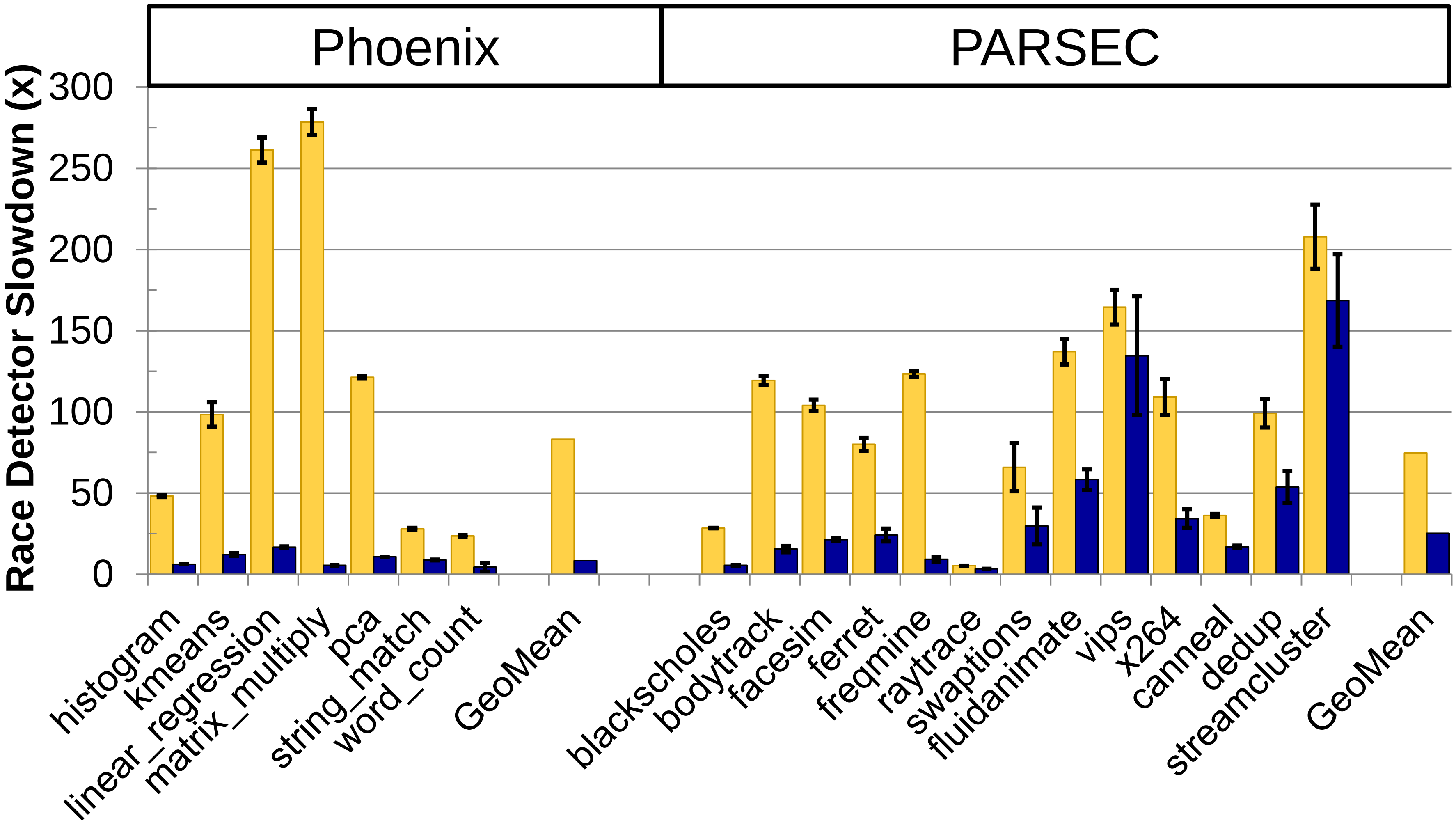
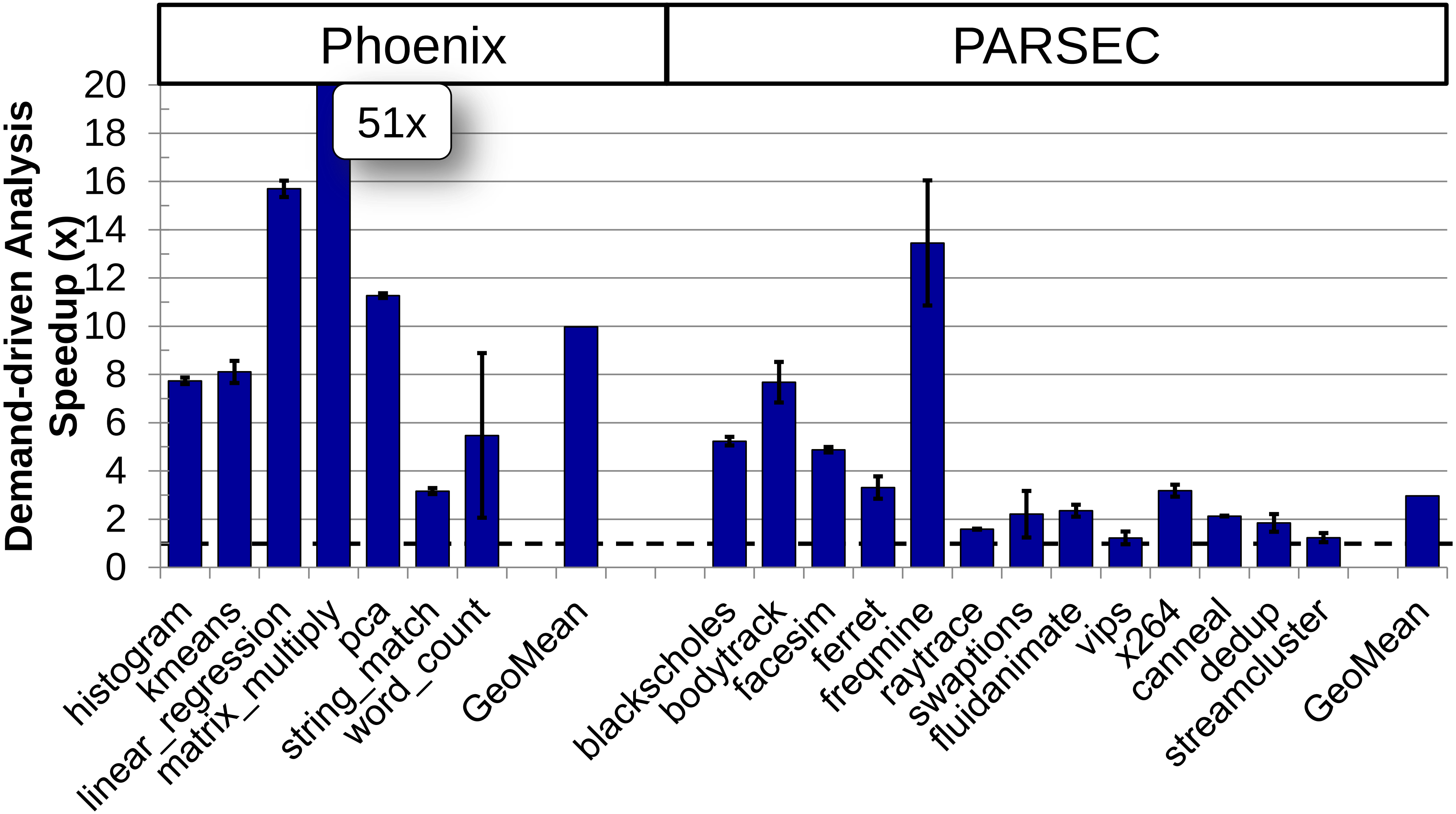


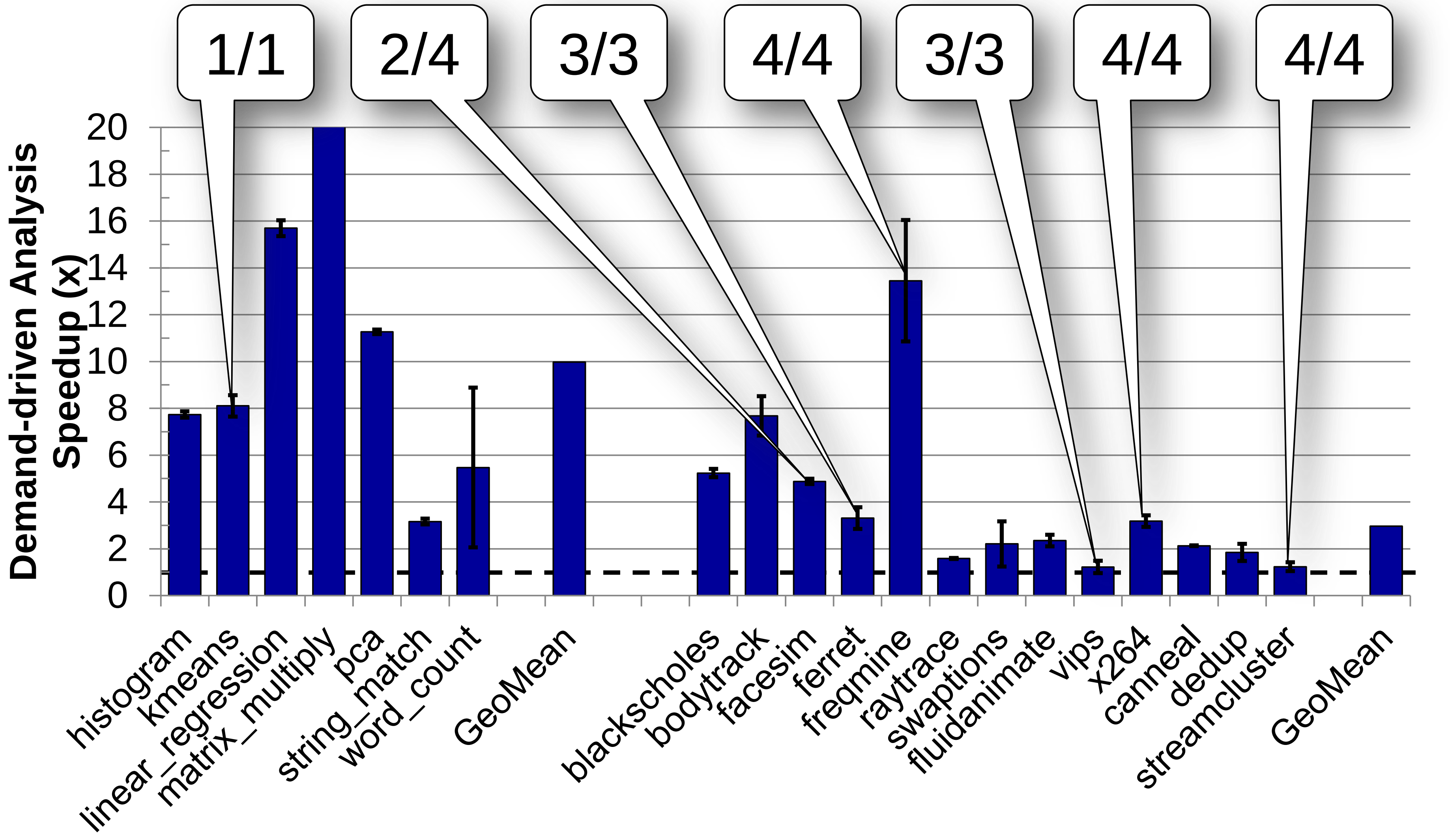
Performance Difference



Performance Increases



Demand-Driven Analysis Accuracy



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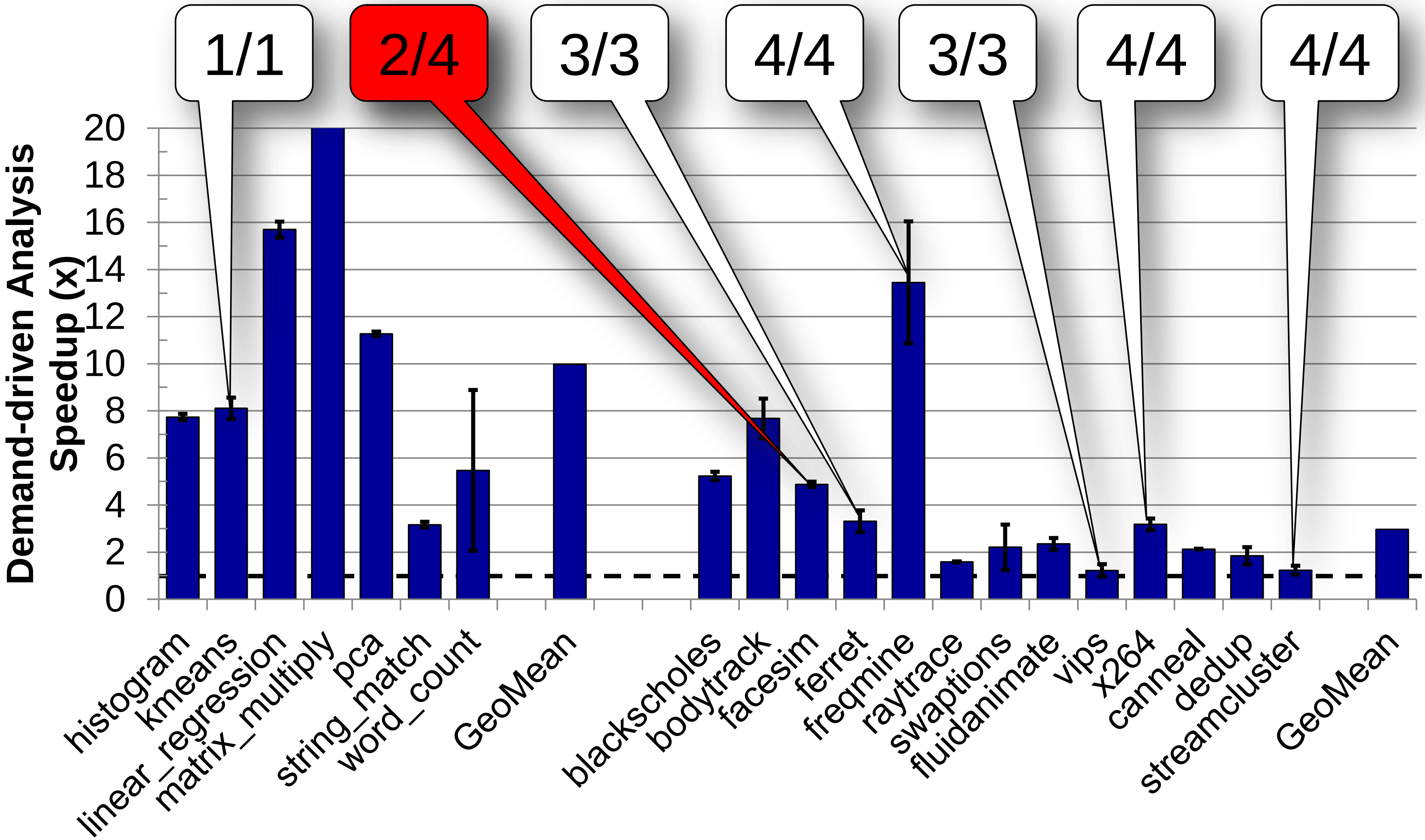

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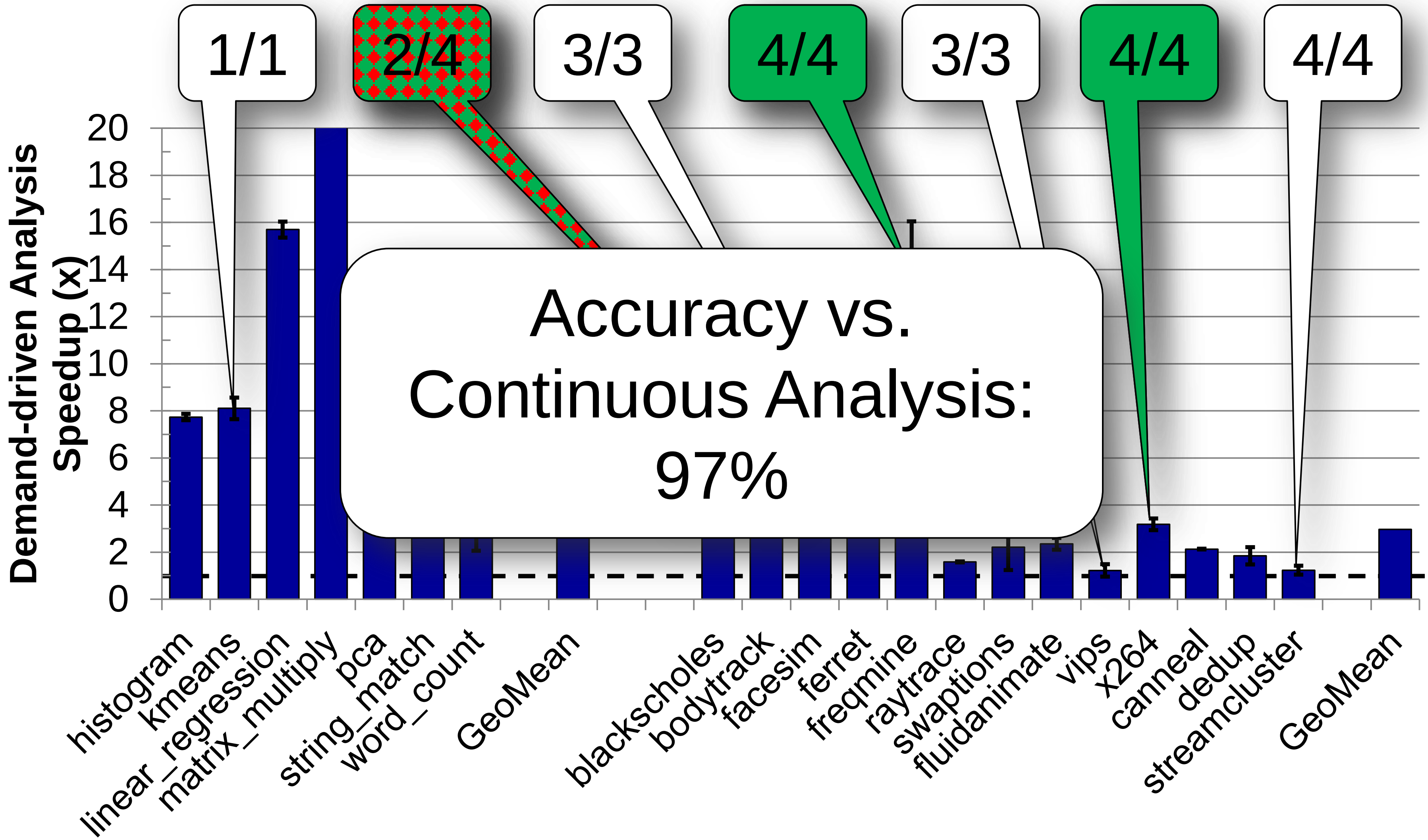

Outline

- Problem Statement
- Background Information
  - Demand-Driven Dynamic Dataflow Analysis
- Proposed Solutions
  - Demand-Driven Data Race Detection
  - Unlimited Hardware Watchpoints

Watchpoints Globally Useful

- Byte/Word Accurate and Per-Thread

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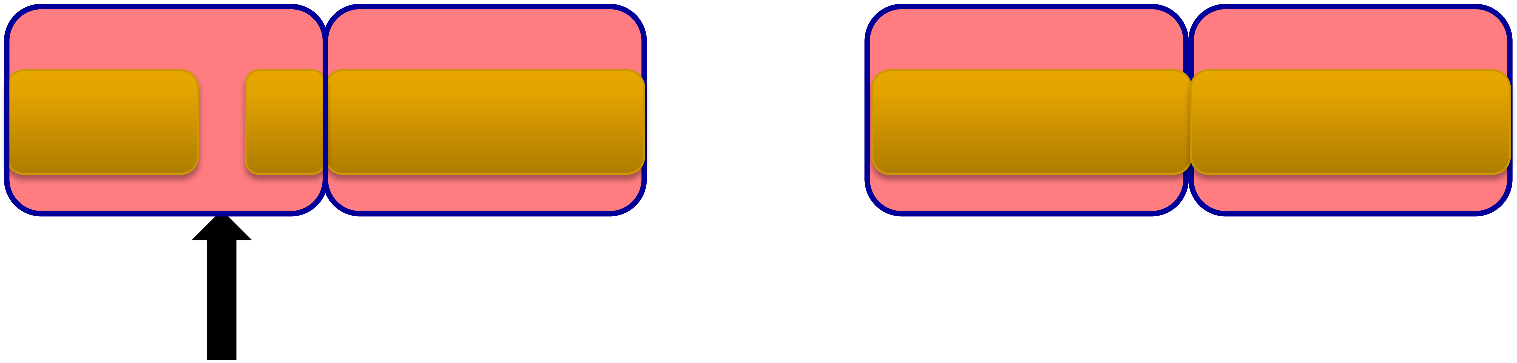

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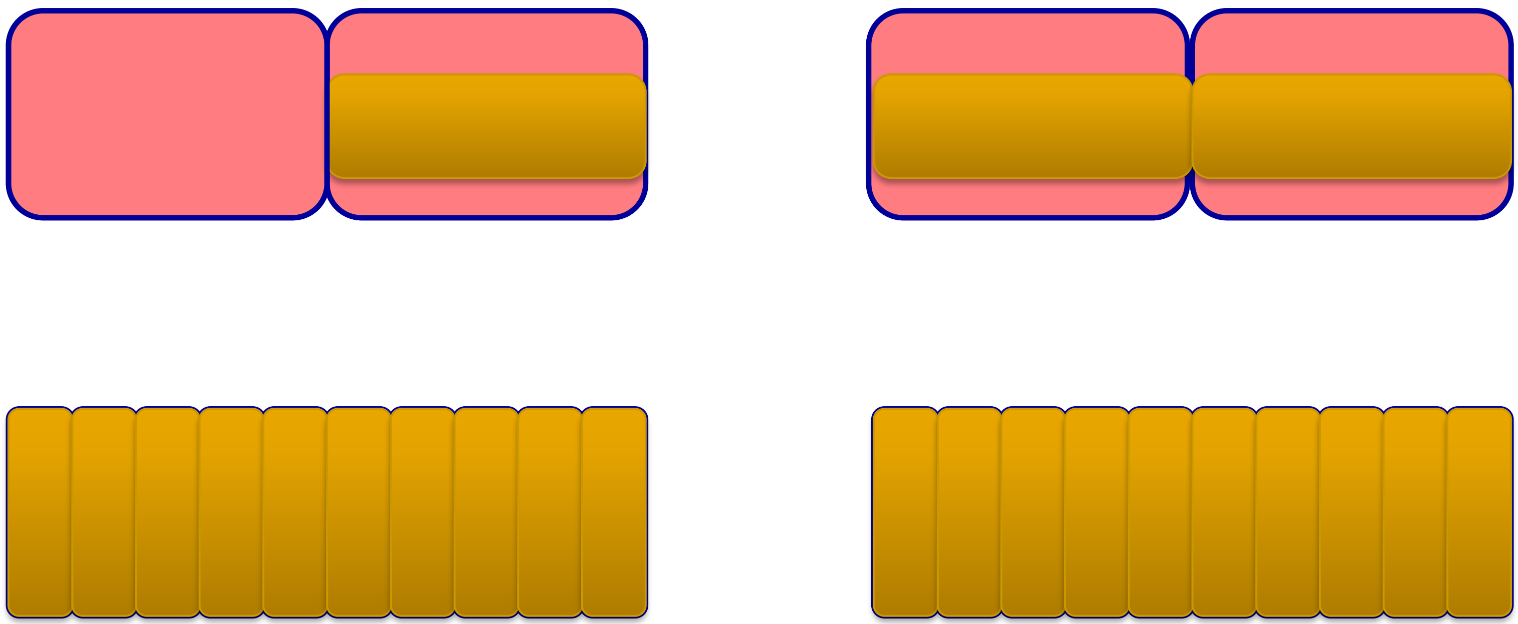

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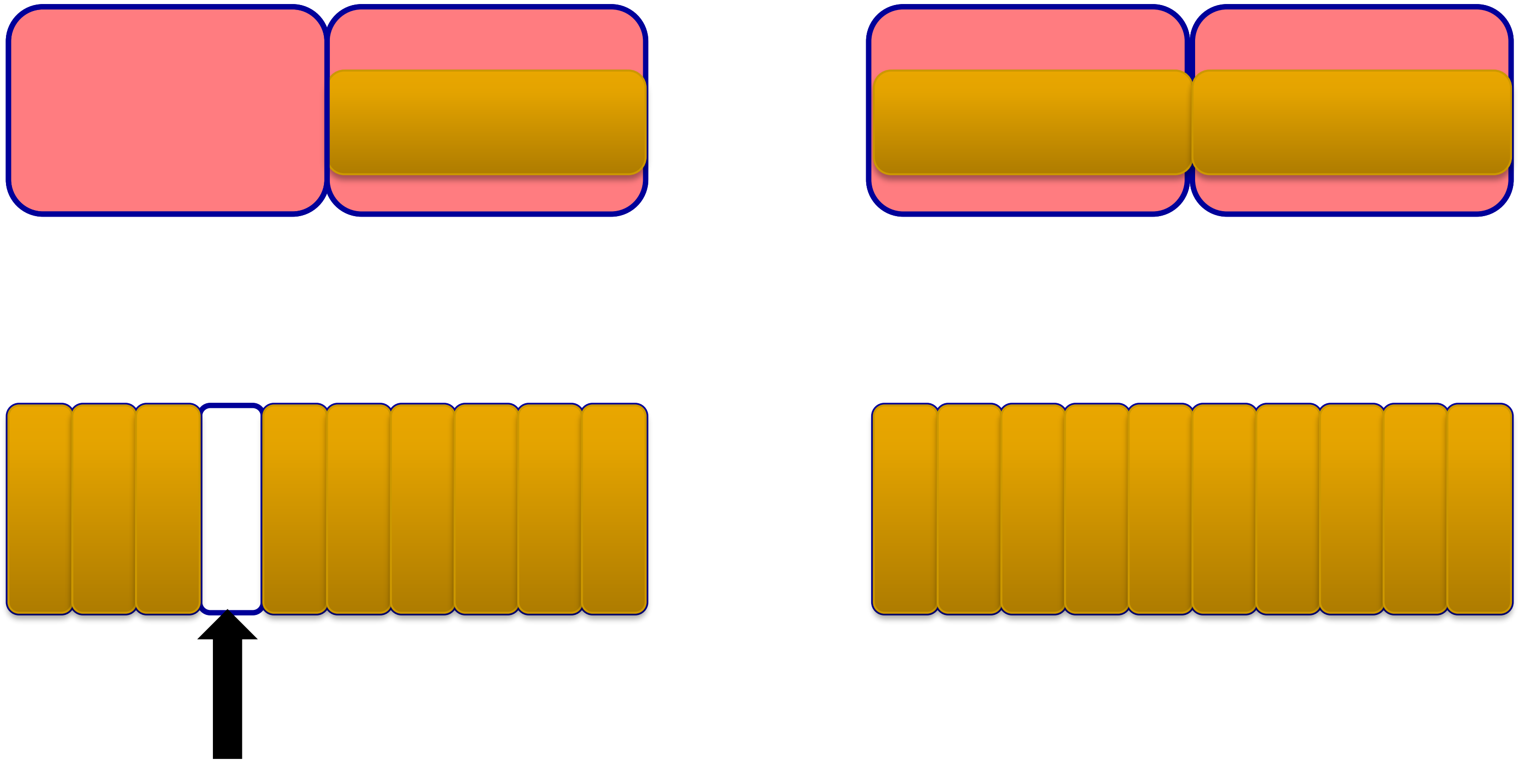

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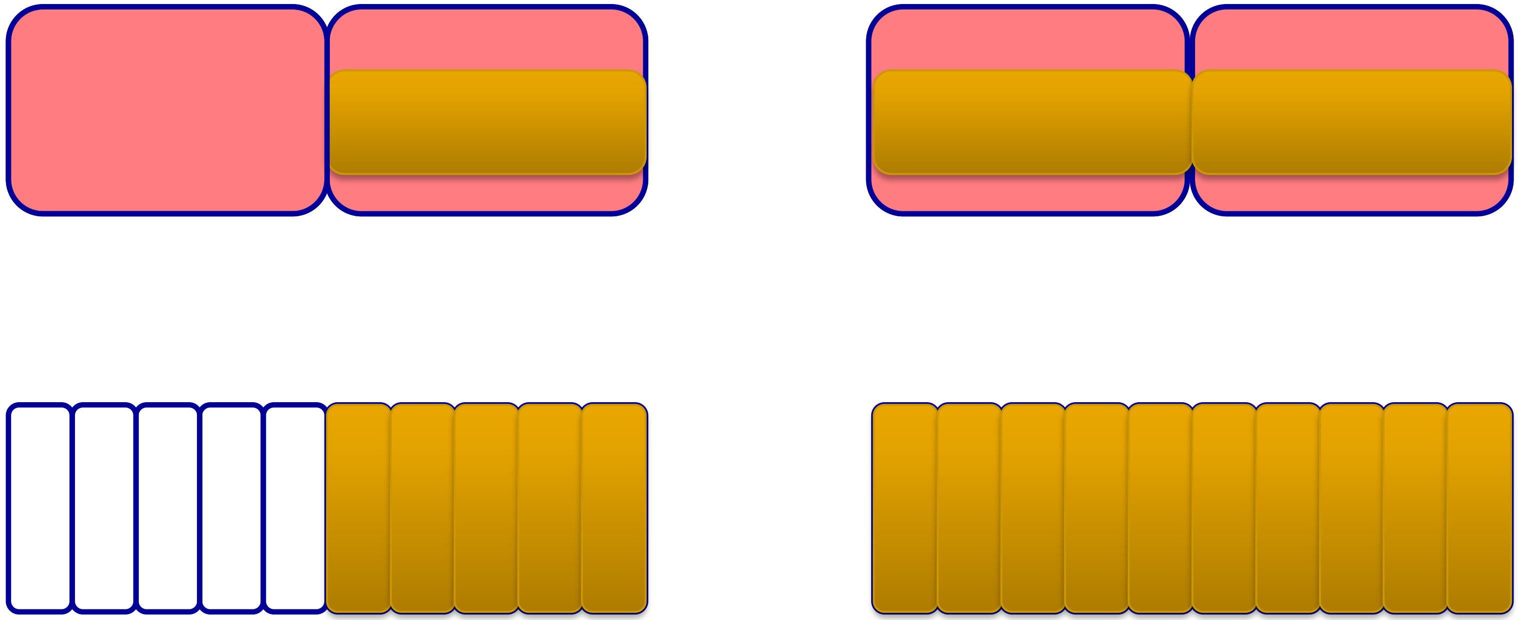


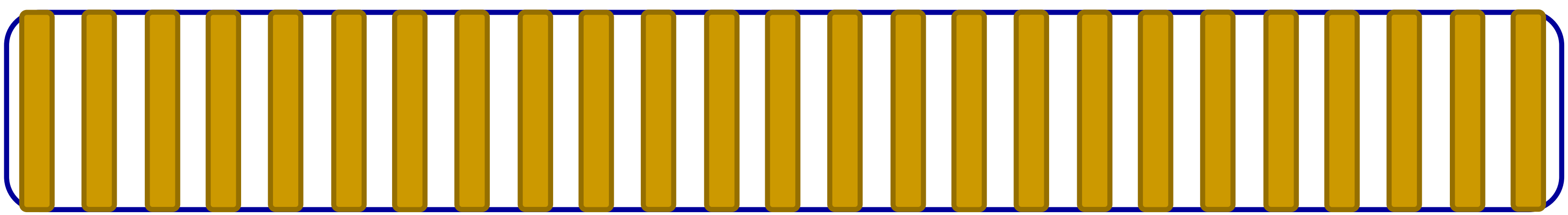
Watchpoint-Based Software Analyses

- Taint Analysis
- Data Race Detection
- Deterministic Execution
- Canary-Based Bounds Checking
- Speculative Program Optimization
- Hybrid Transactional Memory

Challenges

- Some analyses require watchpoint ranges

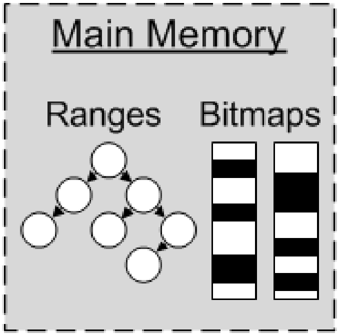
  - Better stored as base + length
- Some need large # of small watchpoints



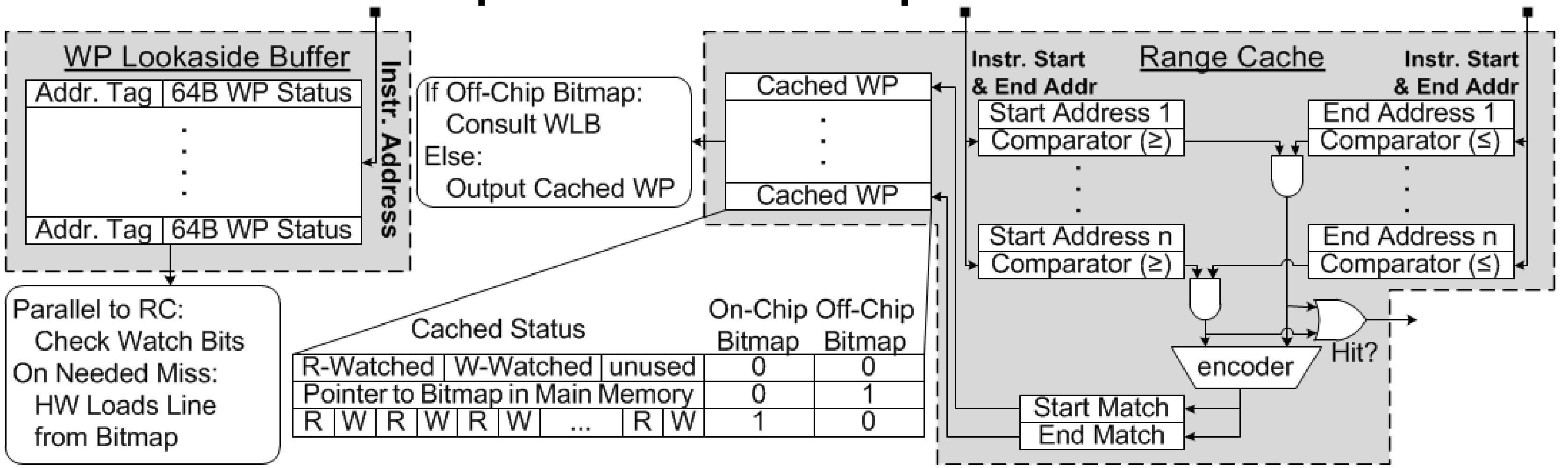
  - Better stored as bitmaps
- Need a large number

The Best of Both Worlds

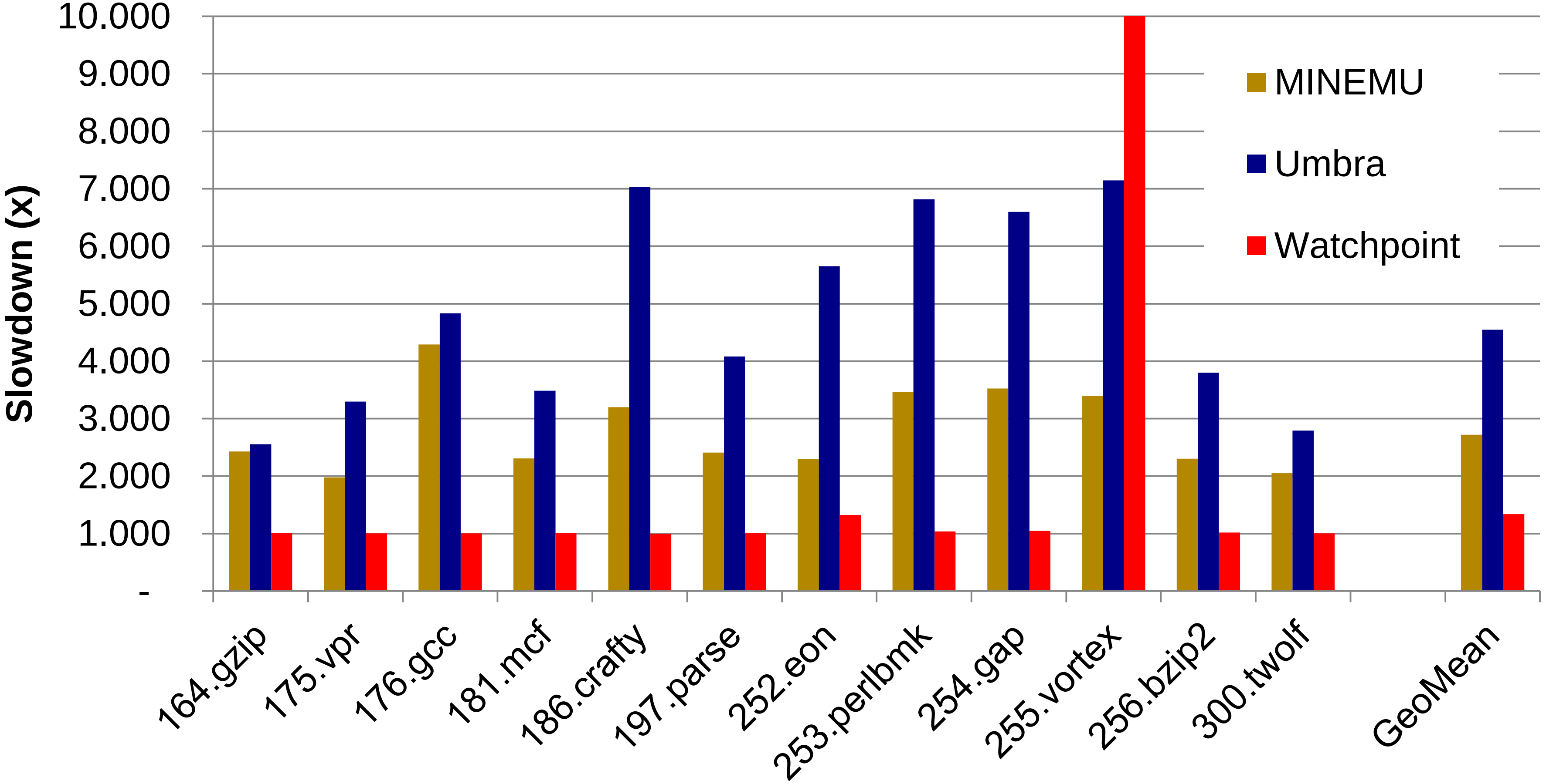
- Store Watchpoints in Main Memory



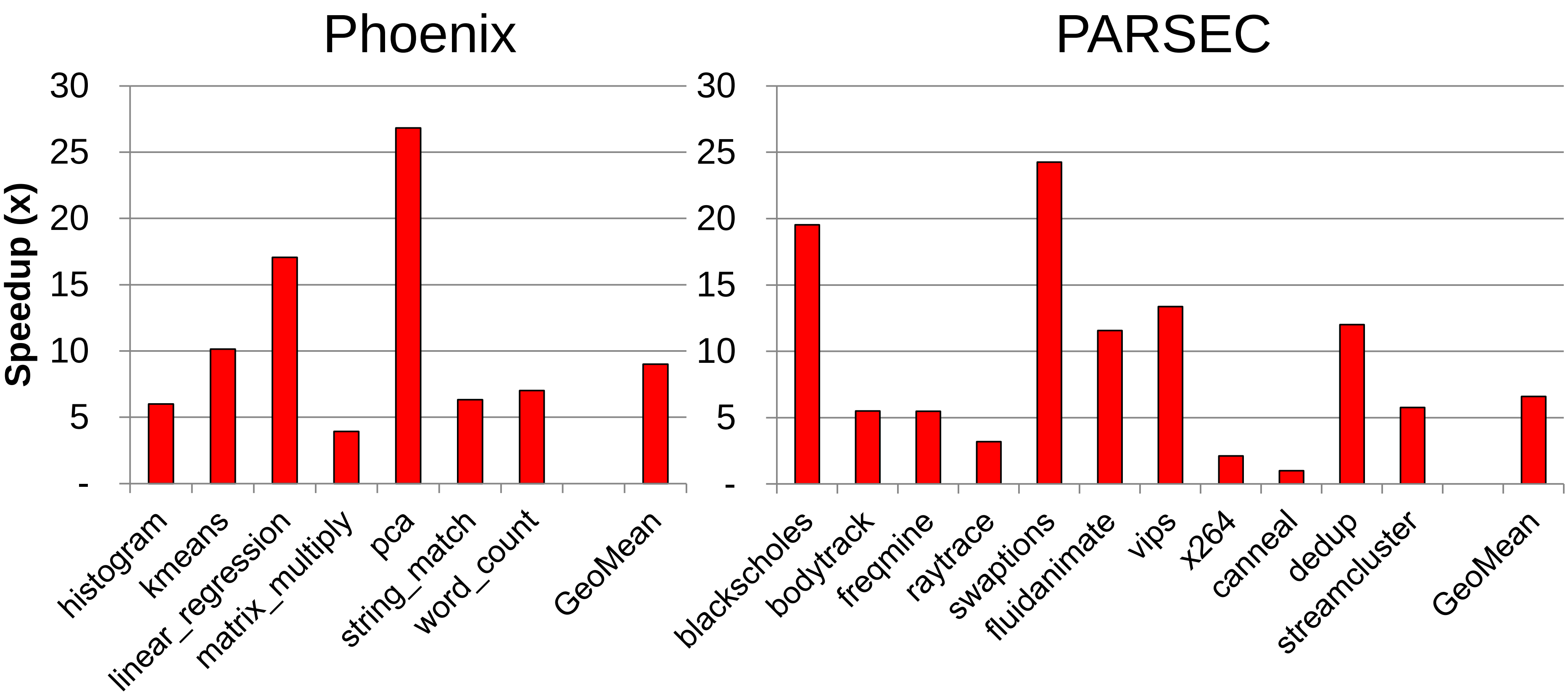
- Cache watchpoints on-chip



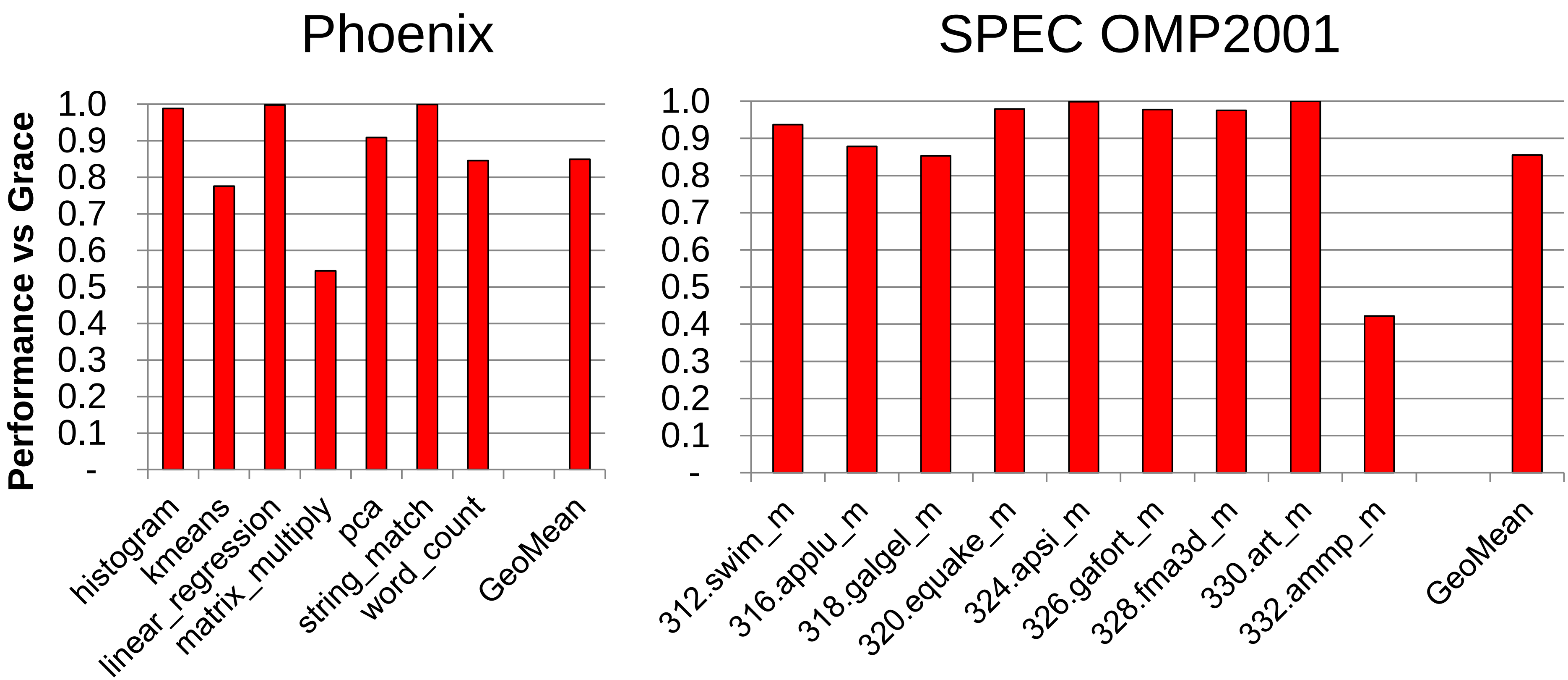
Demand-Driven Taint Analysis



Watchpoint-Based Data Race Detection



Watchpoint Deterministic Execution



BACKUP SLIDES