On-Demand Dynamic Software Analysis

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Software Errors Abound

- NIST: SW errors cost U.S. ~$60 billion/year as of 2002

A problem has been detected and windows has been shut down to prevent damage to your computer.

The problem seems to be caused by the following file: SPCMDCON.SYS

PAGE_FAULT_IN_NONPAGED_AREA

If this is the first time you've seen this Stop error screen,
restart your computer. If this screen appears again, follow
these steps:

Check to make sure any new hardware or software is properly installed.
If this is a new installation, ask your hardware or software manufacturer
for any windows updates you might need.

If problems continue, disable or remove any newly installed hardware
or software. Disable BIOS memory options such as caching or shadowing.
If you need to use Safe Mode to remove or disable components, restart
your computer, press F8 to select Advanced Startup Options, and then
select Safe Mode.

Technical information:

*** STOP: 0x00000050 (0xFD3094C2,0x00000001,0xFBFE7617,0x00000000)

*** SPCMDCON.SYS - Address FBFE7617 base at FBFE5000, DateStamp 3d6dd67c

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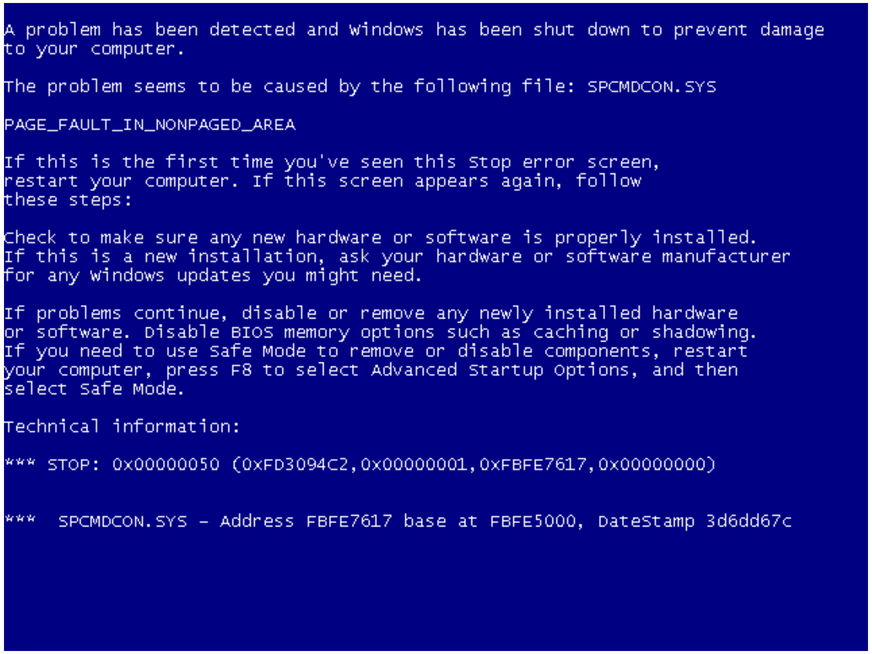

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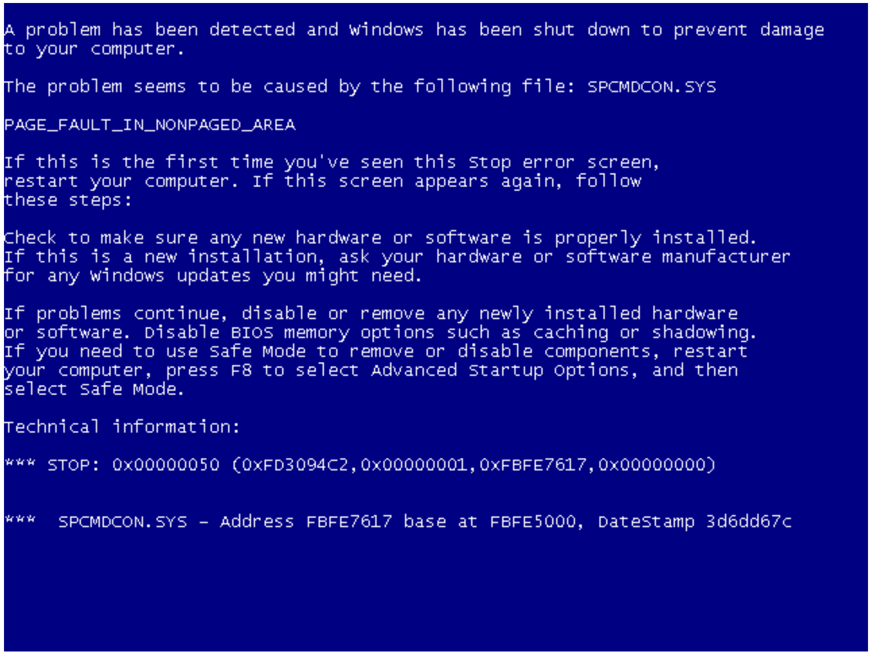
  - >⅓ from viruses, network intrusion, etc.



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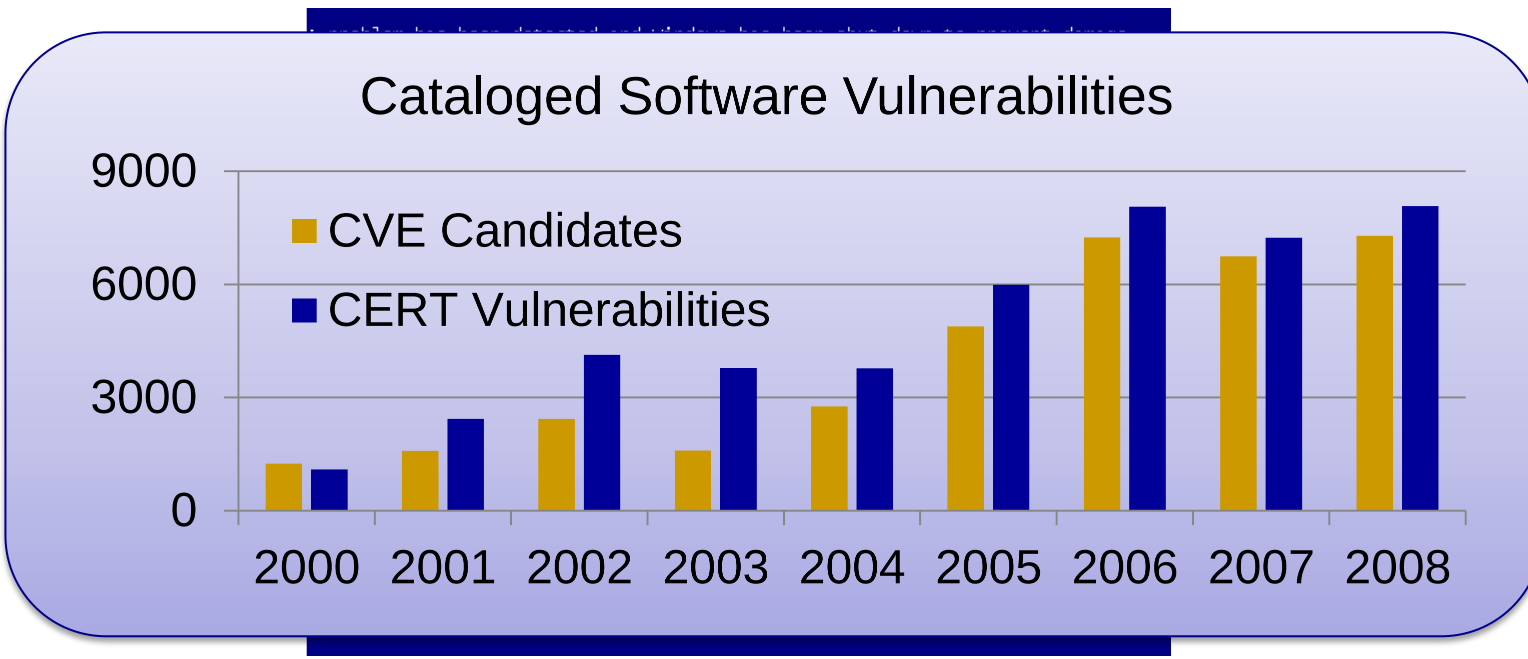
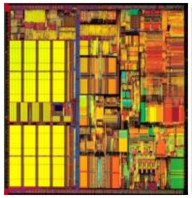
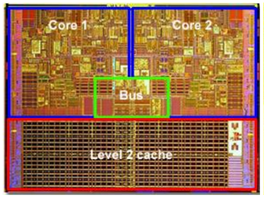
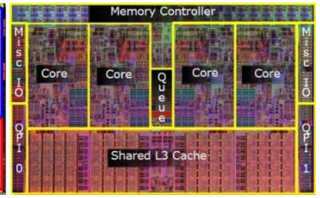
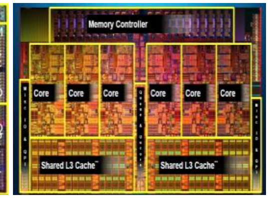
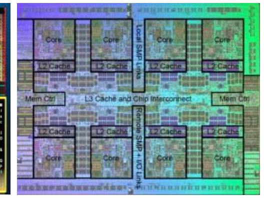


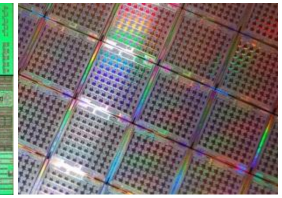
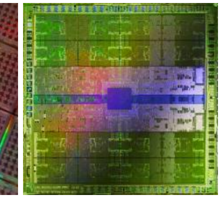
Hardware Plays a Role







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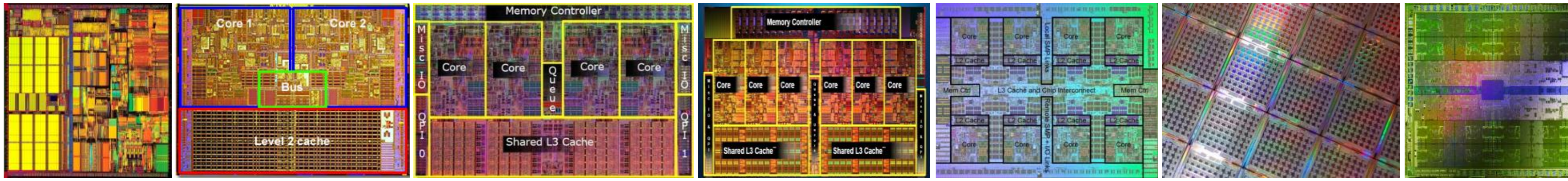

In spite of proposed solutions

Hardware Data Race Recording

Bulk Memory Commits

Deterministic Execution/Replay

Bug-Free Memory Models

Atomicity Violation Detectors

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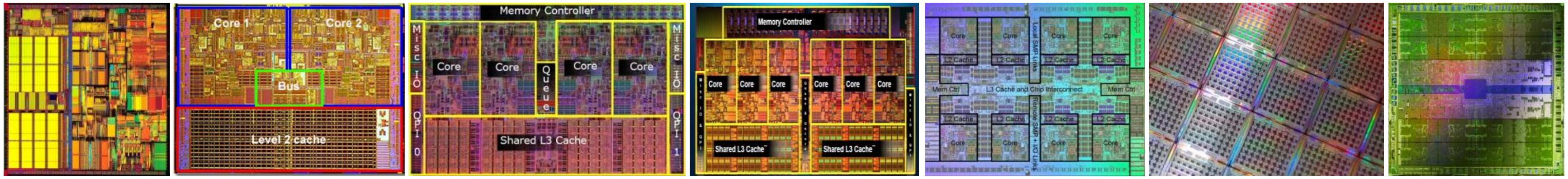

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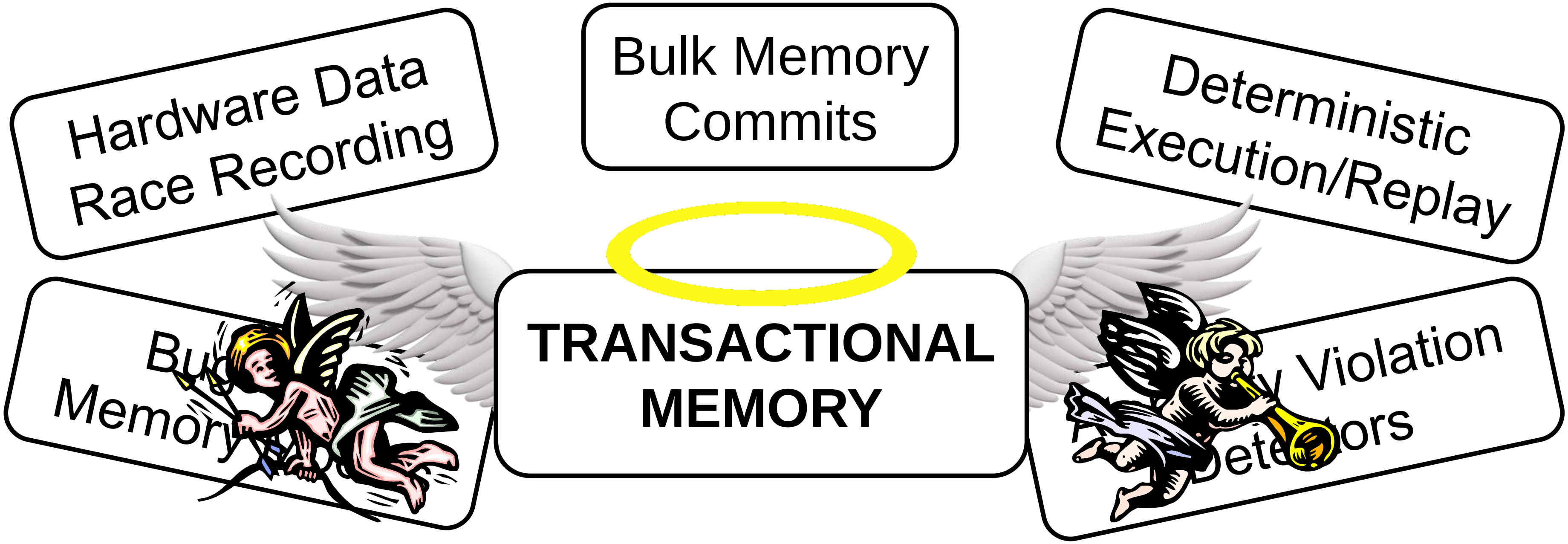

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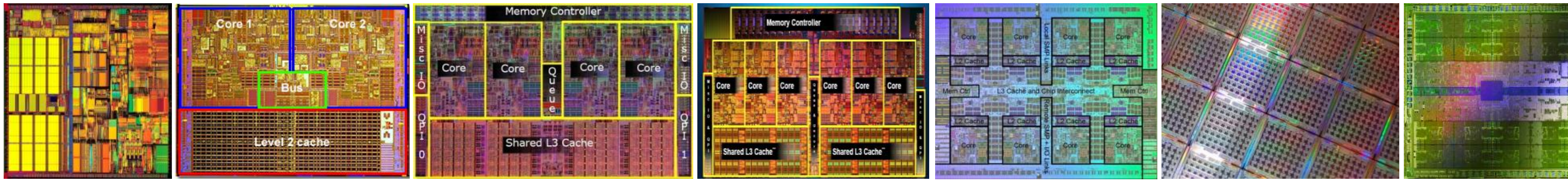

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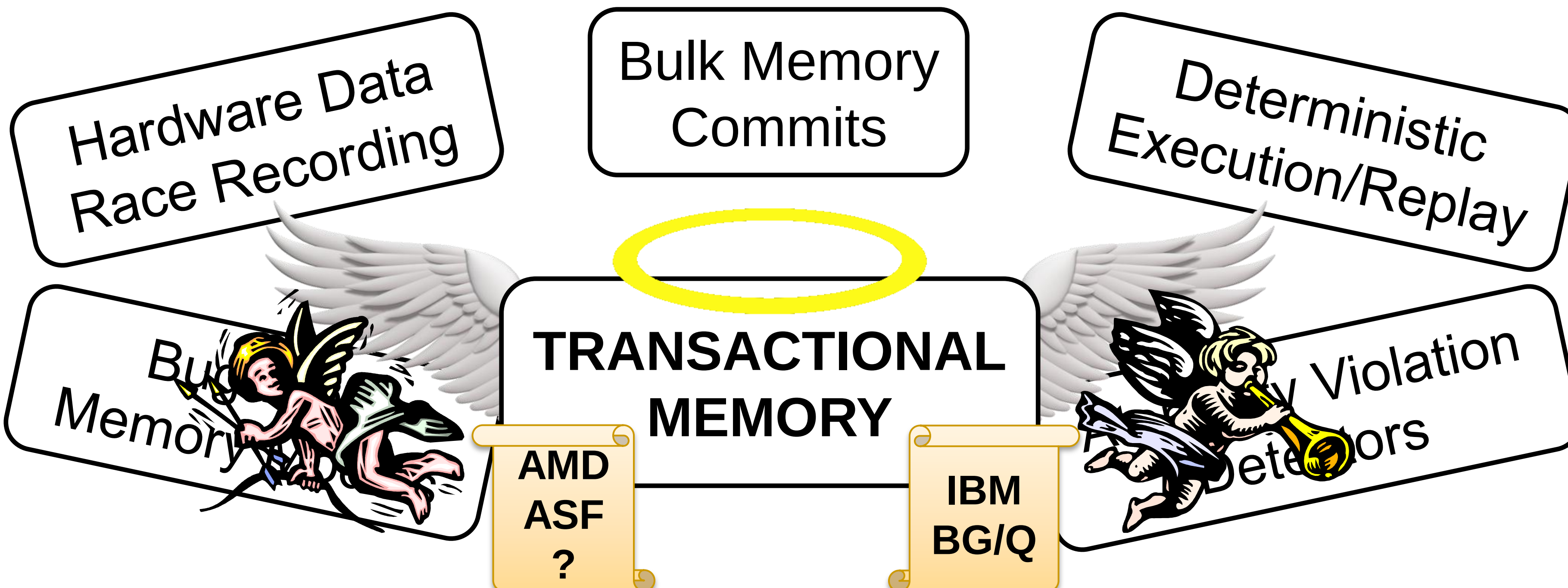

Example of Modern Bug

Nov. 2010 OpenSSL Security Flaw

Example of Modern Bug

TIME

Thread 1 mylen=small	Thread 2 mylen=large
`if(ptr==NULL)`	
	`if(ptr==NULL)`
	`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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`ptr`

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mylen=small

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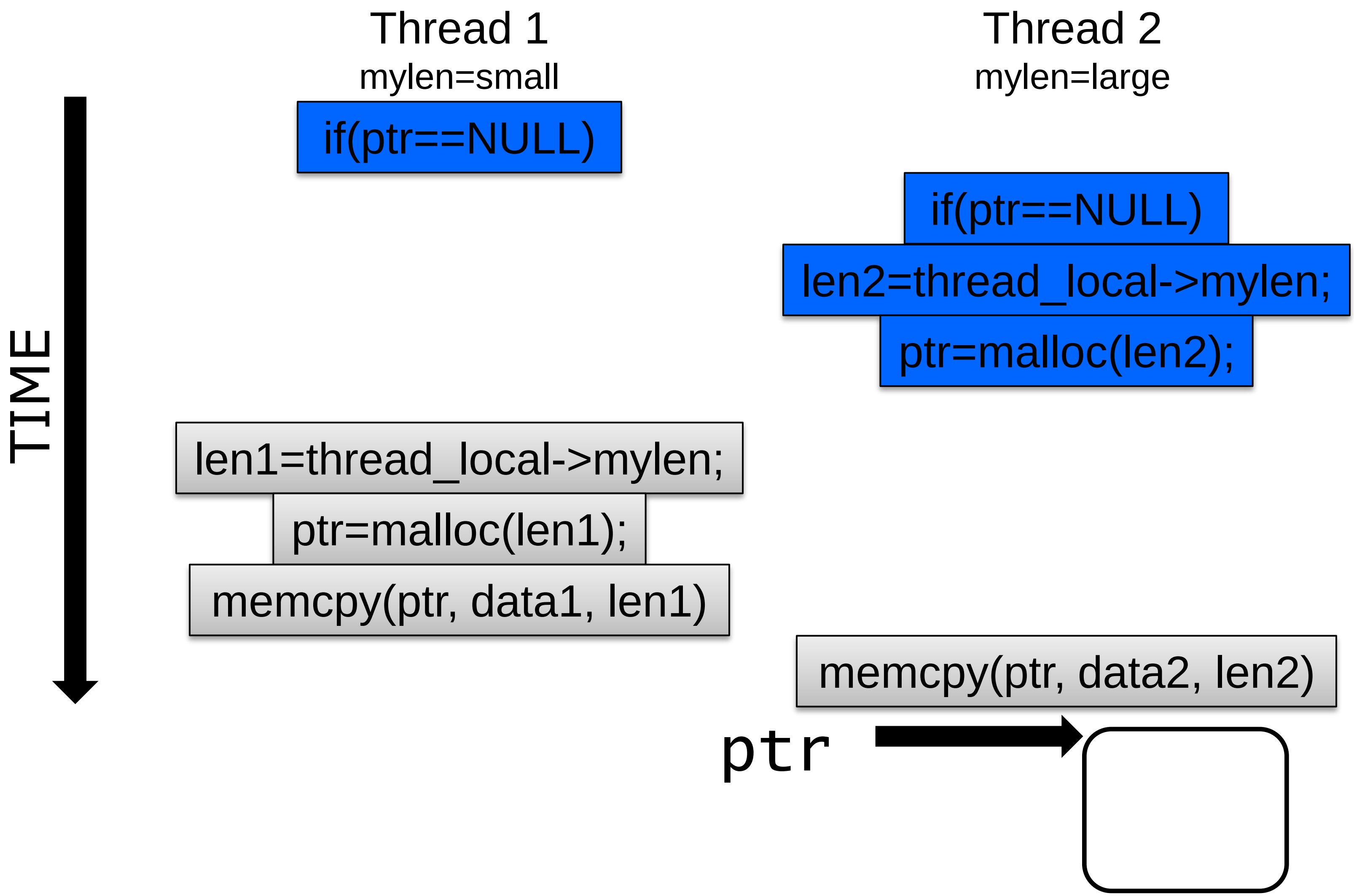

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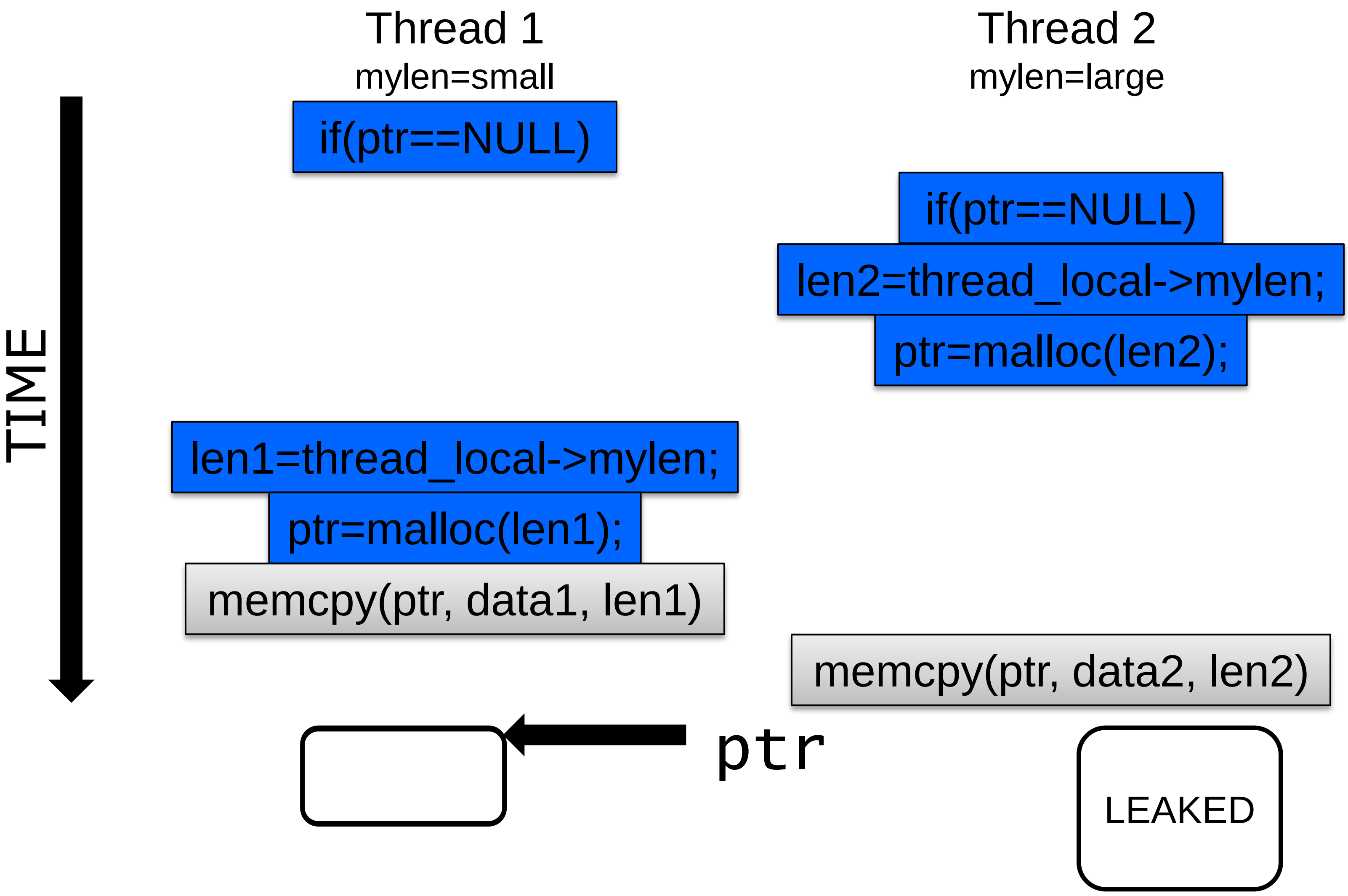

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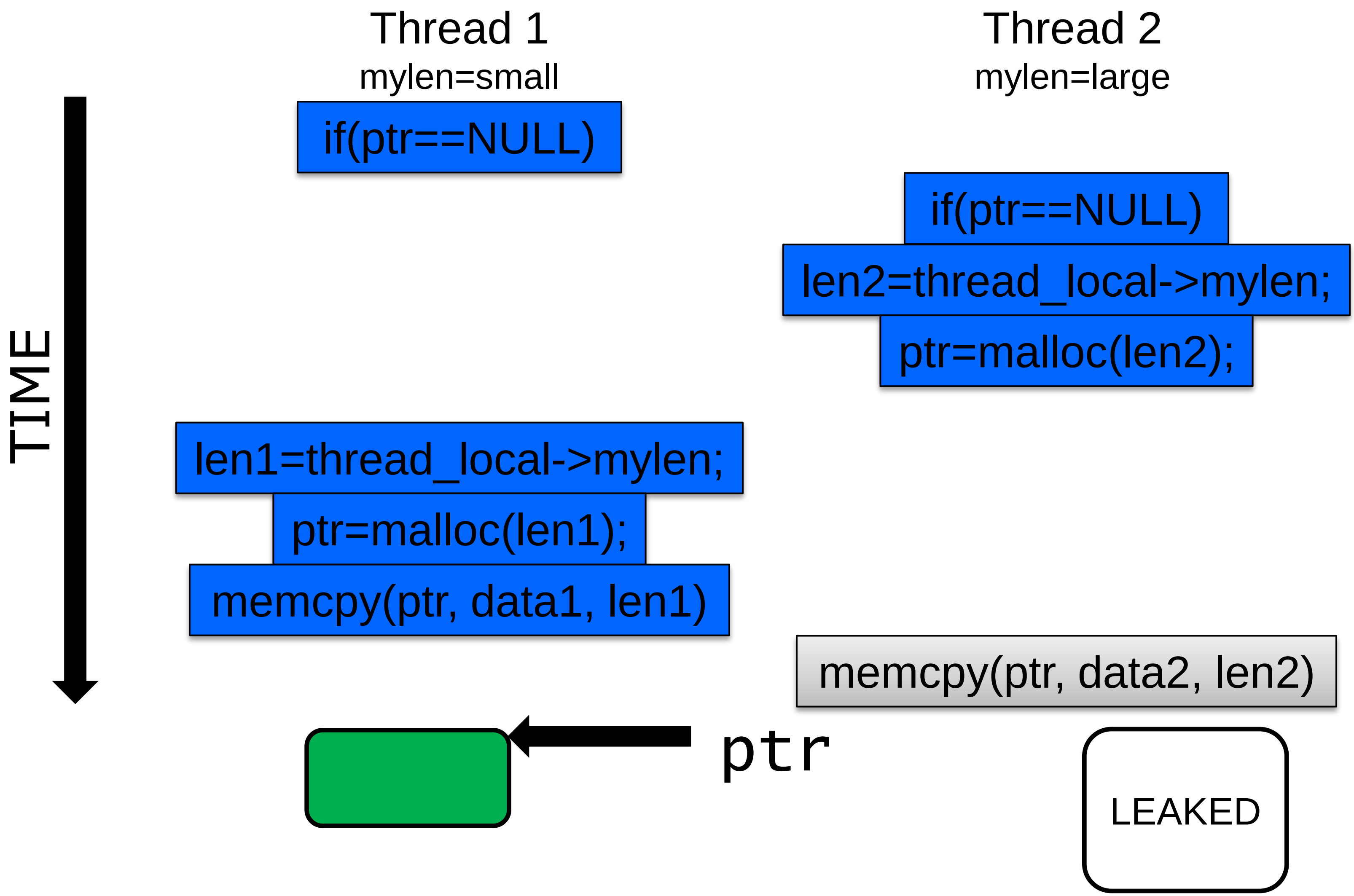

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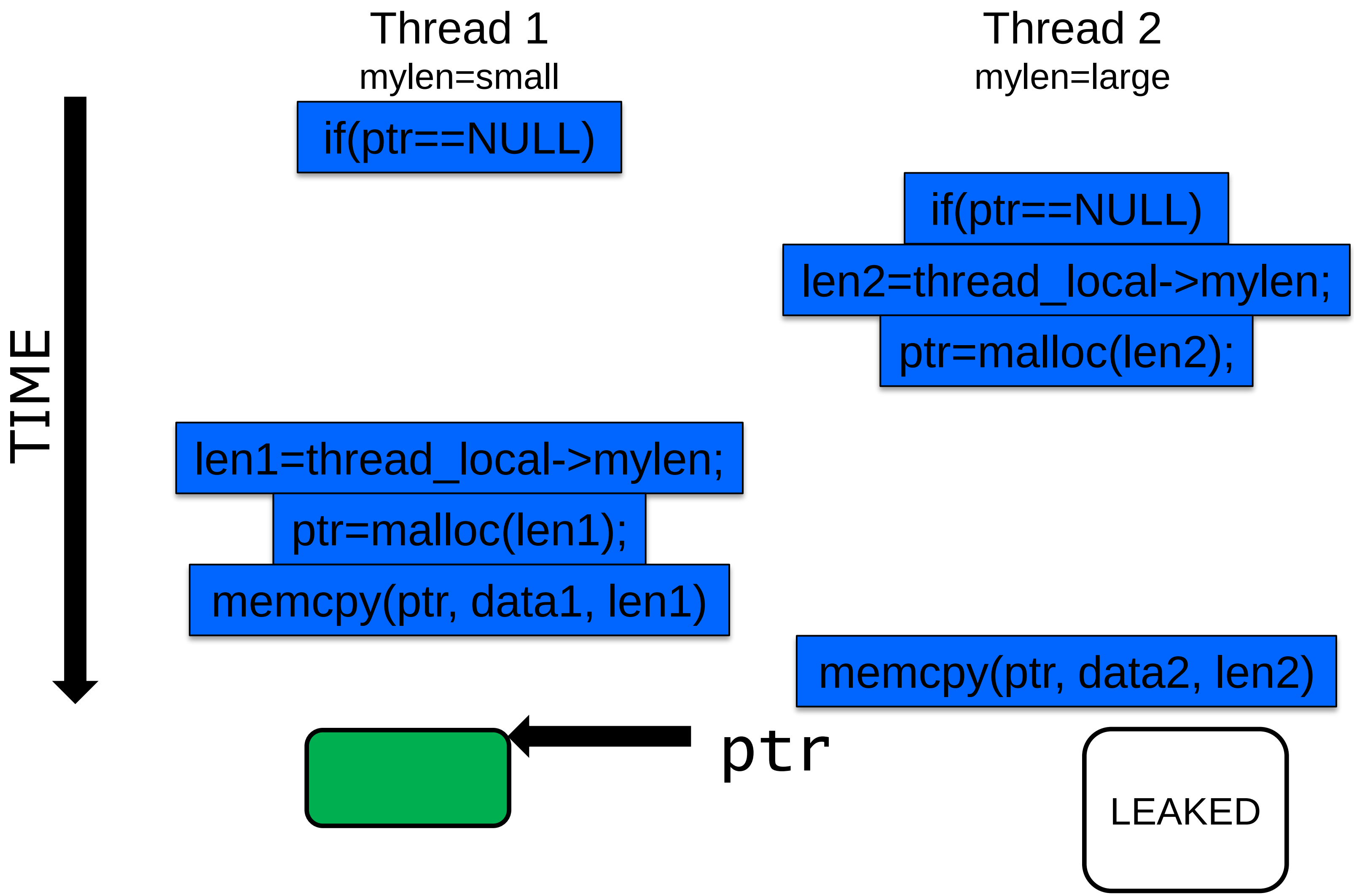

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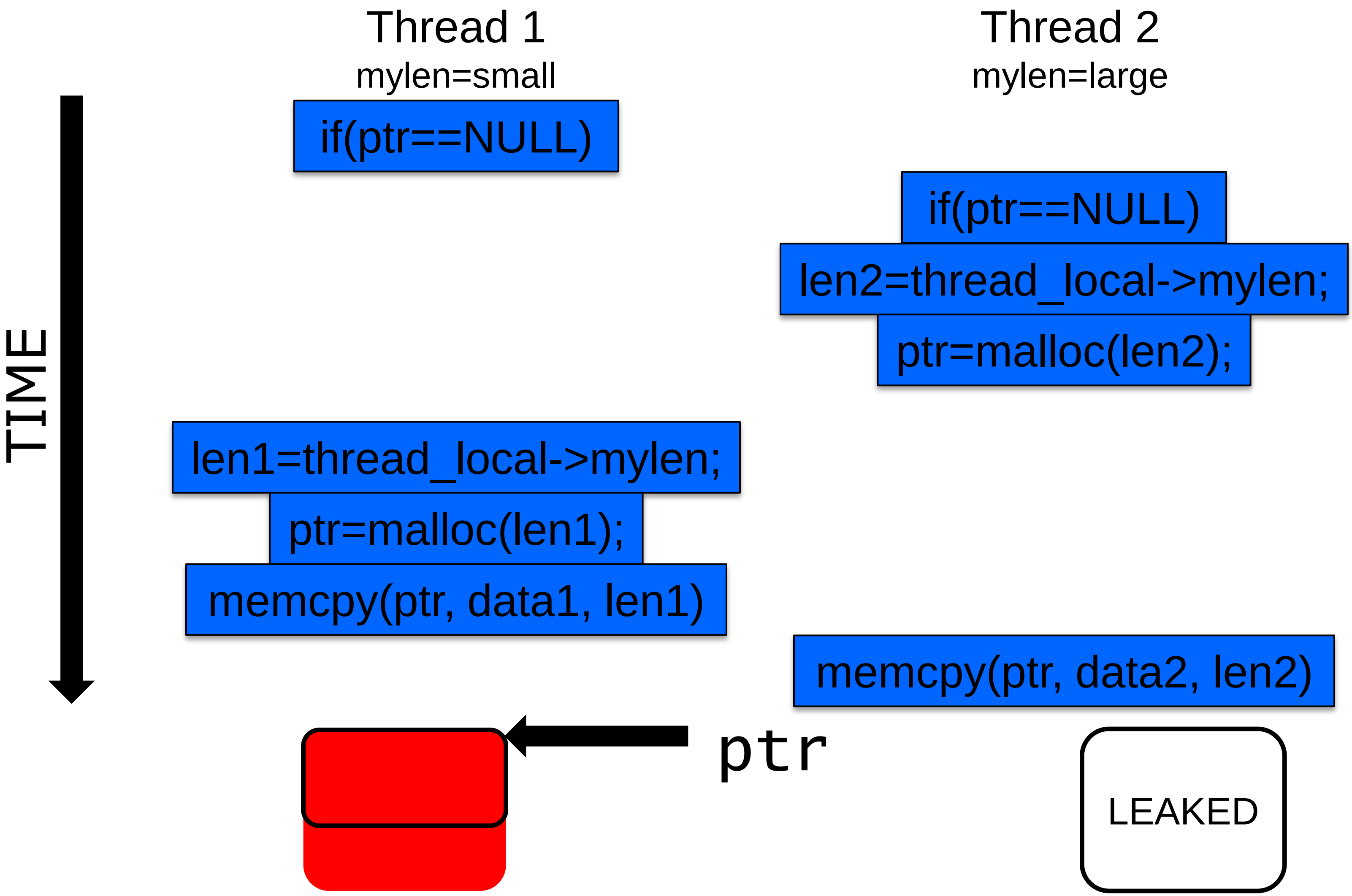
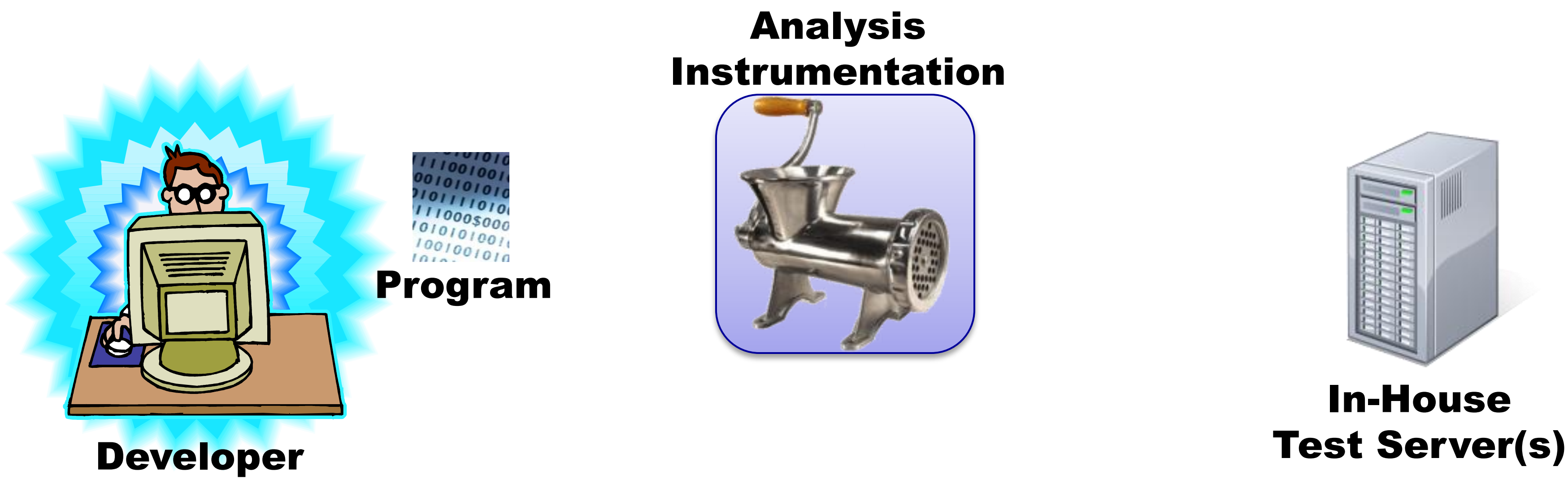


Dynamic Software Analysis

- 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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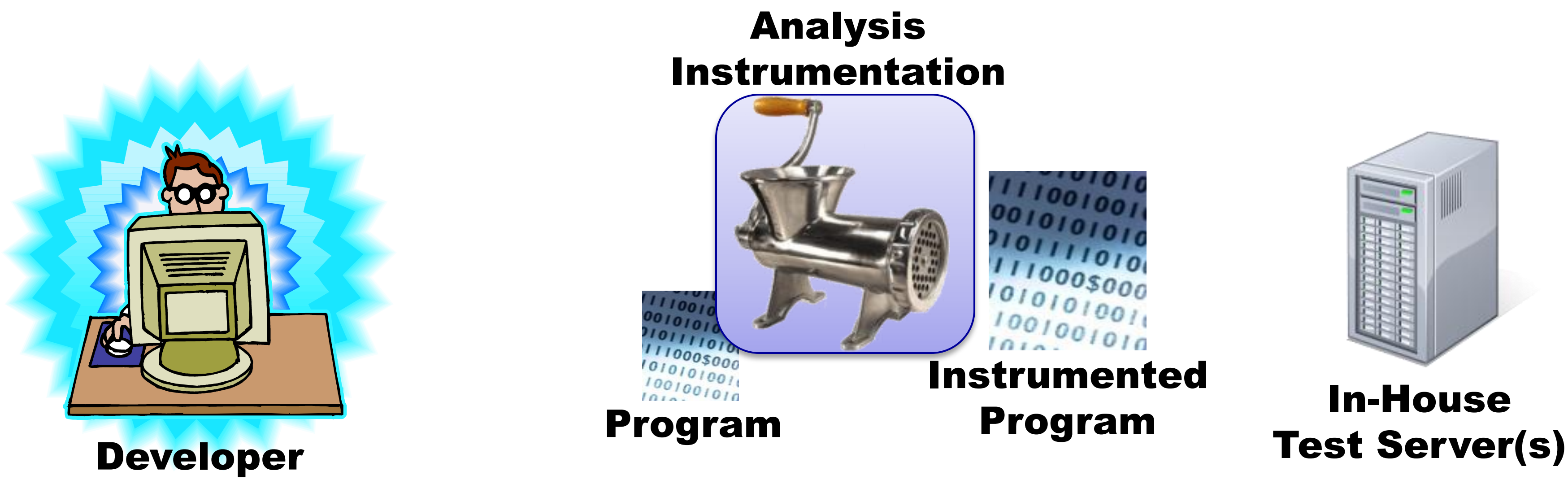

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Developer

Analysis Instrumentation

LONG run time

In-House Test Server(s)

Dynamic Software Analysis

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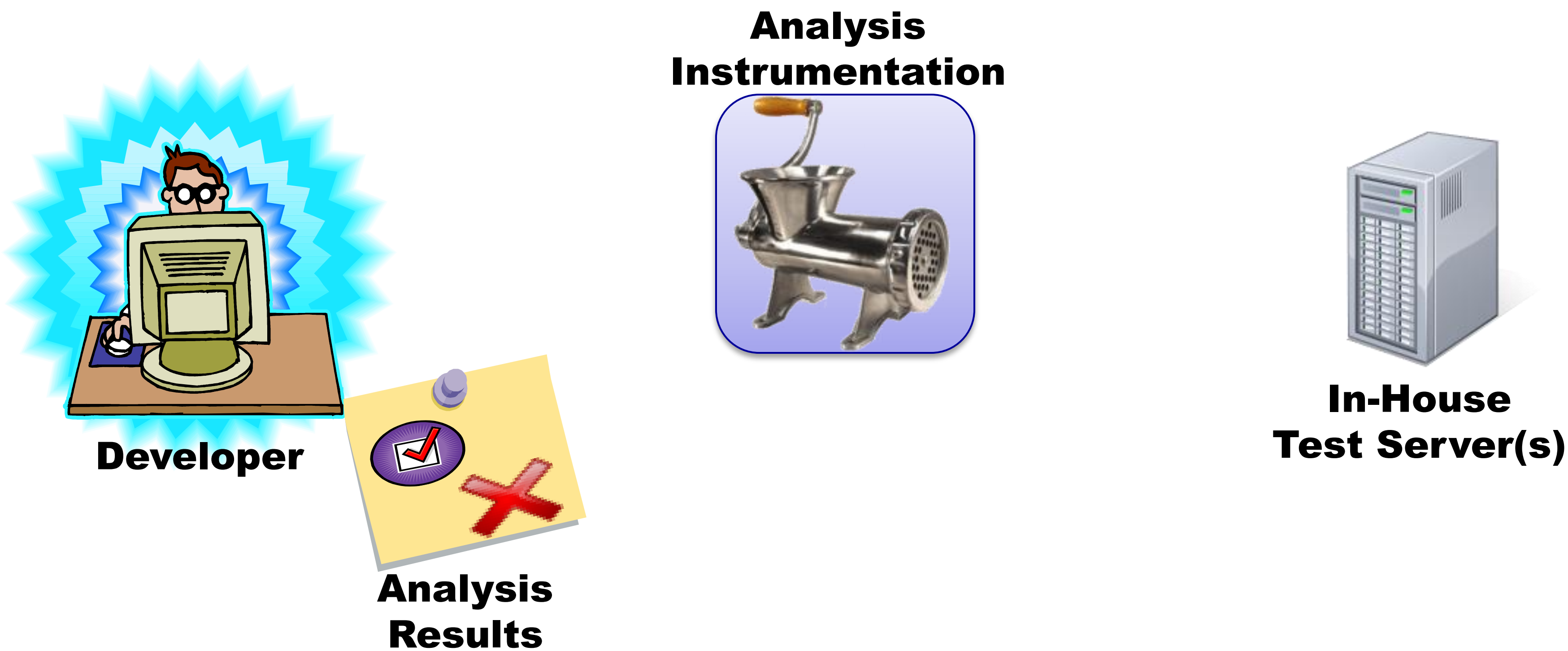


Runtime Overheads: How Large?

- 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

Dynamic Dataflow Analysis

- **Associate** meta-data with program values
- **Propagate/Clear** meta-data while executing
- **Check** meta-data for safety & correctness
- Forms dataflows of meta/shadow information

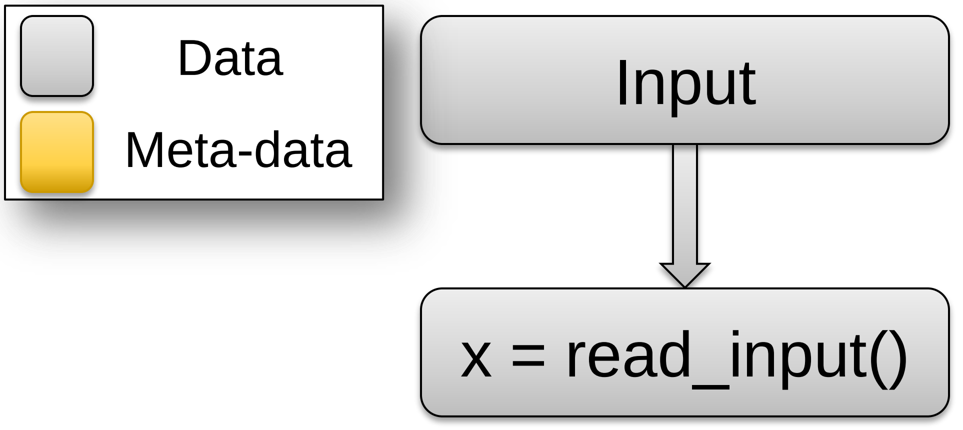
Example: Taint Analysis

Data

Meta-data

Input

Example: Taint Analysis



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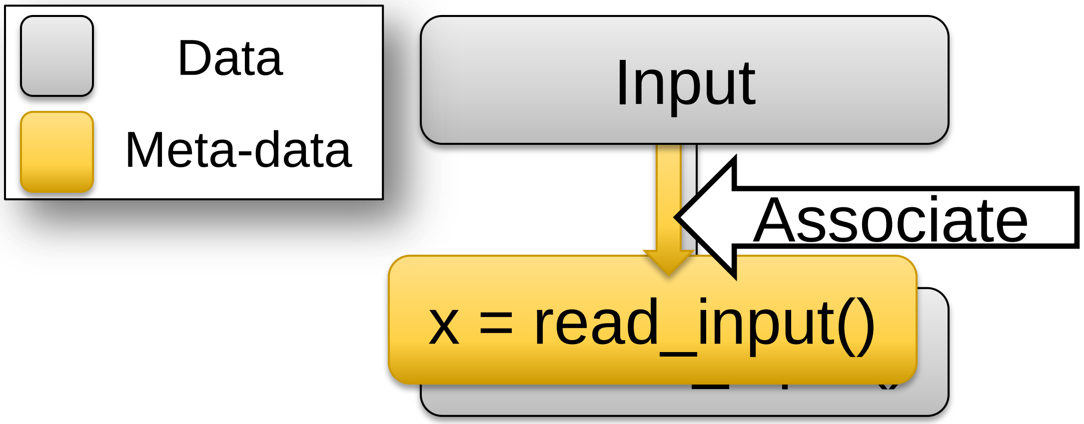

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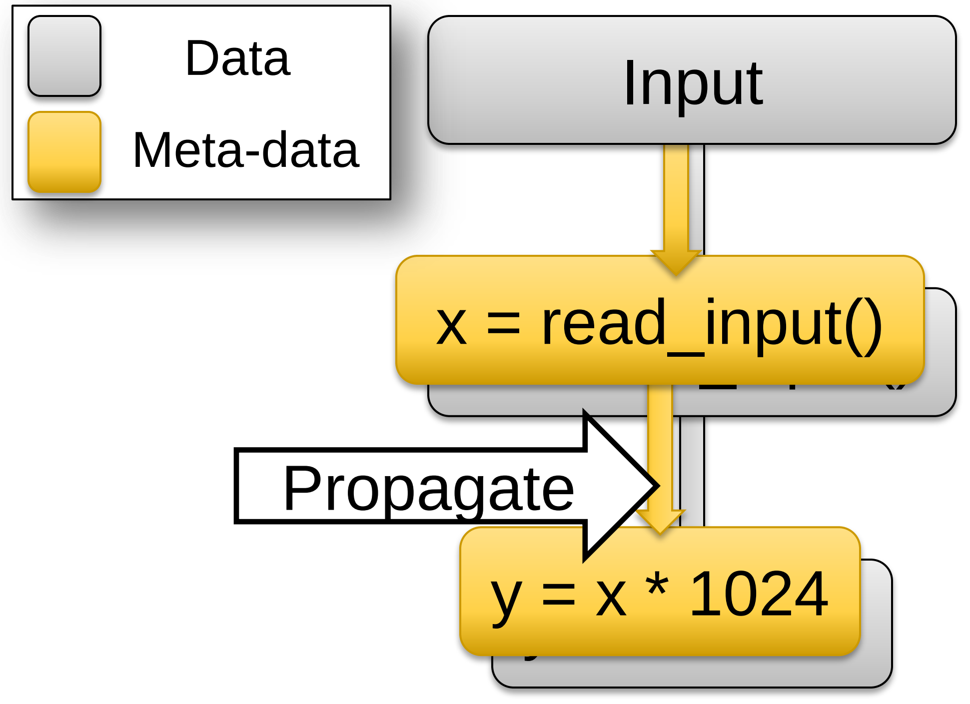

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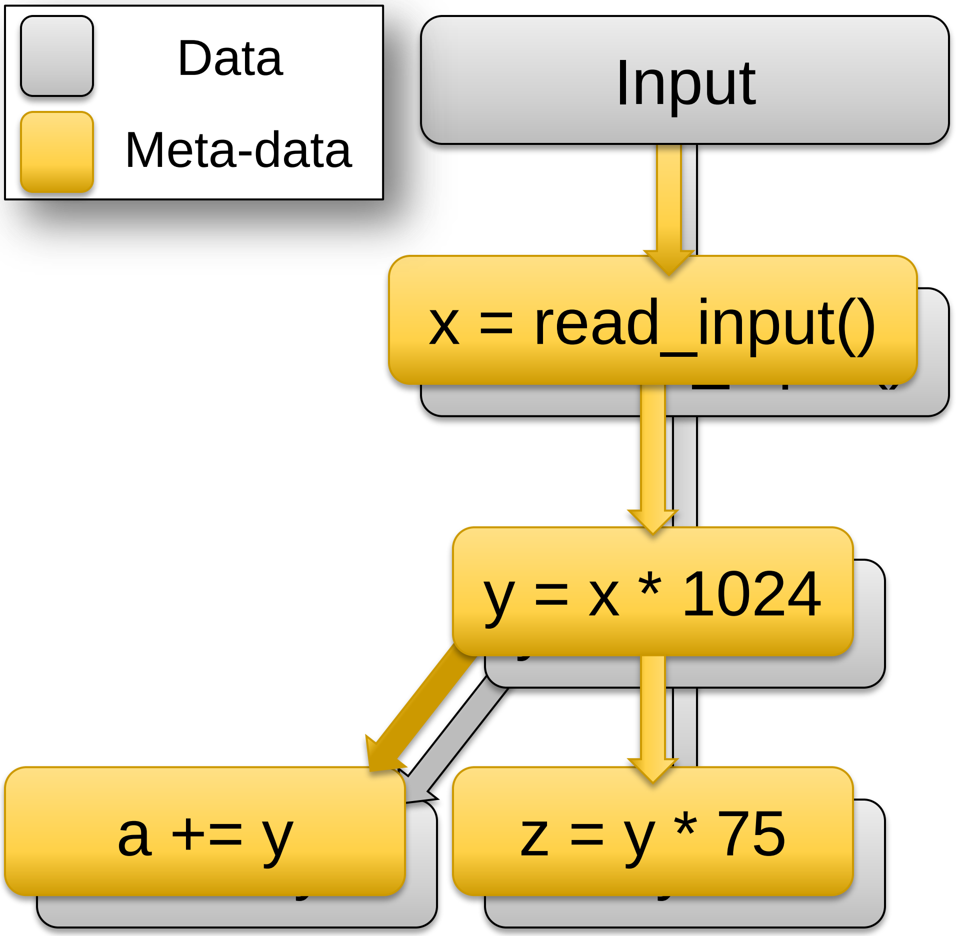

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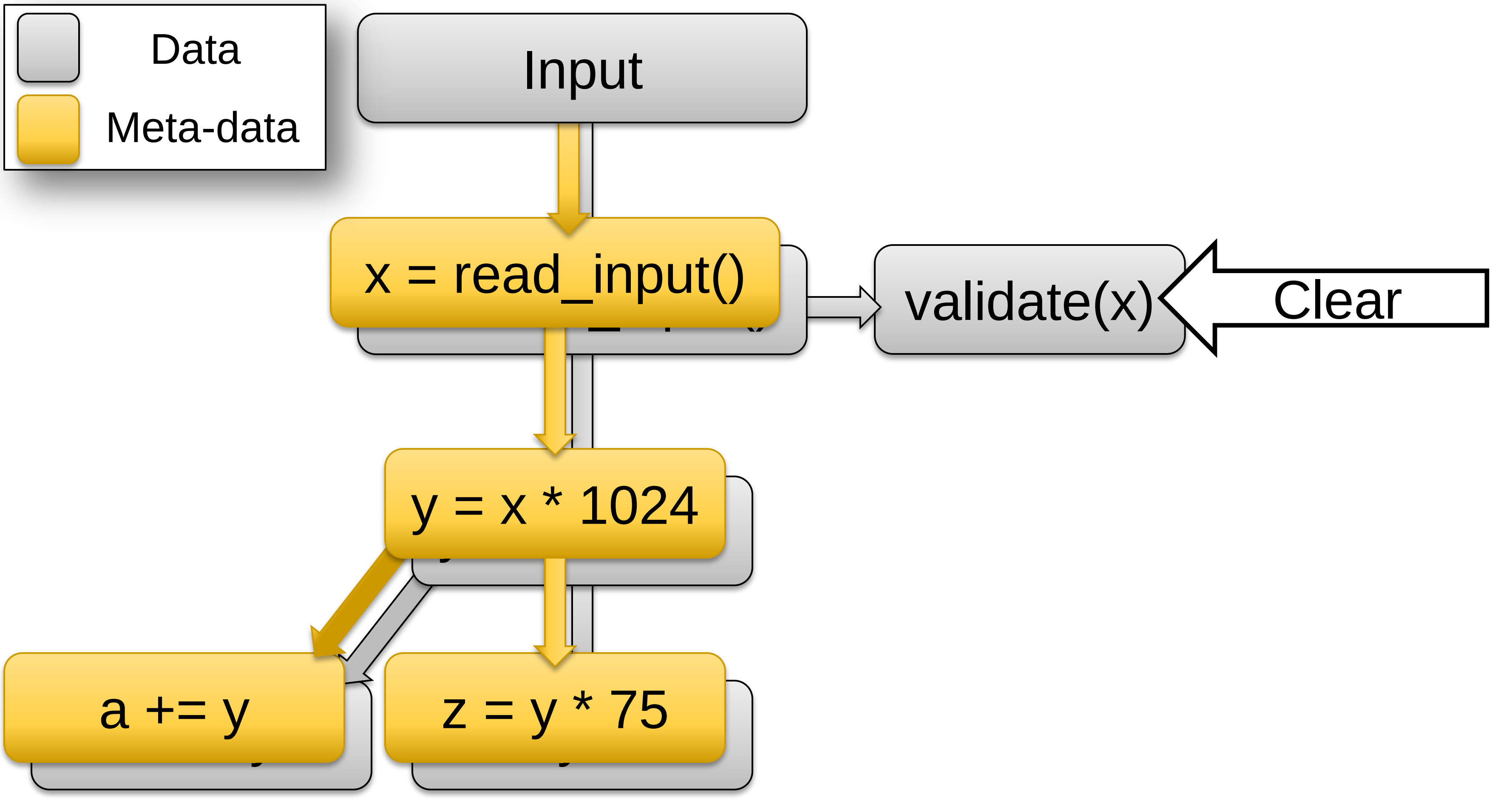

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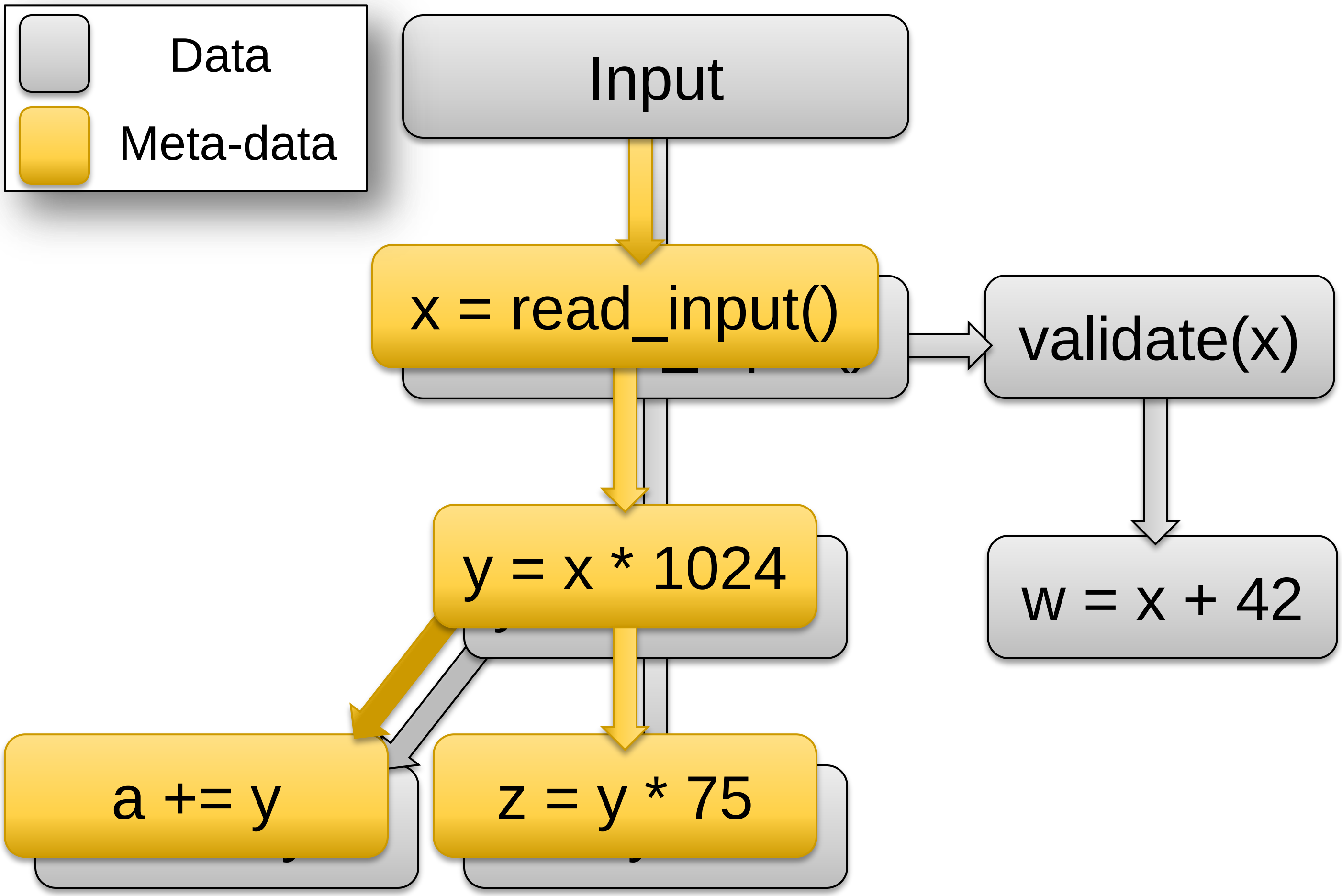

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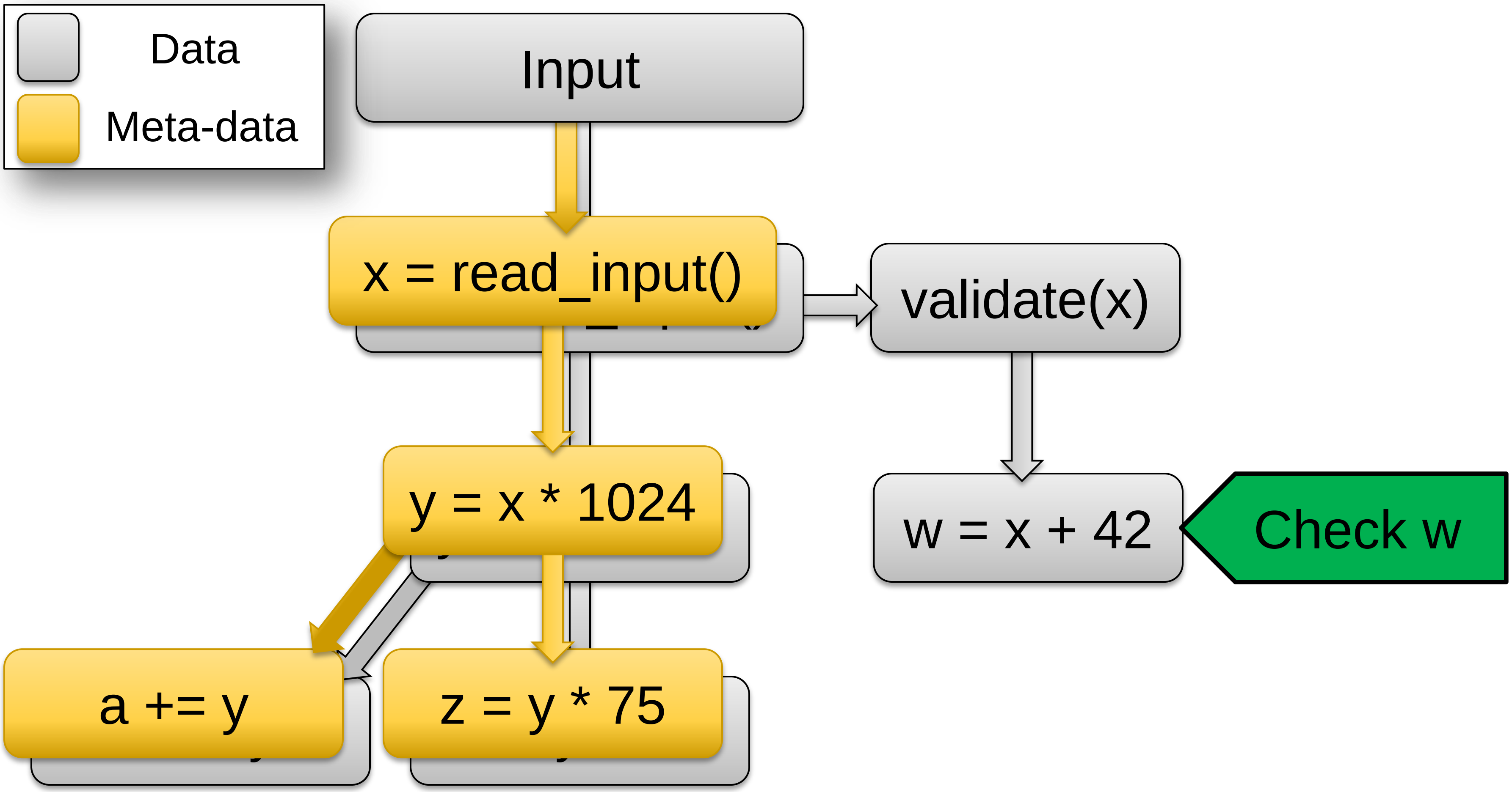

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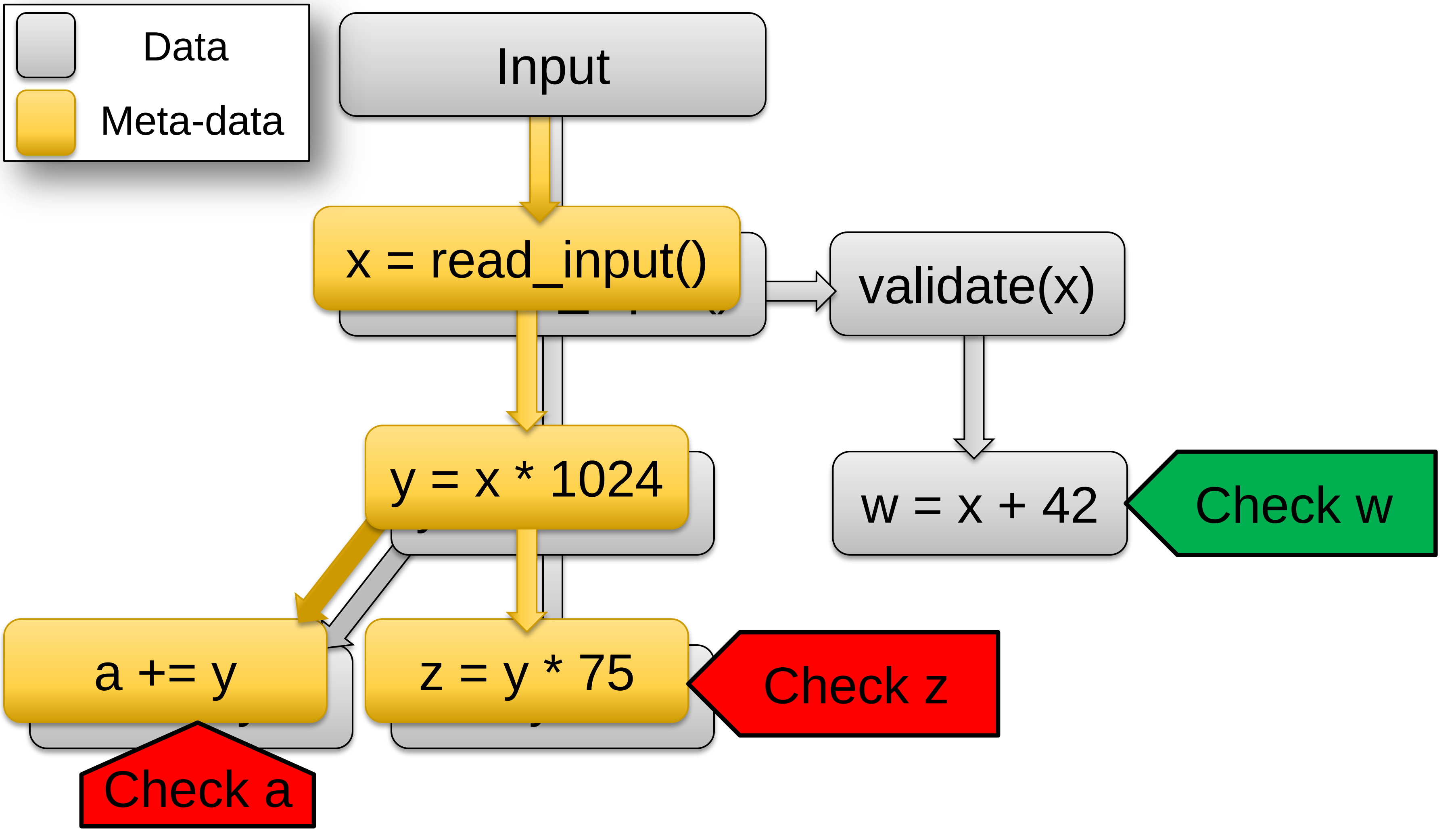

Demand-Driven Dataflow Analysis

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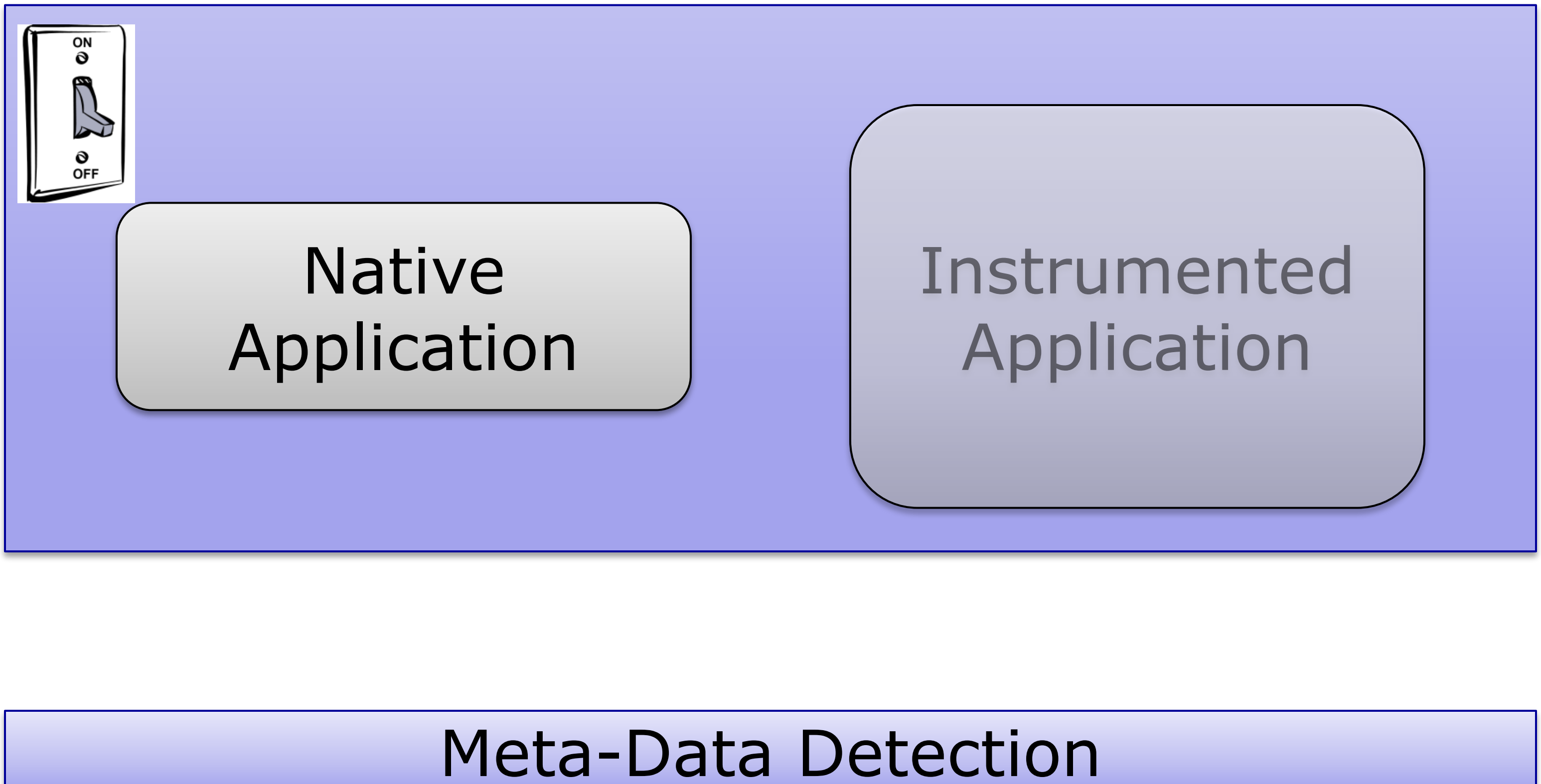

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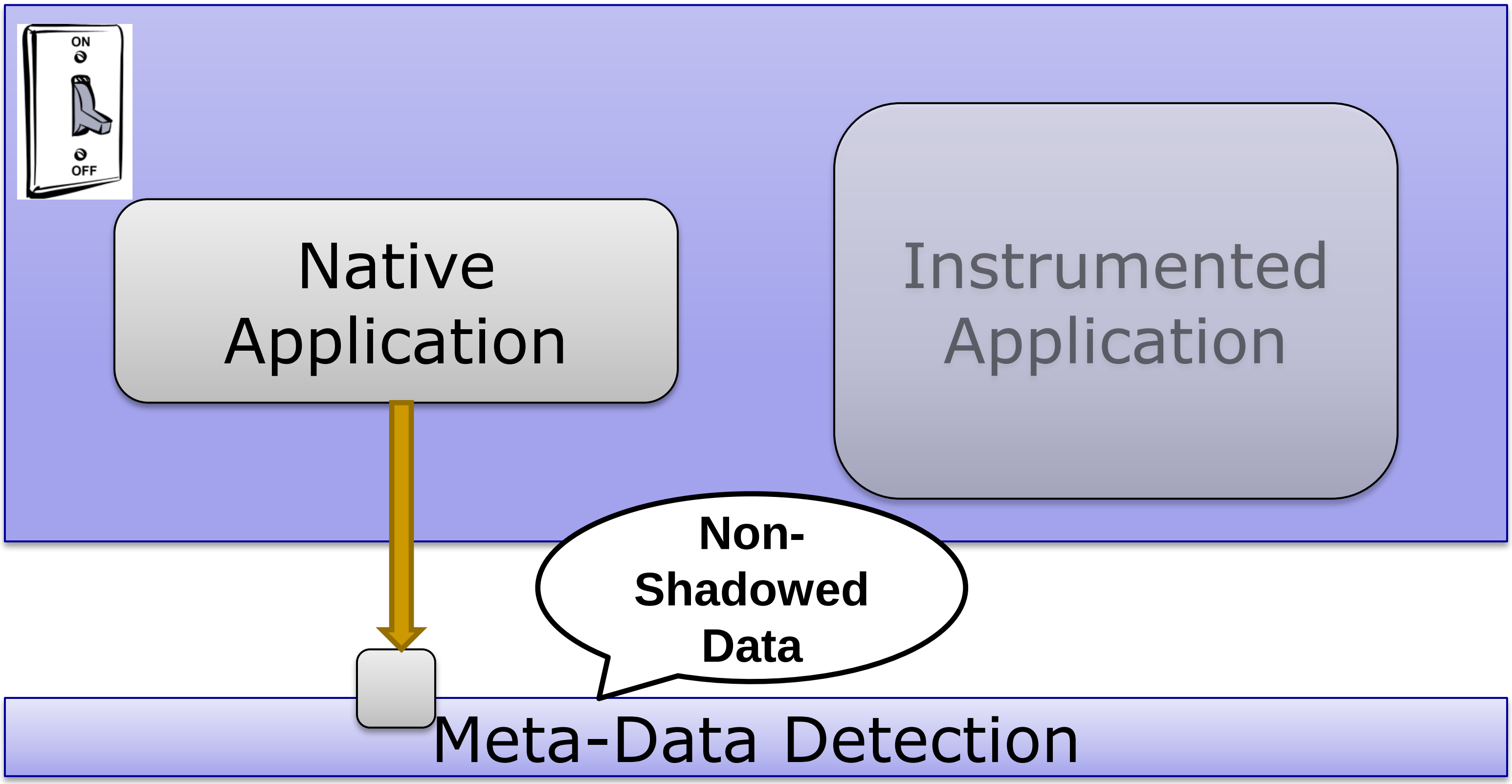

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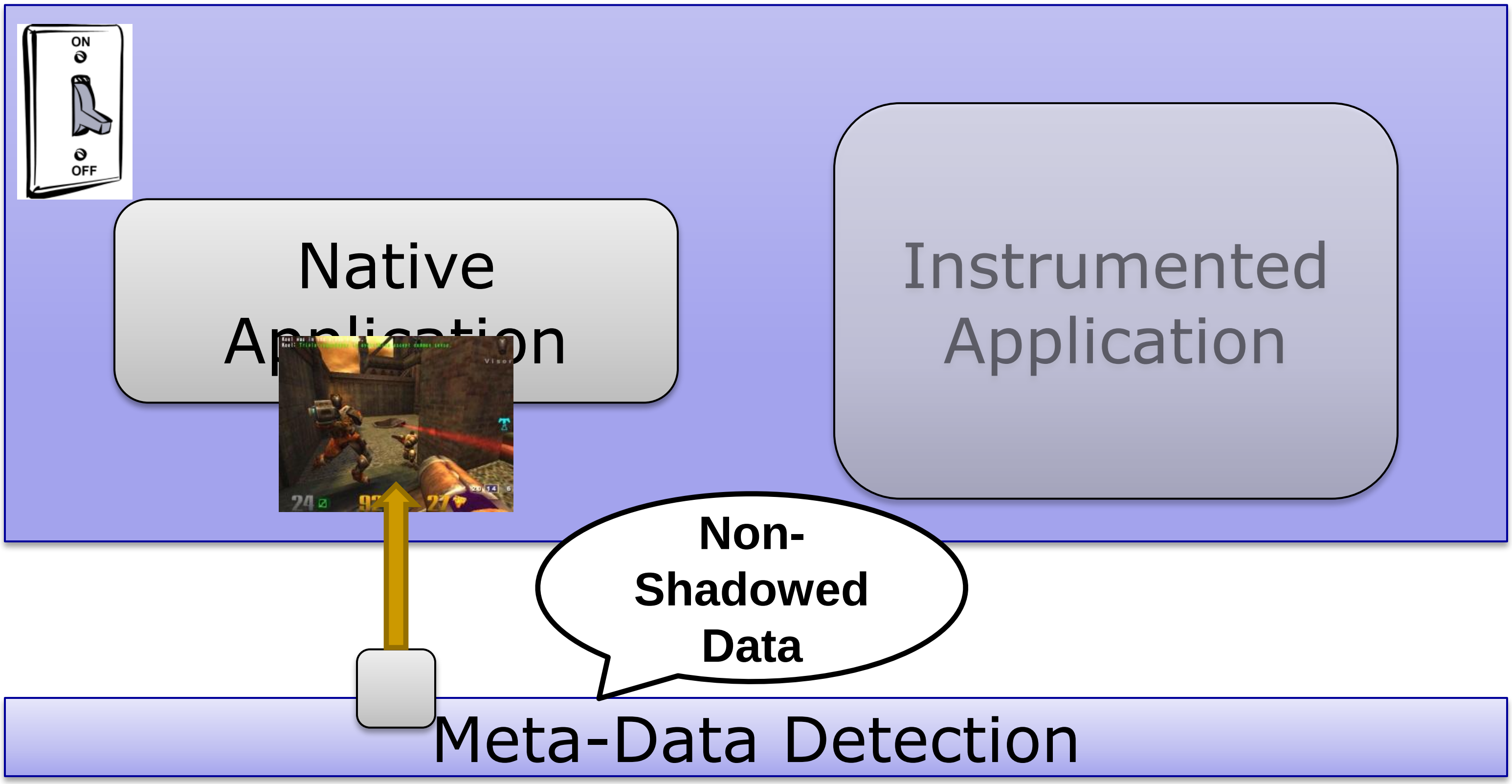

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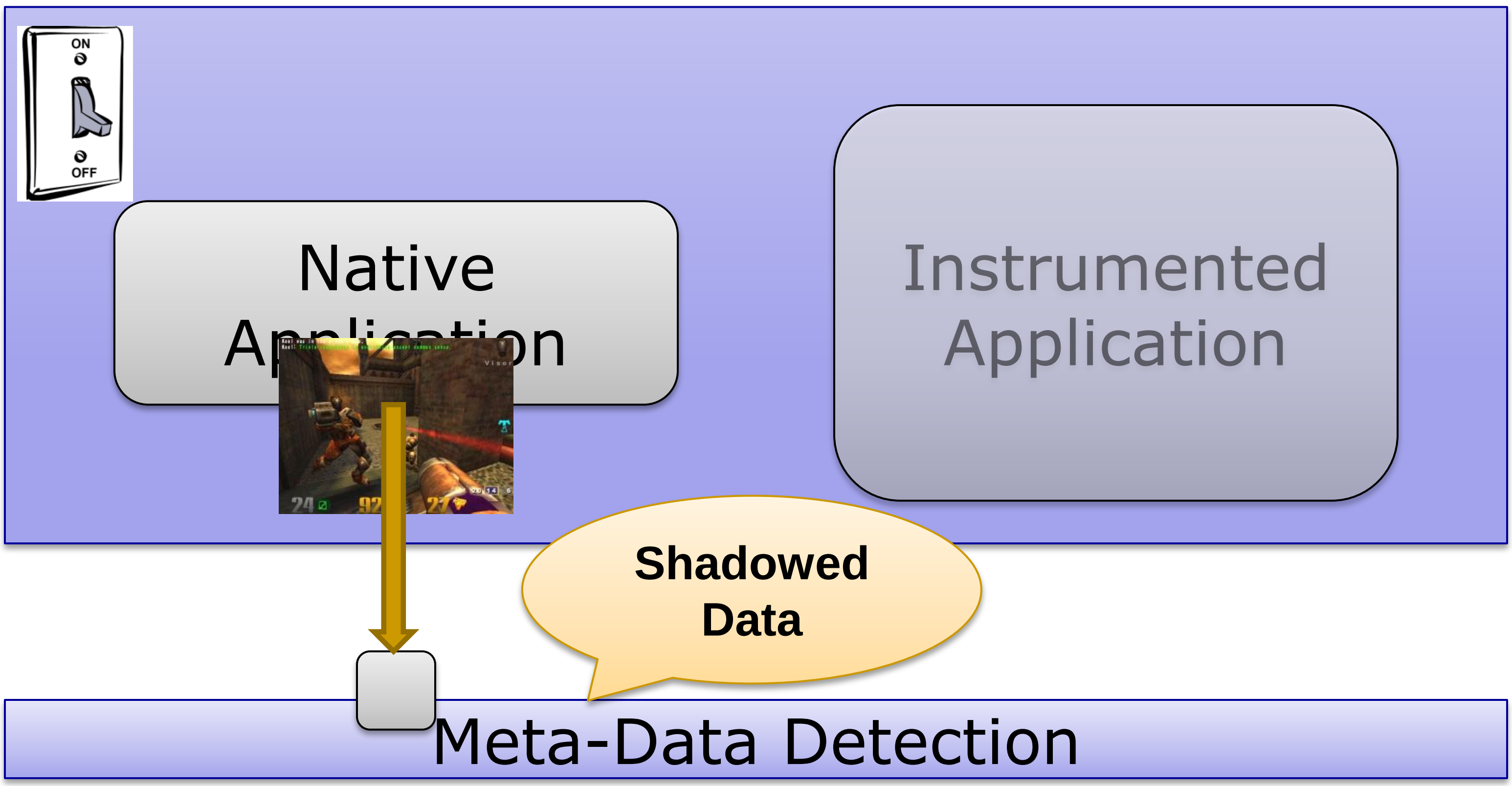

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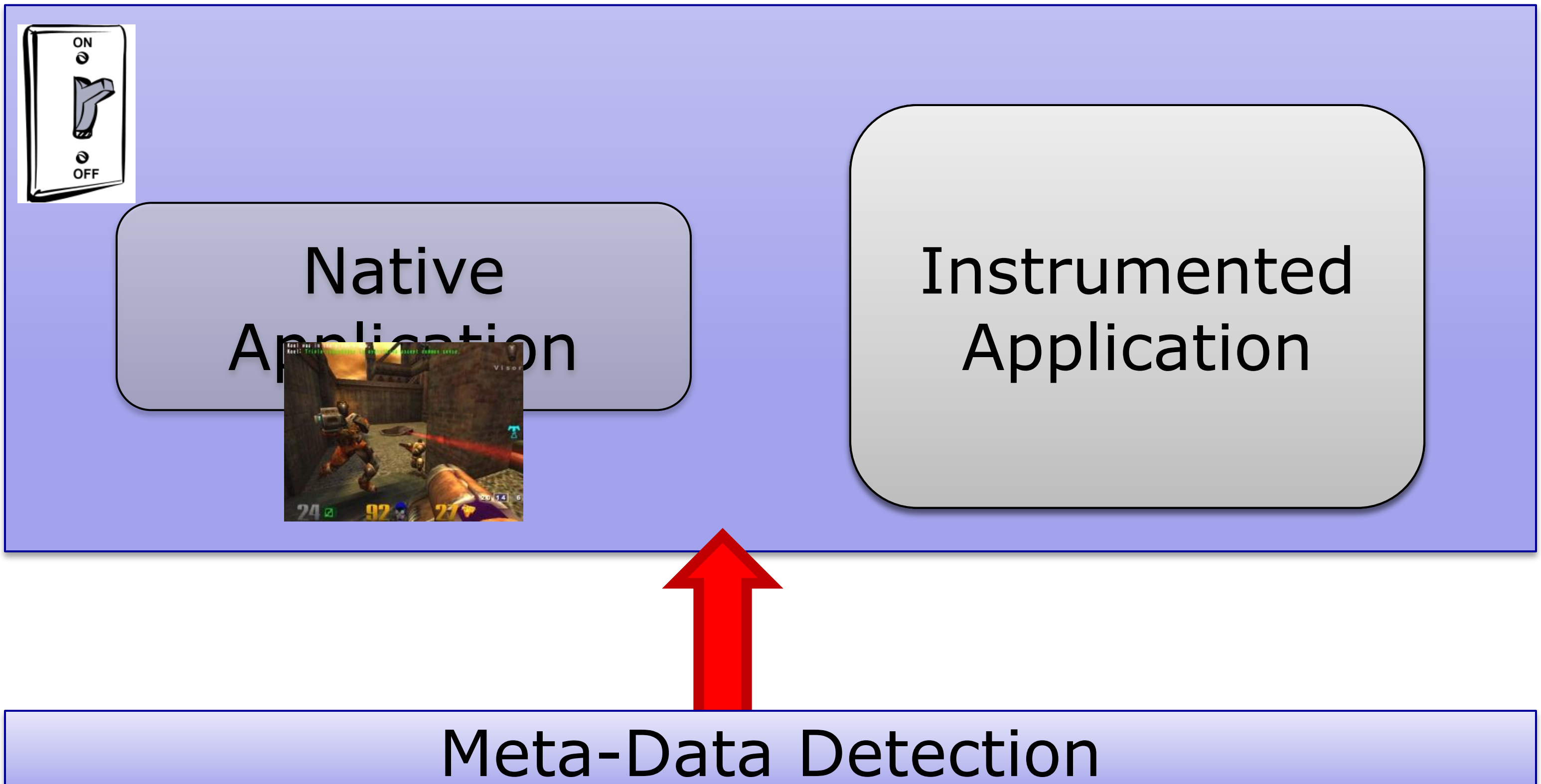

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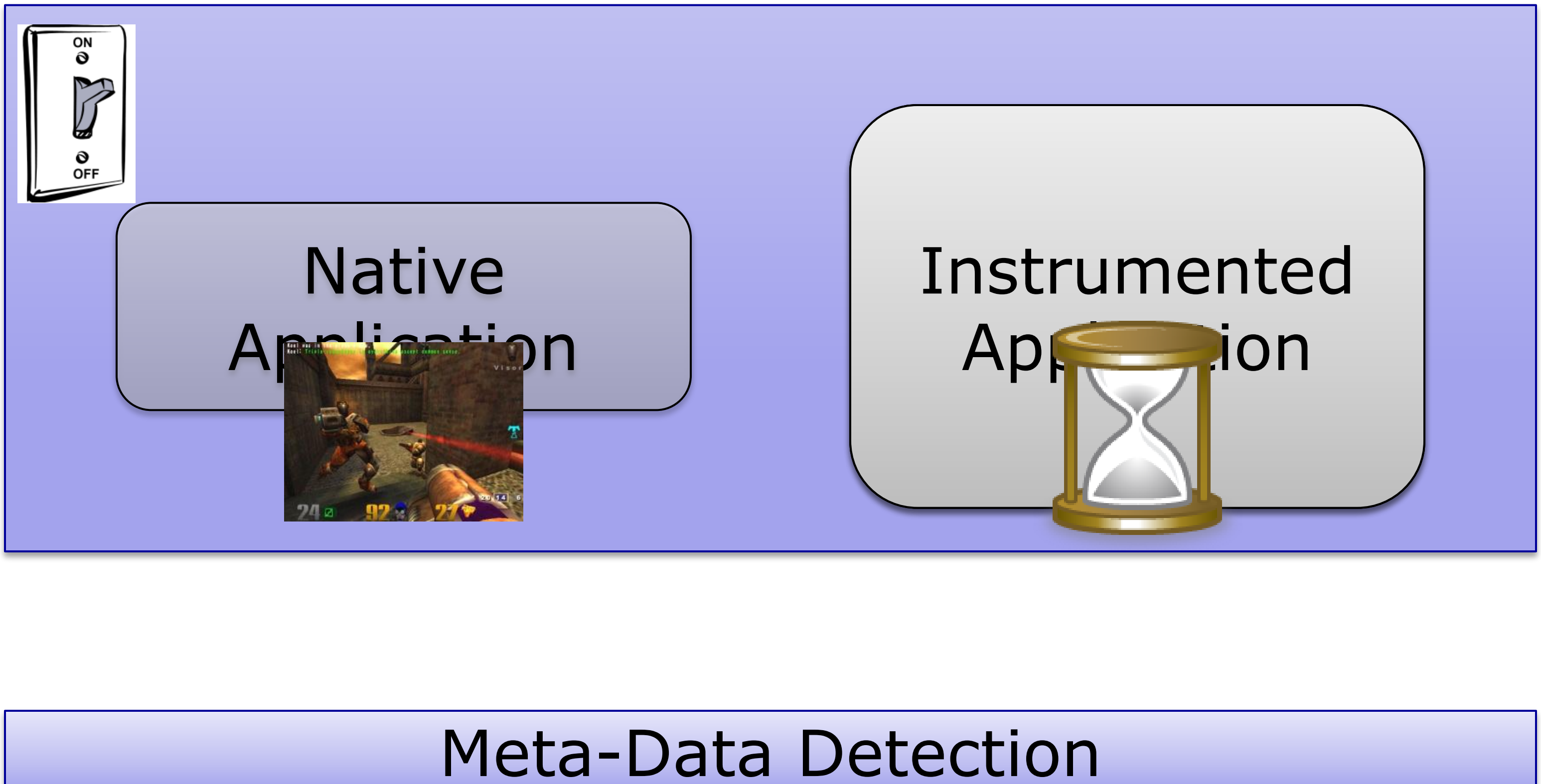

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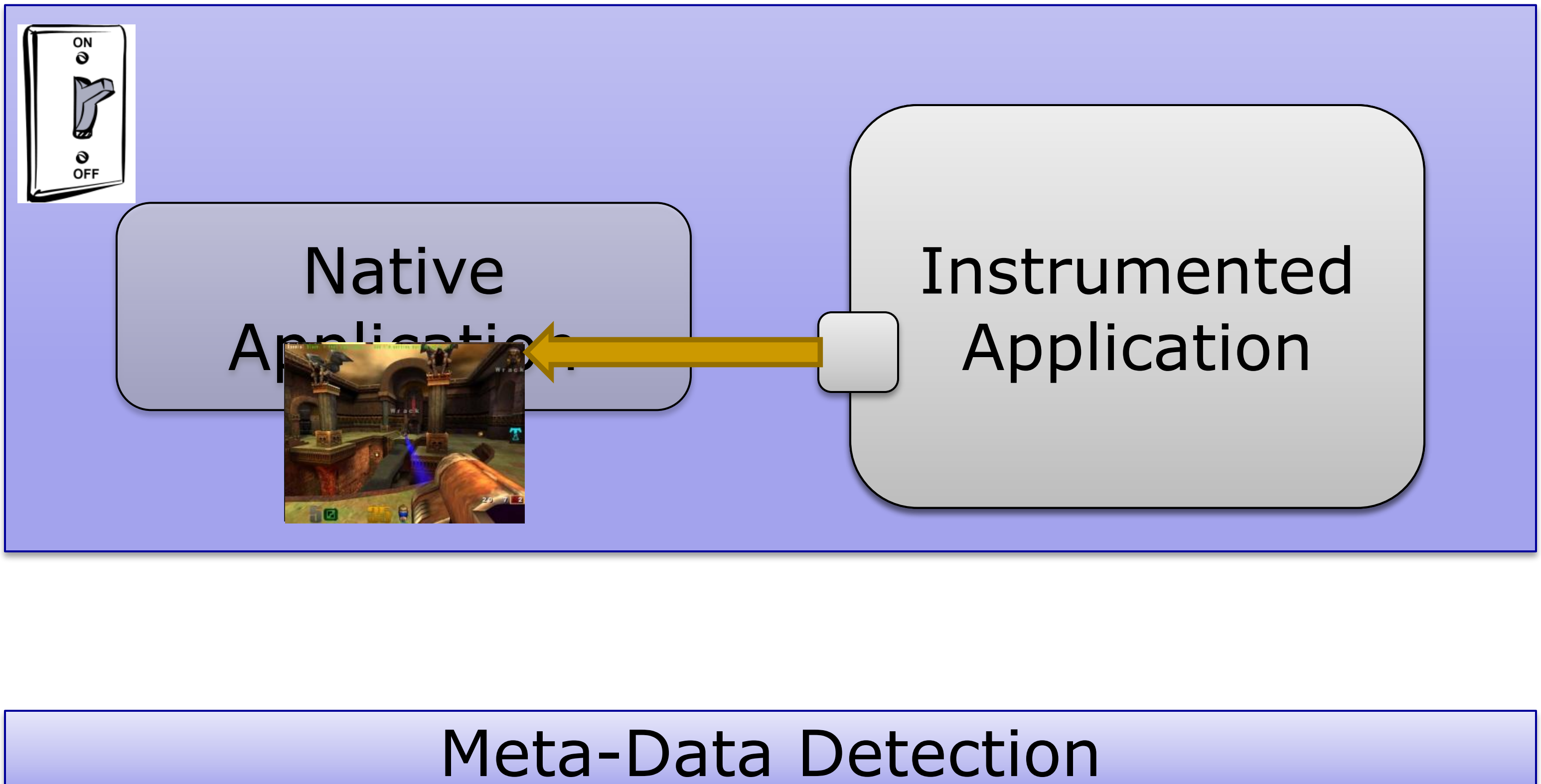

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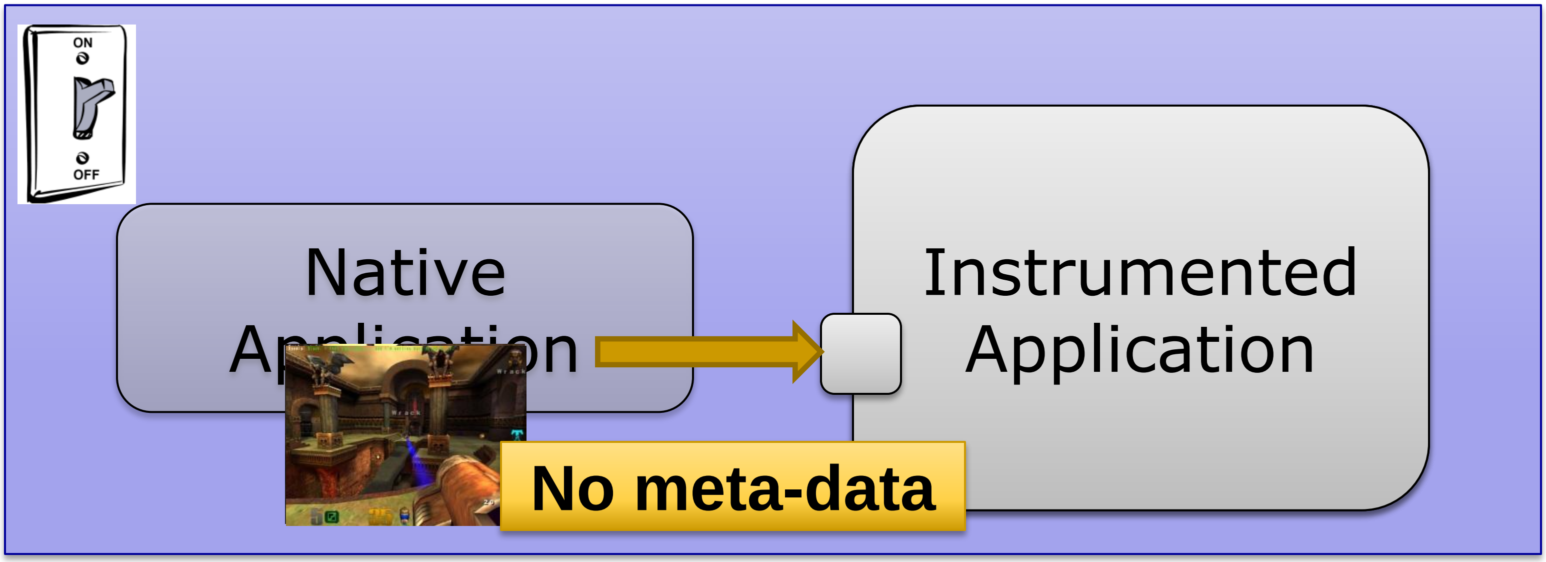

Meta-Data Detection

Demand-Driven Dataflow Analysis

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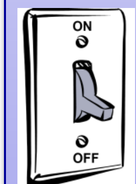

Native Application

Instrumented Application

Meta-Data Detection

Finding Meta-Data

- No additional overhead when no meta-data
  - Needs hardware support
- Take a fault when touching shadowed data

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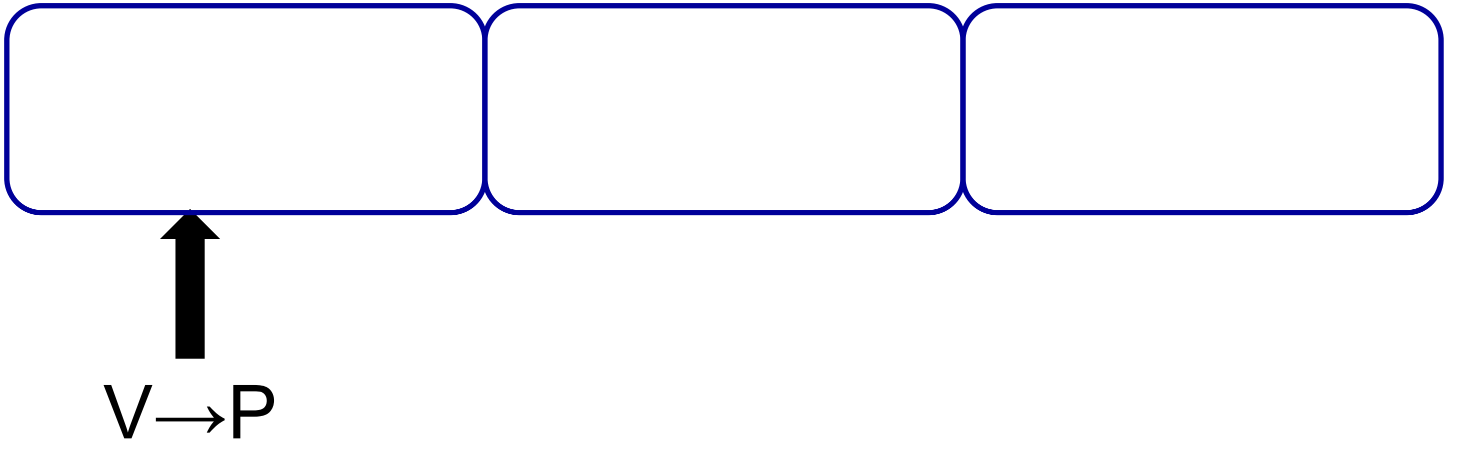

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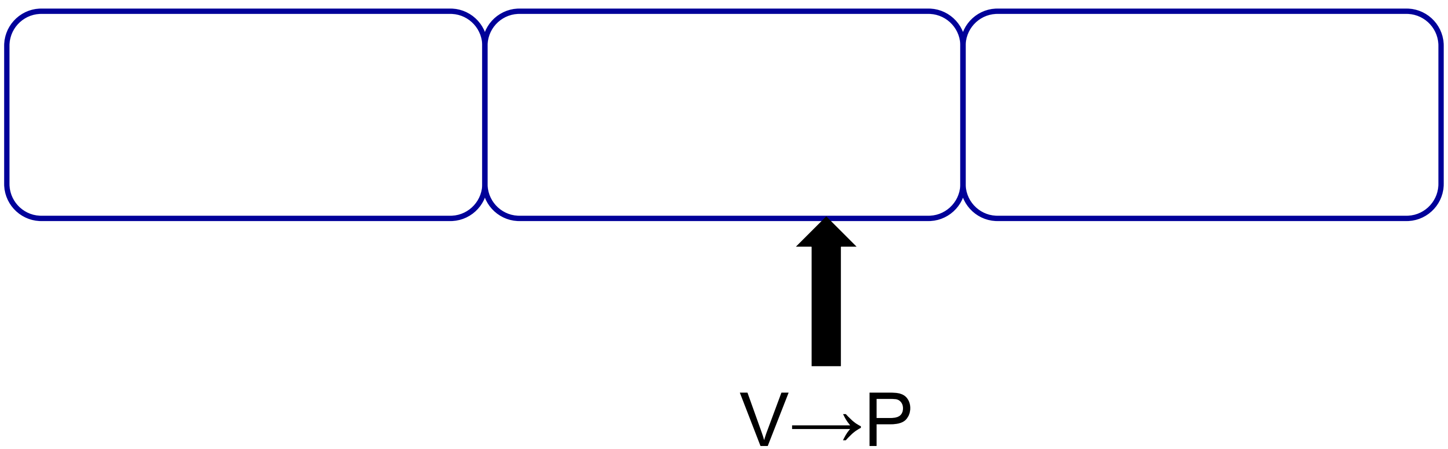

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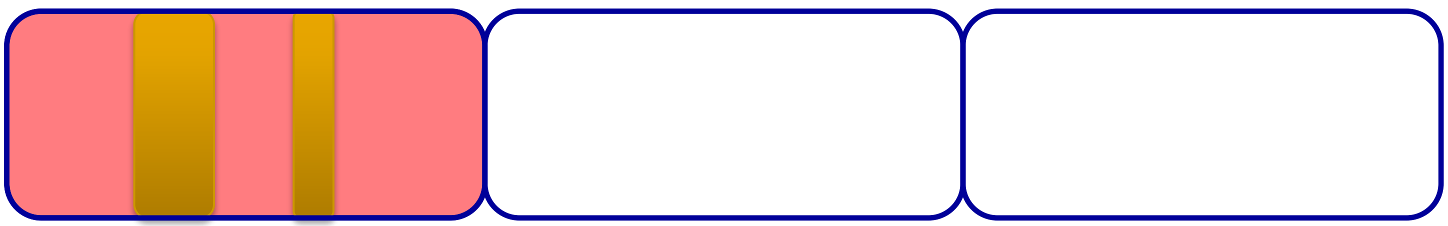

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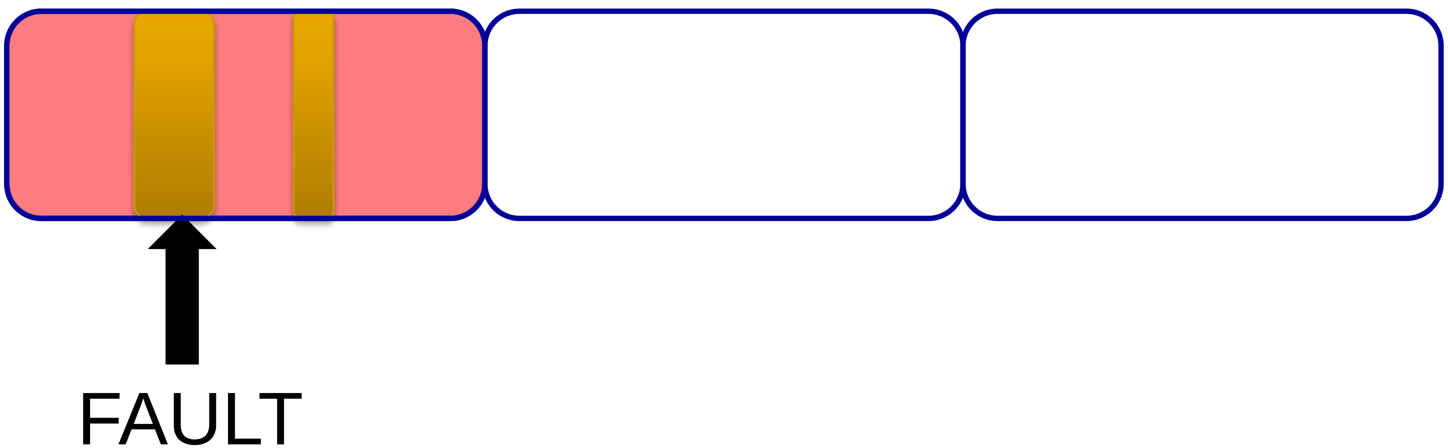

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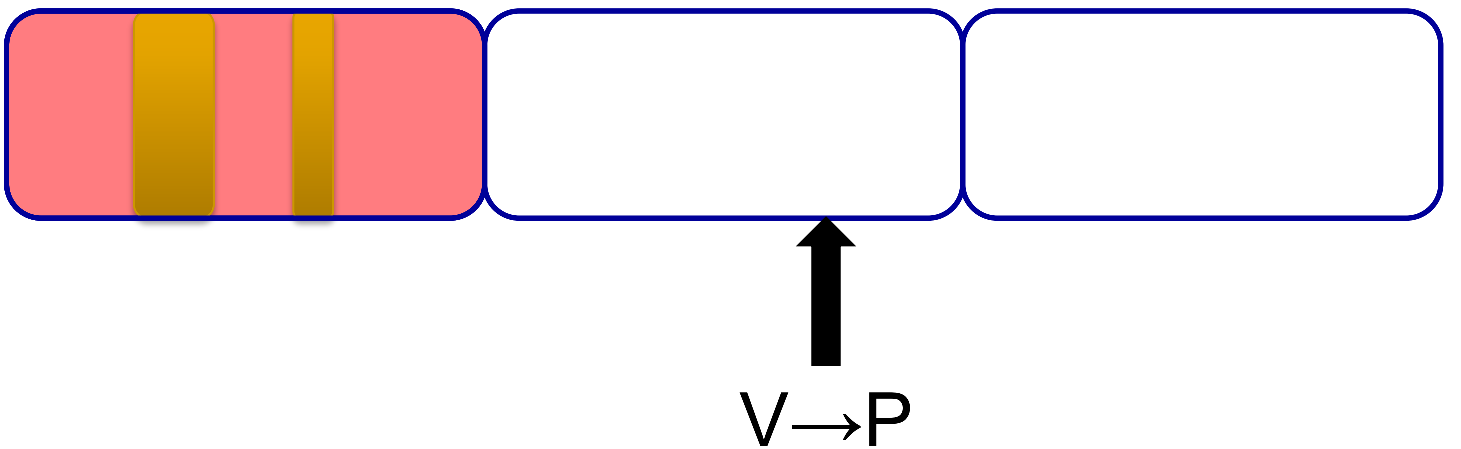
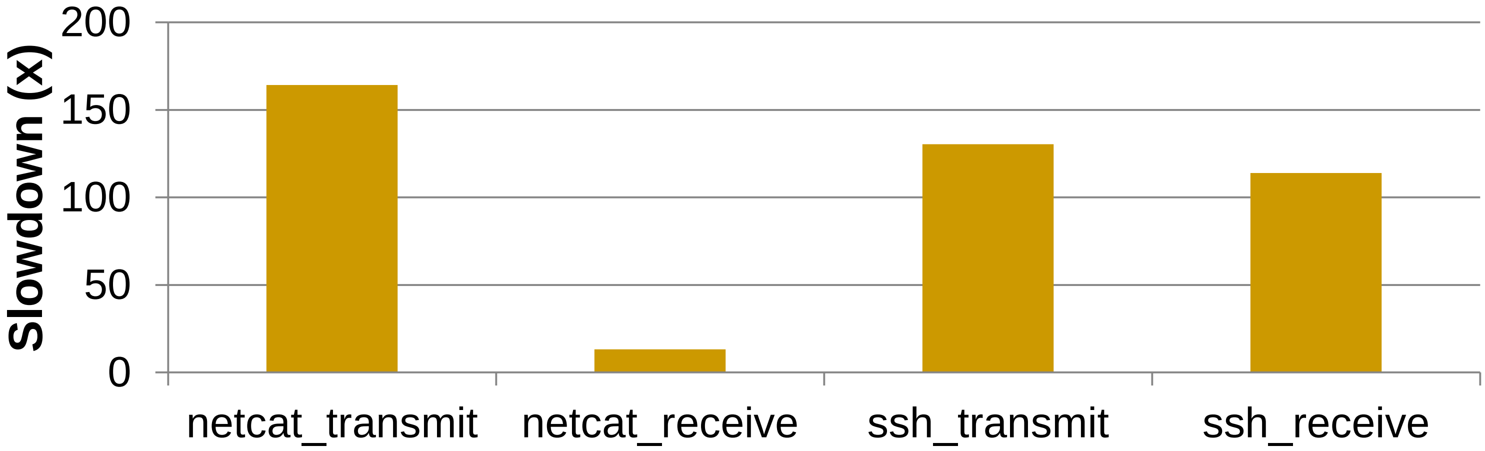


Results by Ho et al.

- lmbench Best Case Results:

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

- Results when everything is tainted:



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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.

Example of 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

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if(ptr==NULL)
len2=thread_local->mylen;
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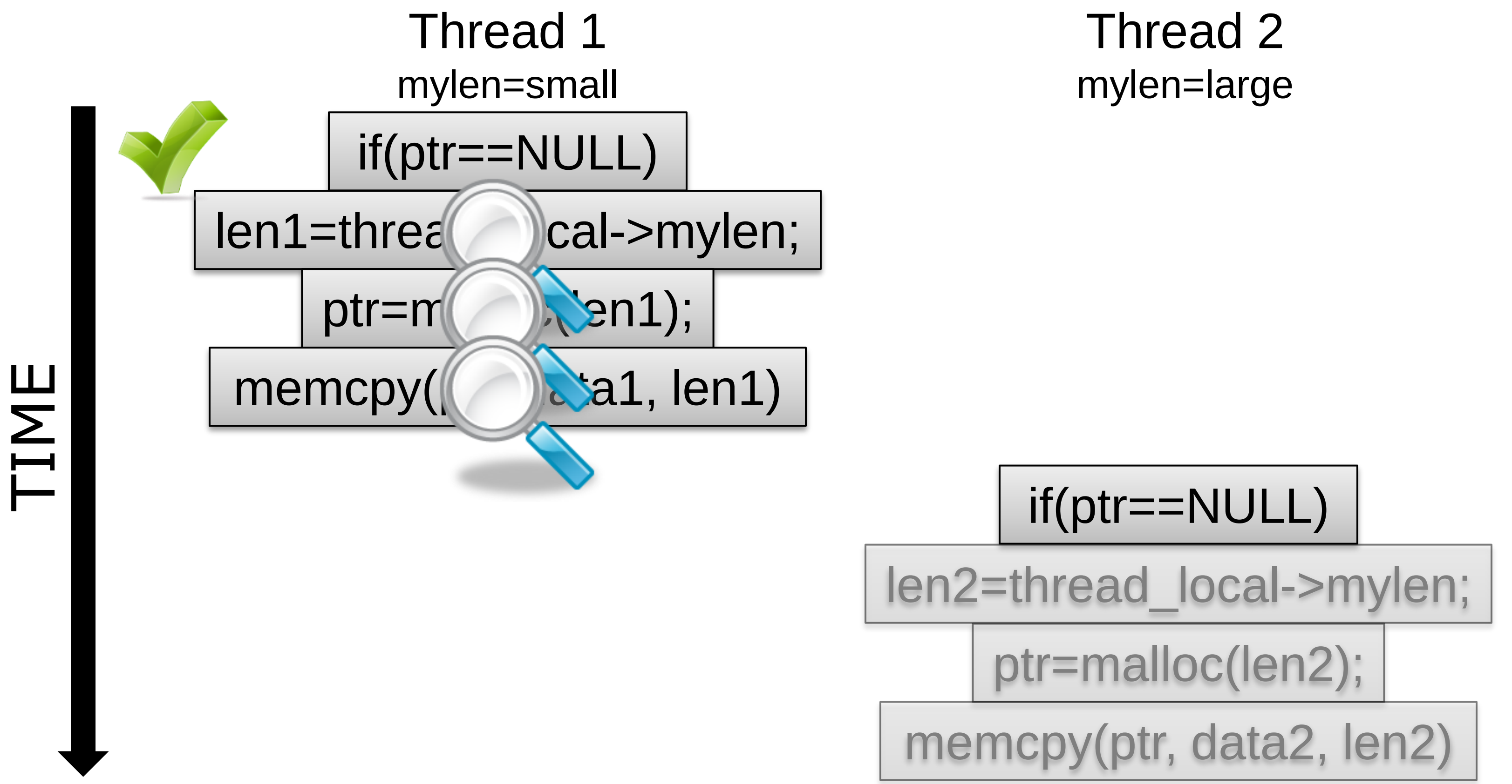

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ptr write-shared?

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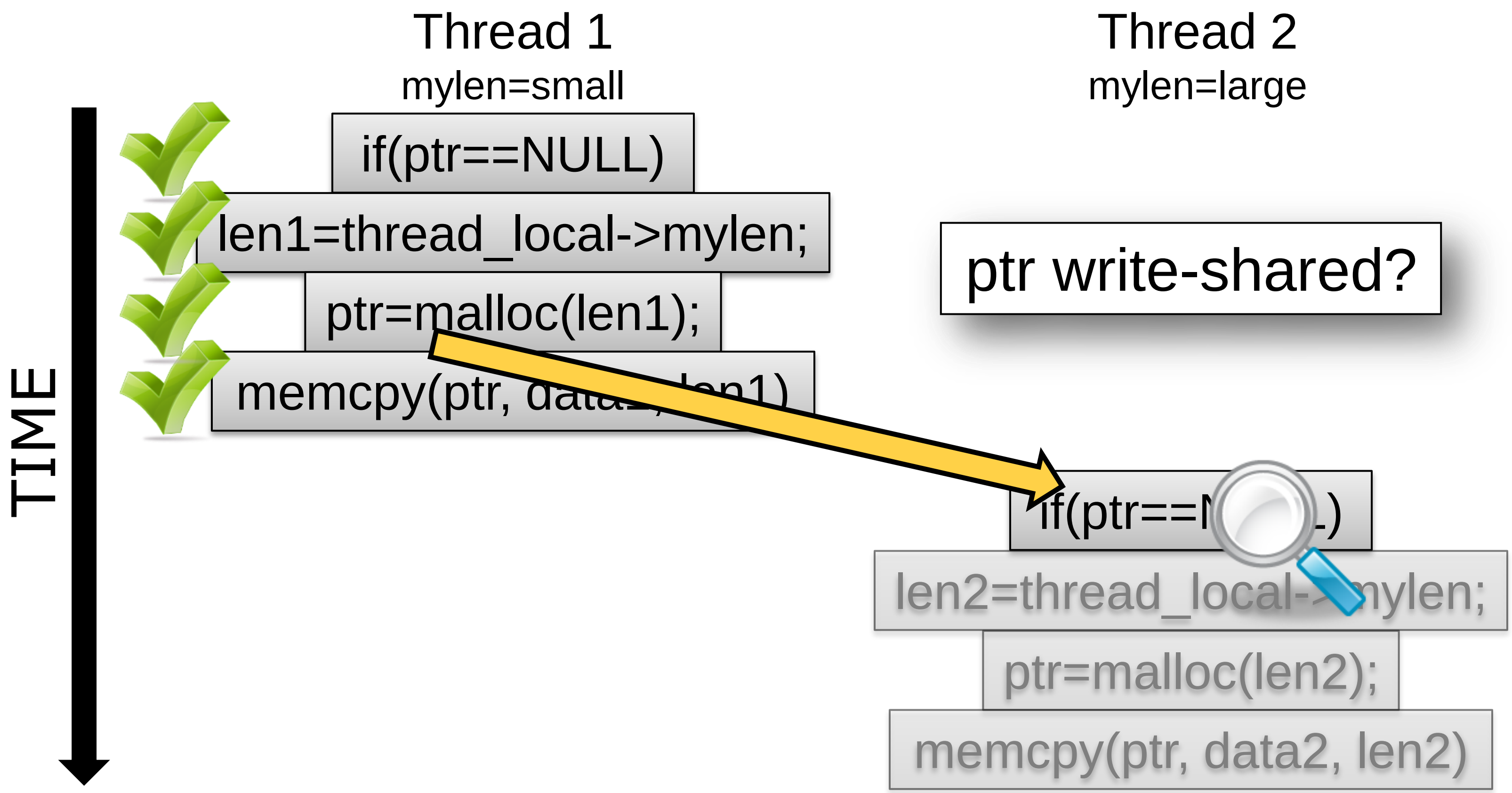

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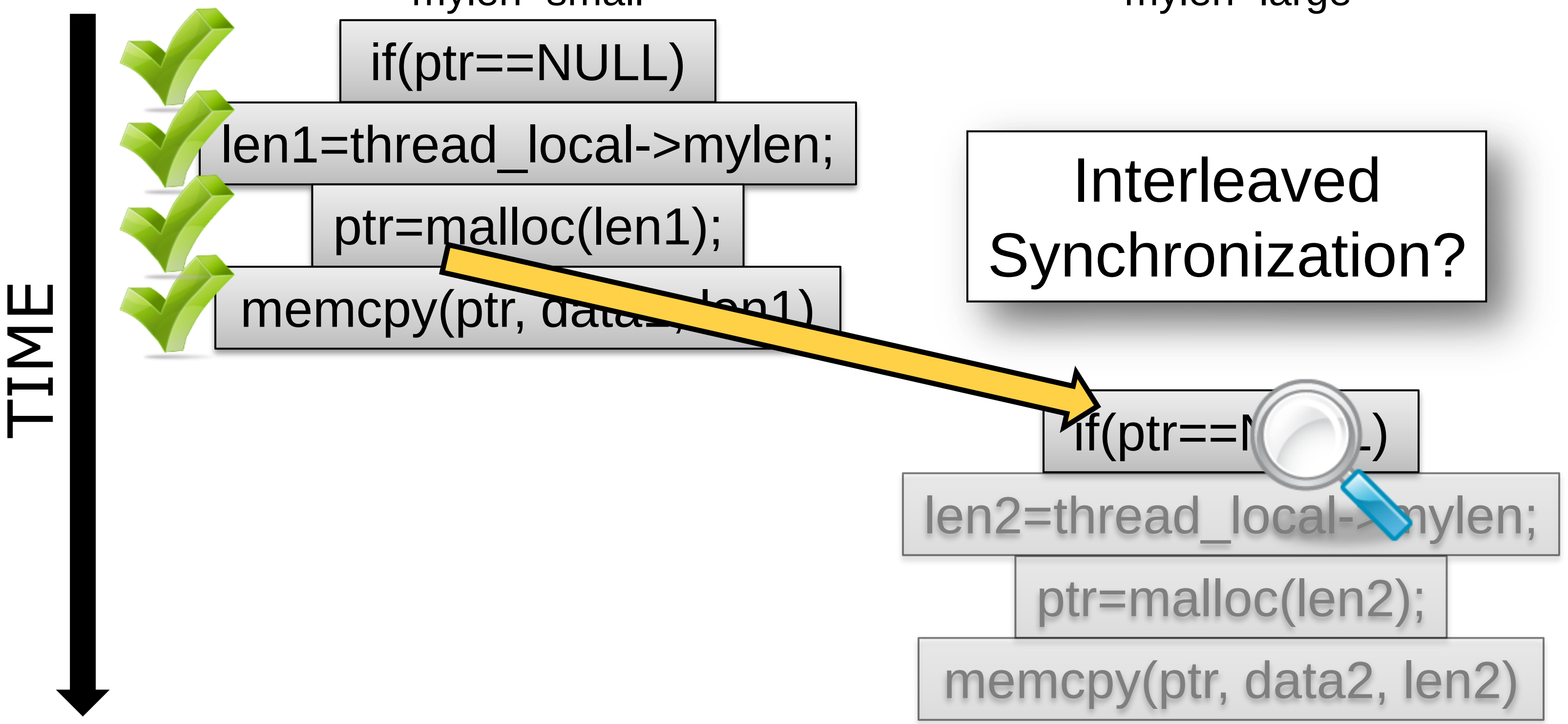

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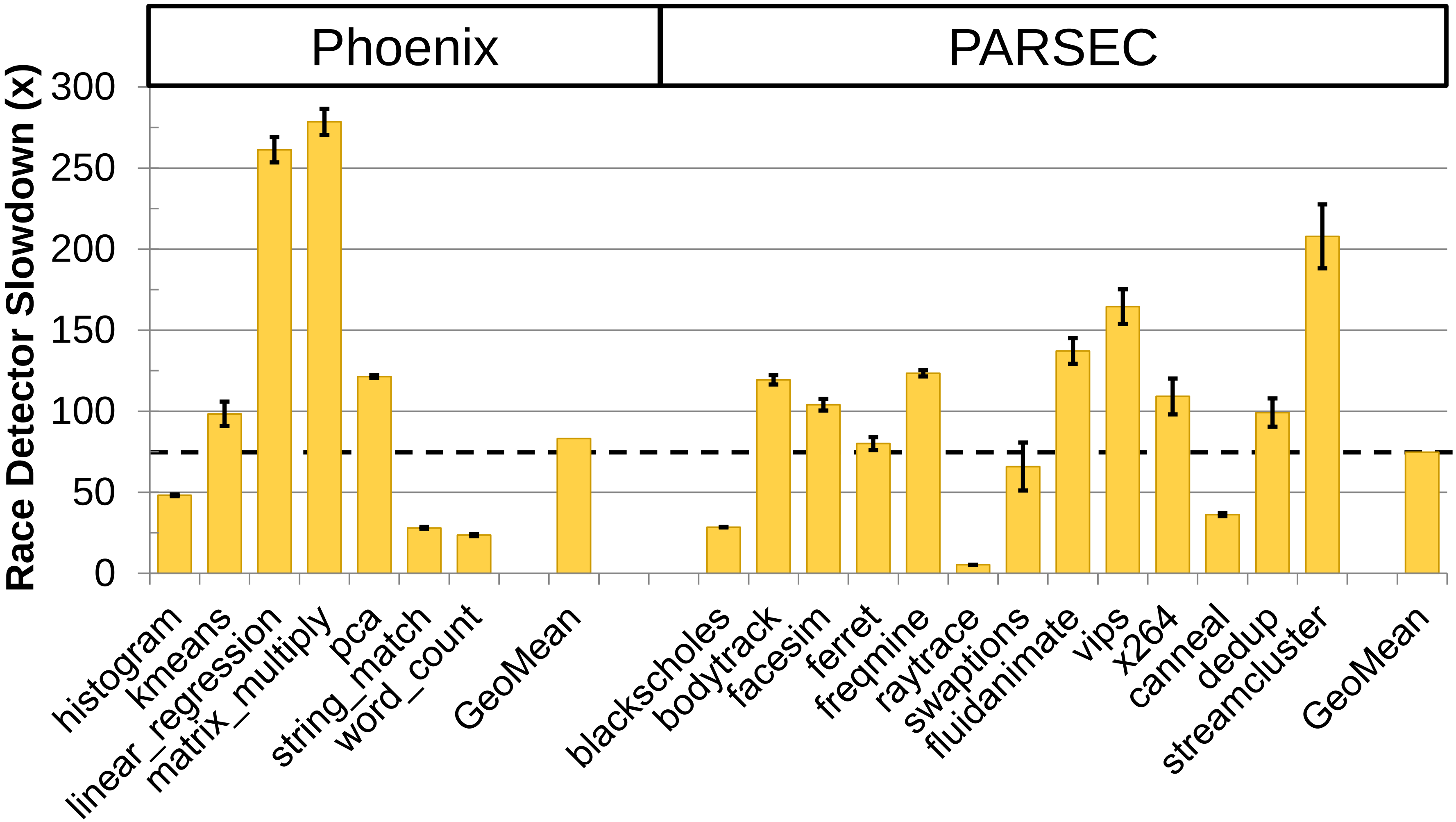
mylen=large

Interleaved Synchronization?

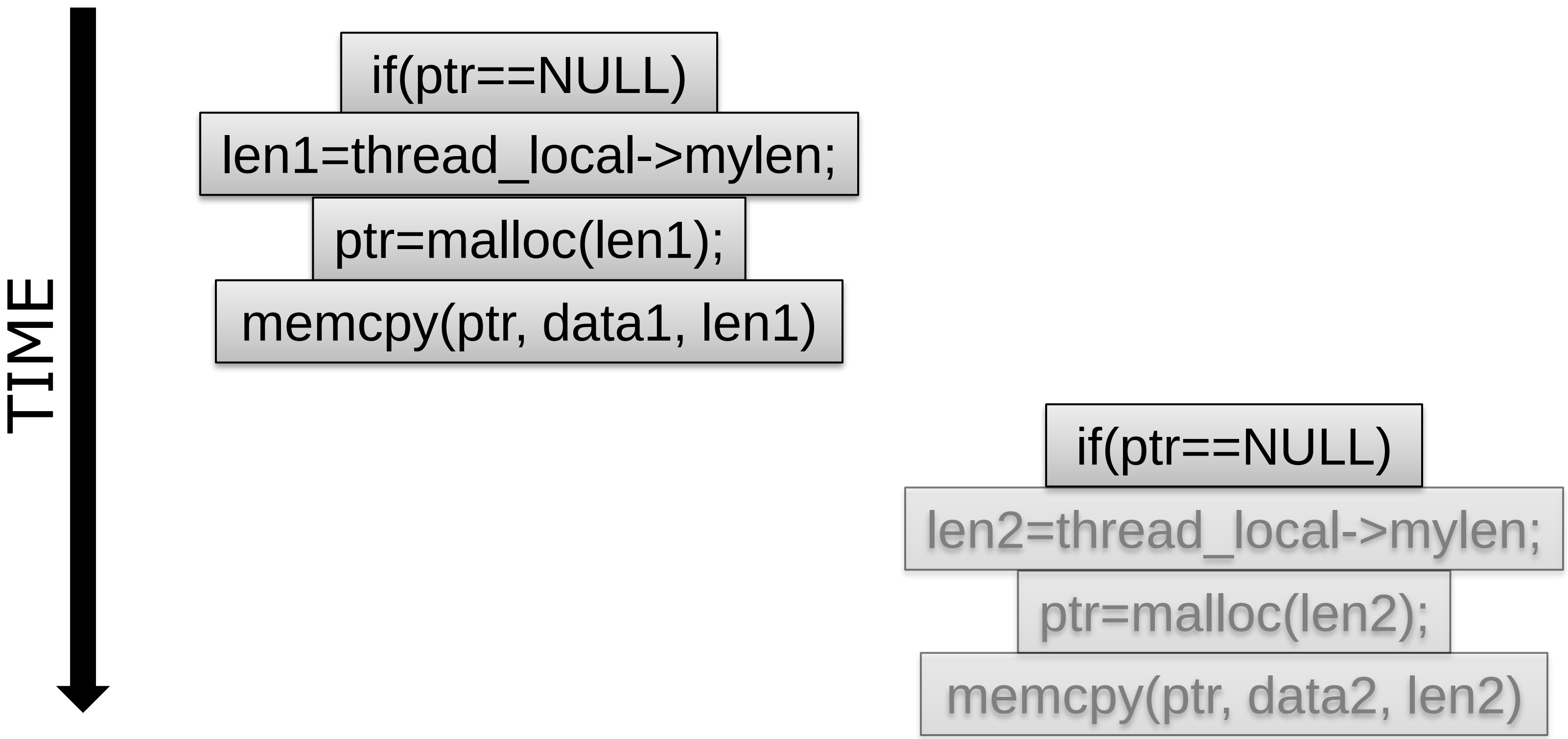
if(ptr==NULL)
len2=thread_local->mylen;
ptr=malloc(len2);
memcpy(ptr, data2, len2)

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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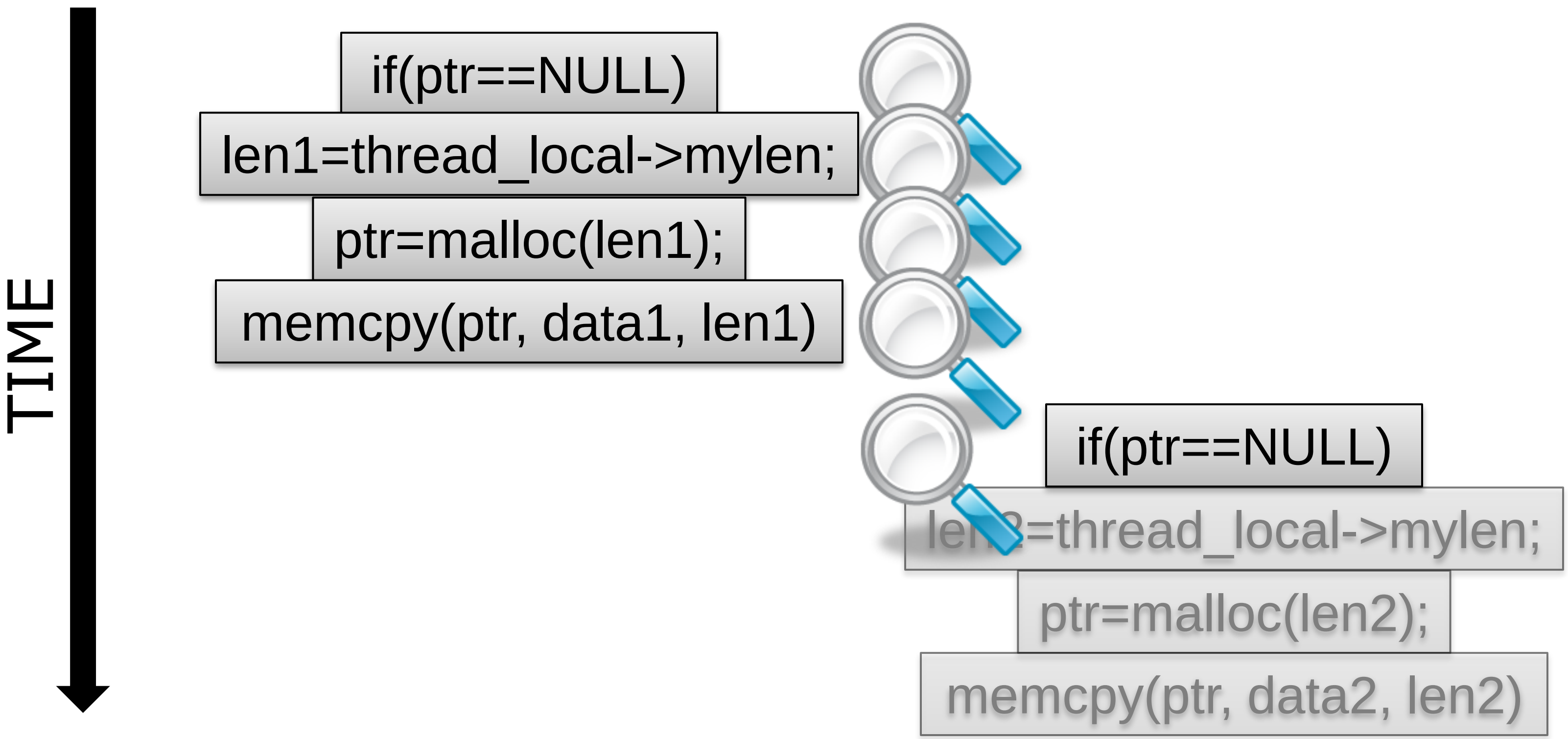

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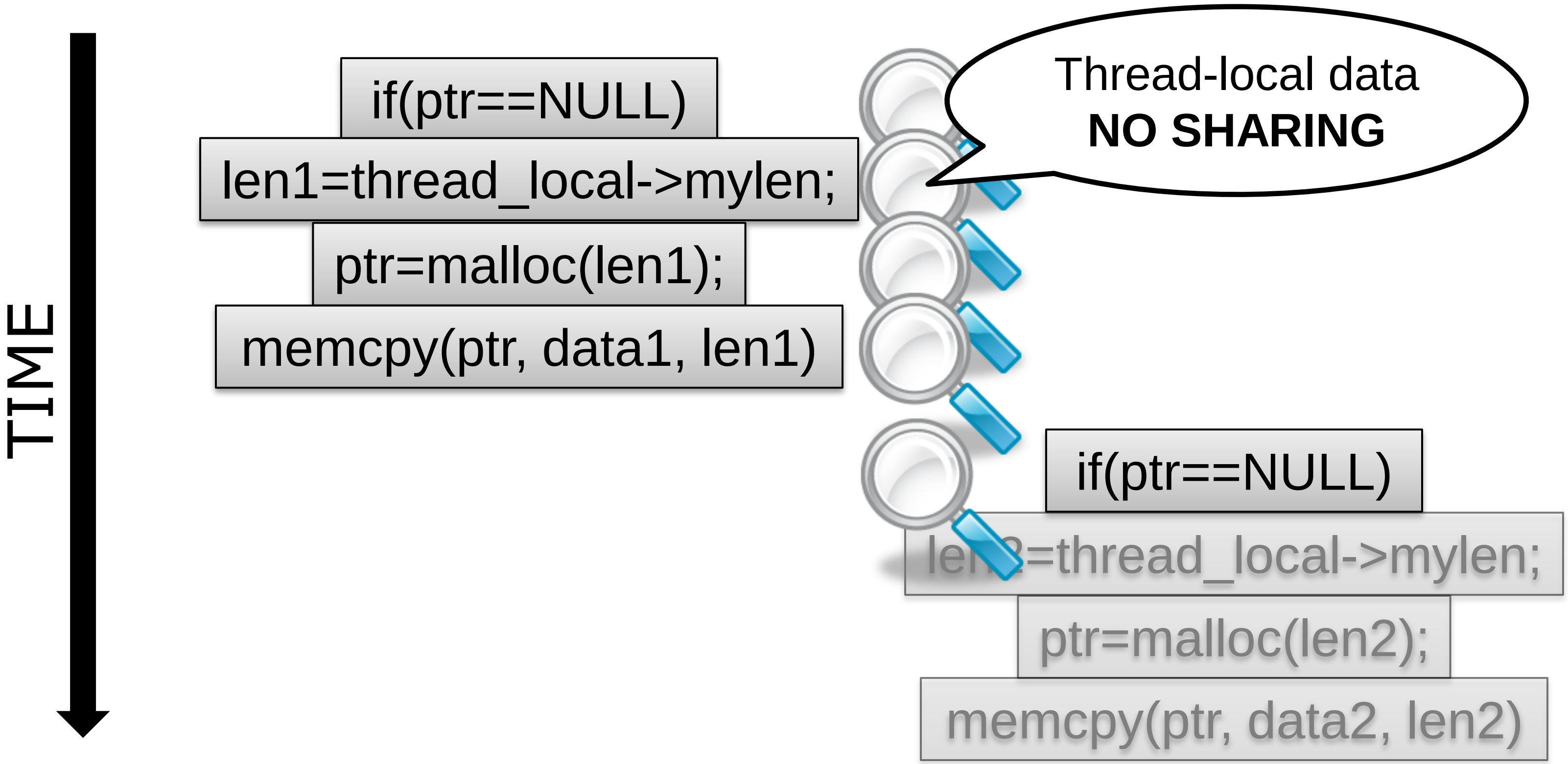

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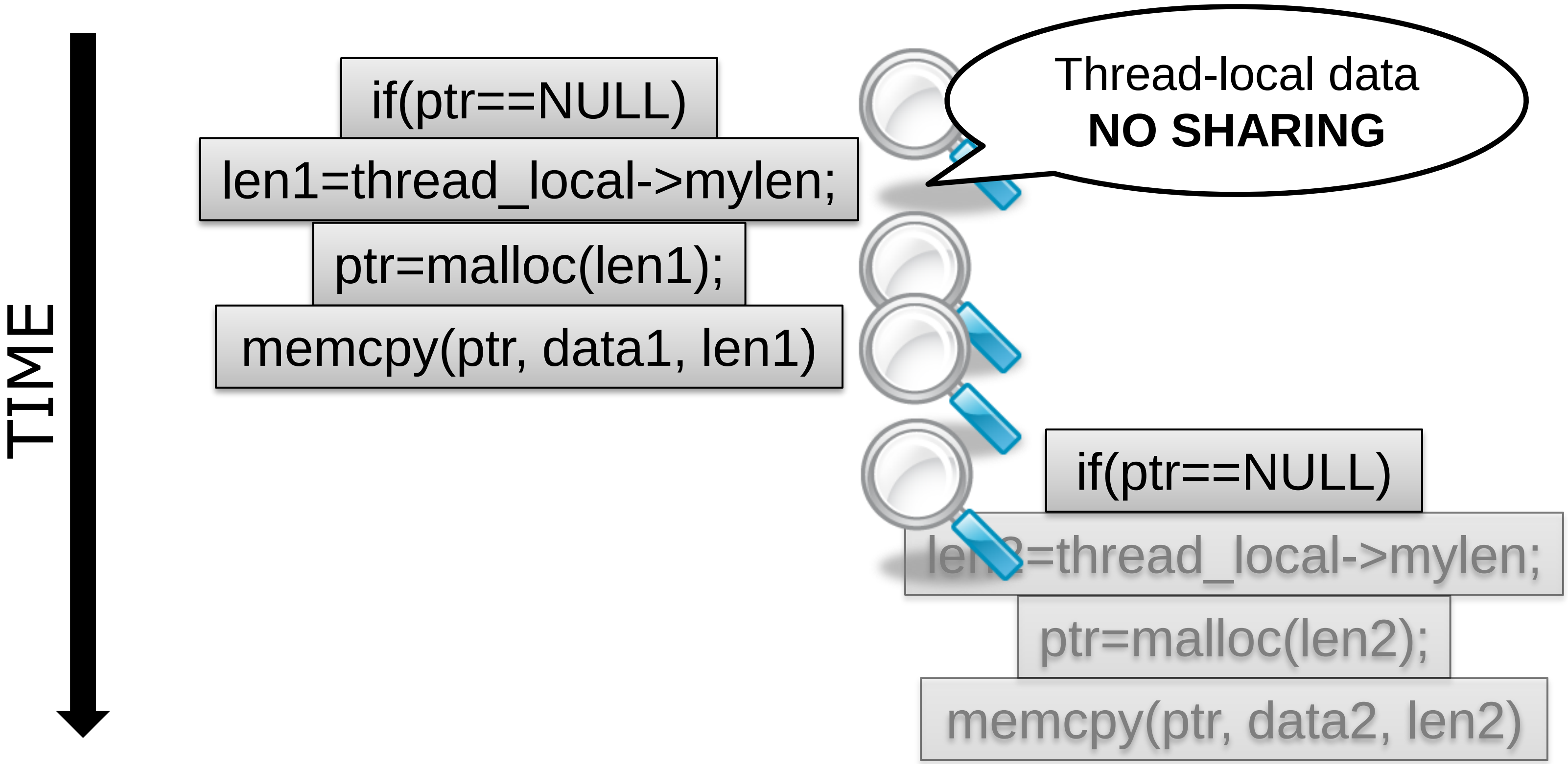

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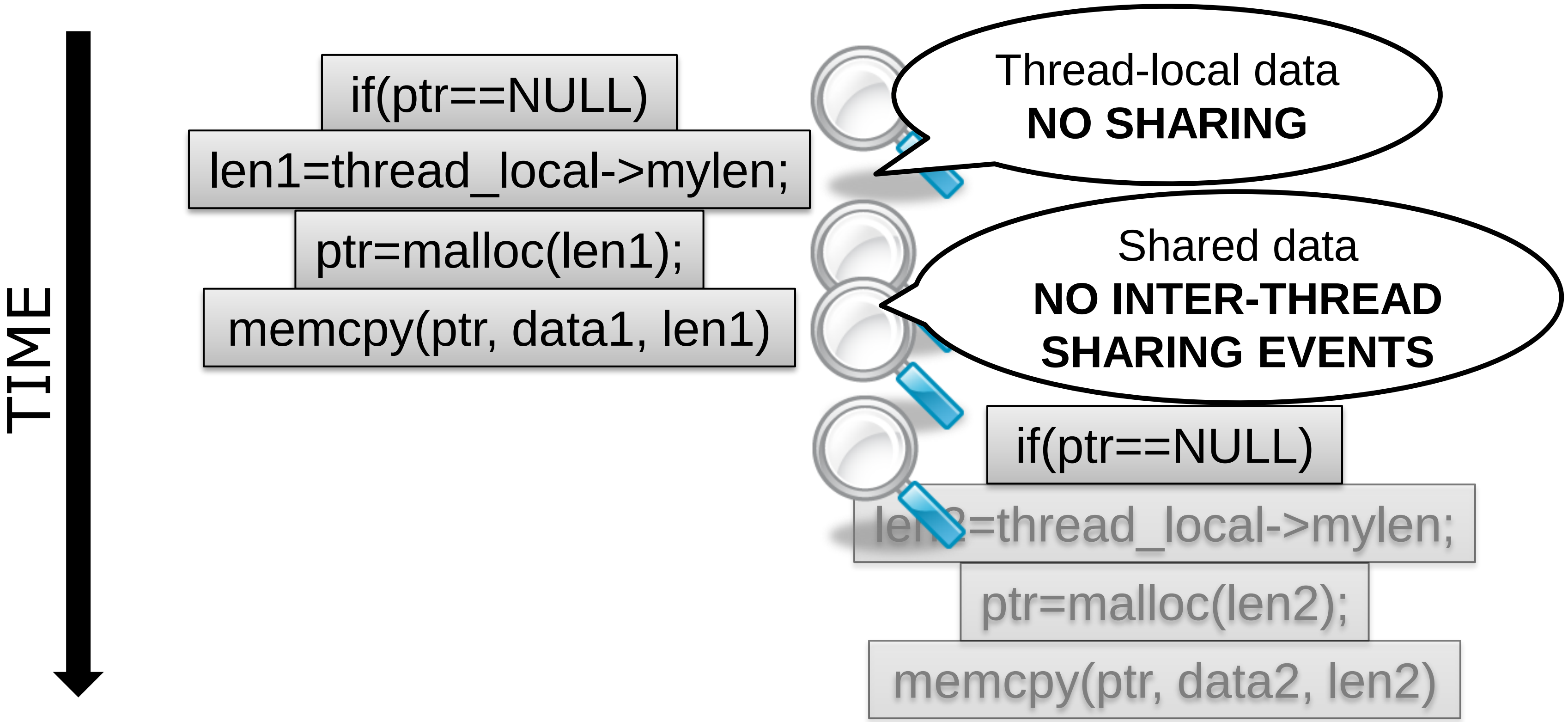

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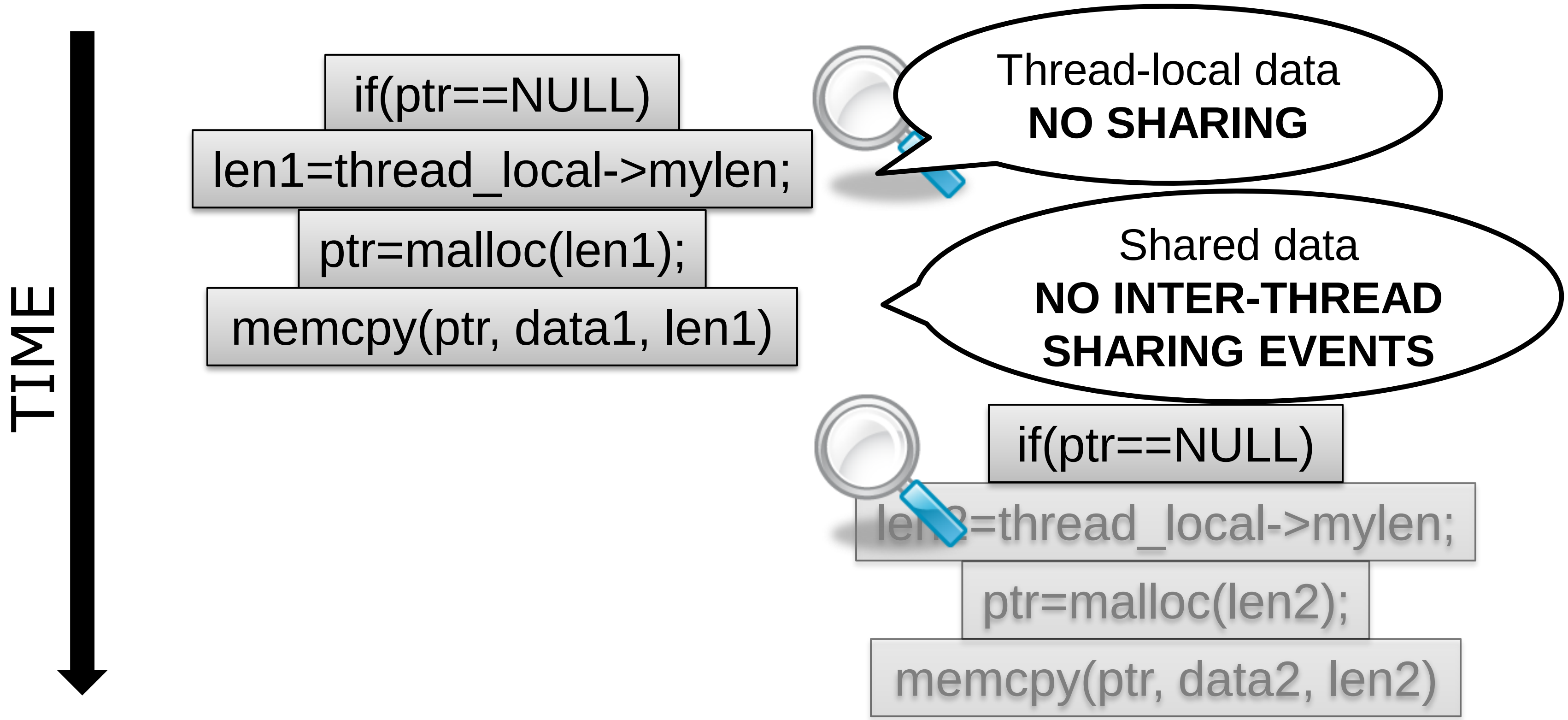

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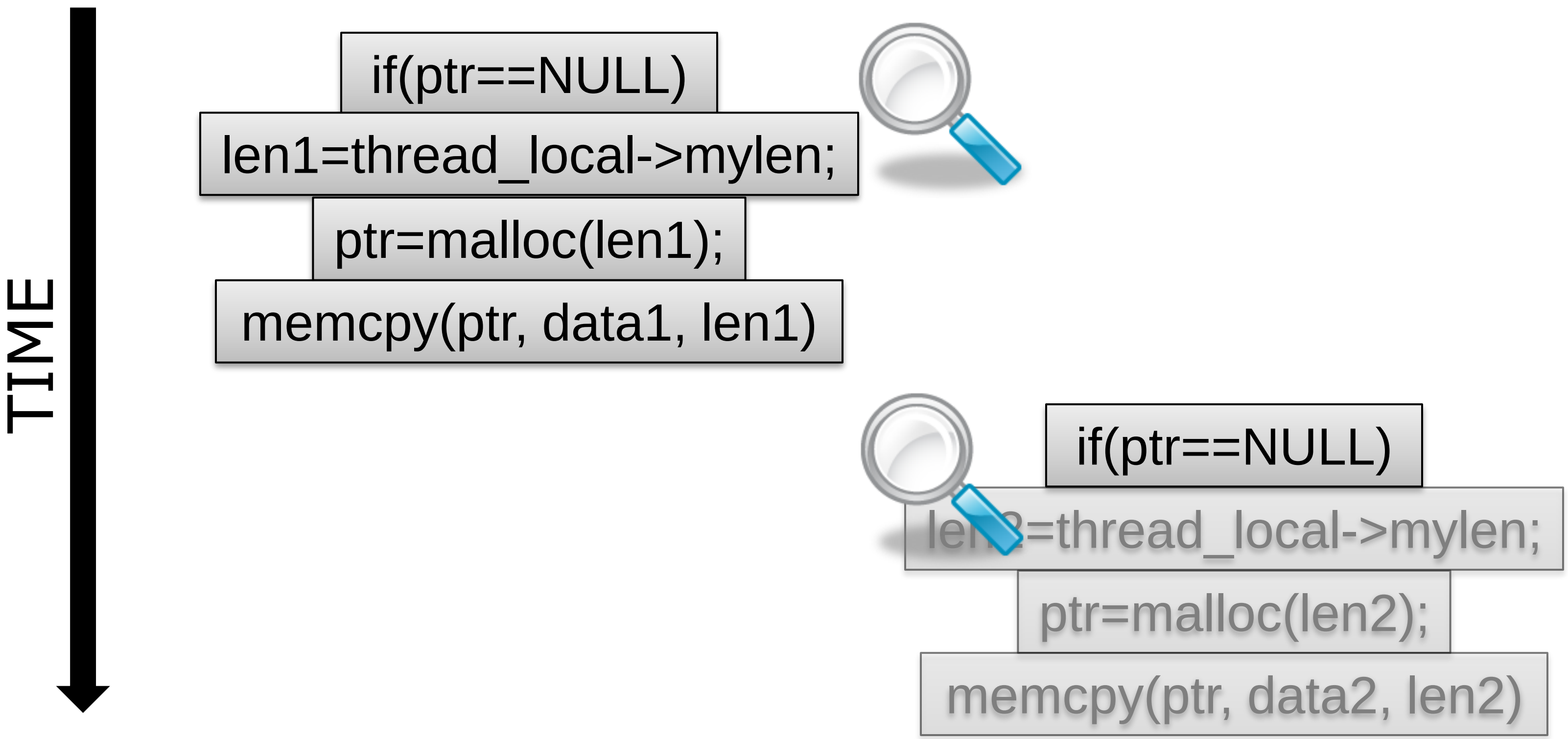

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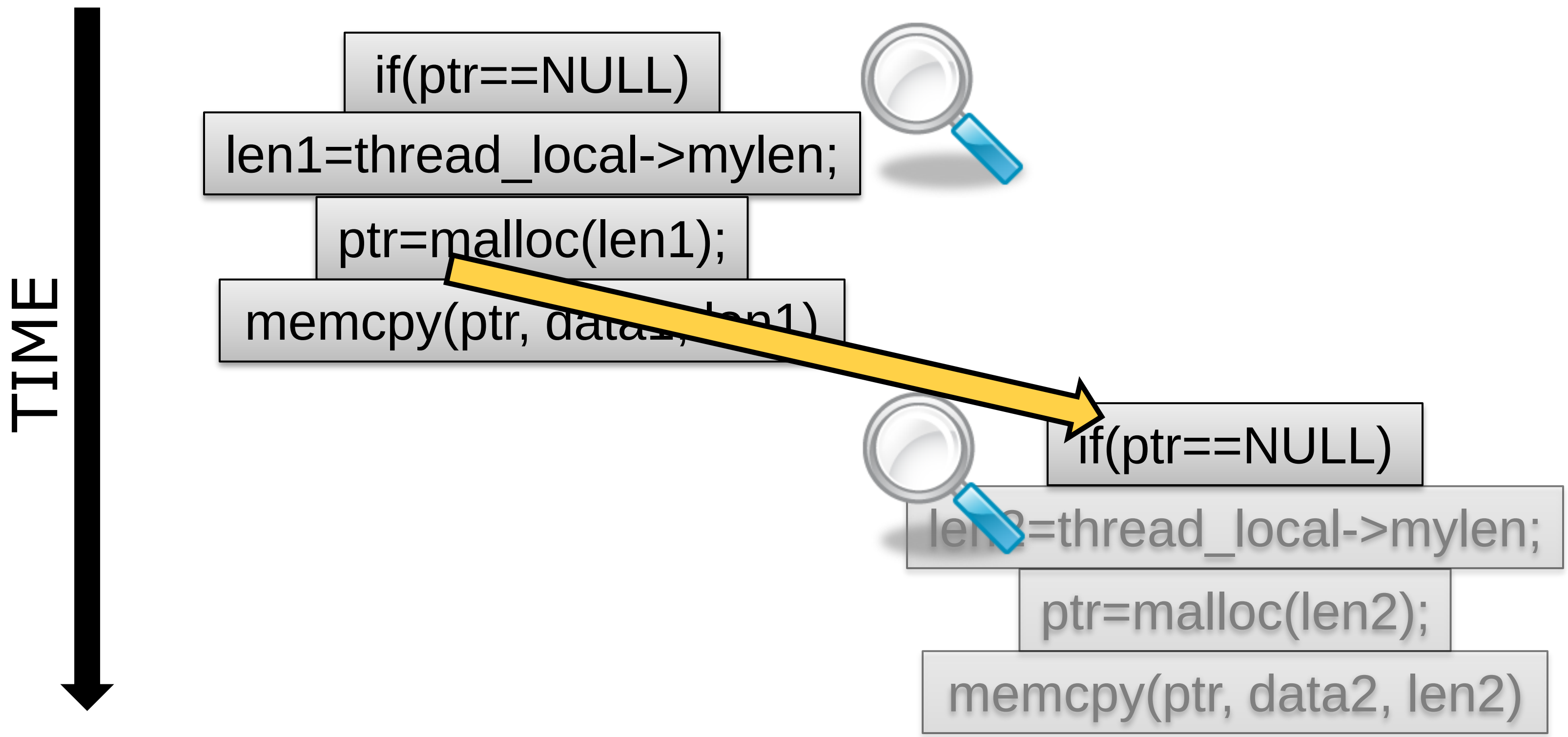
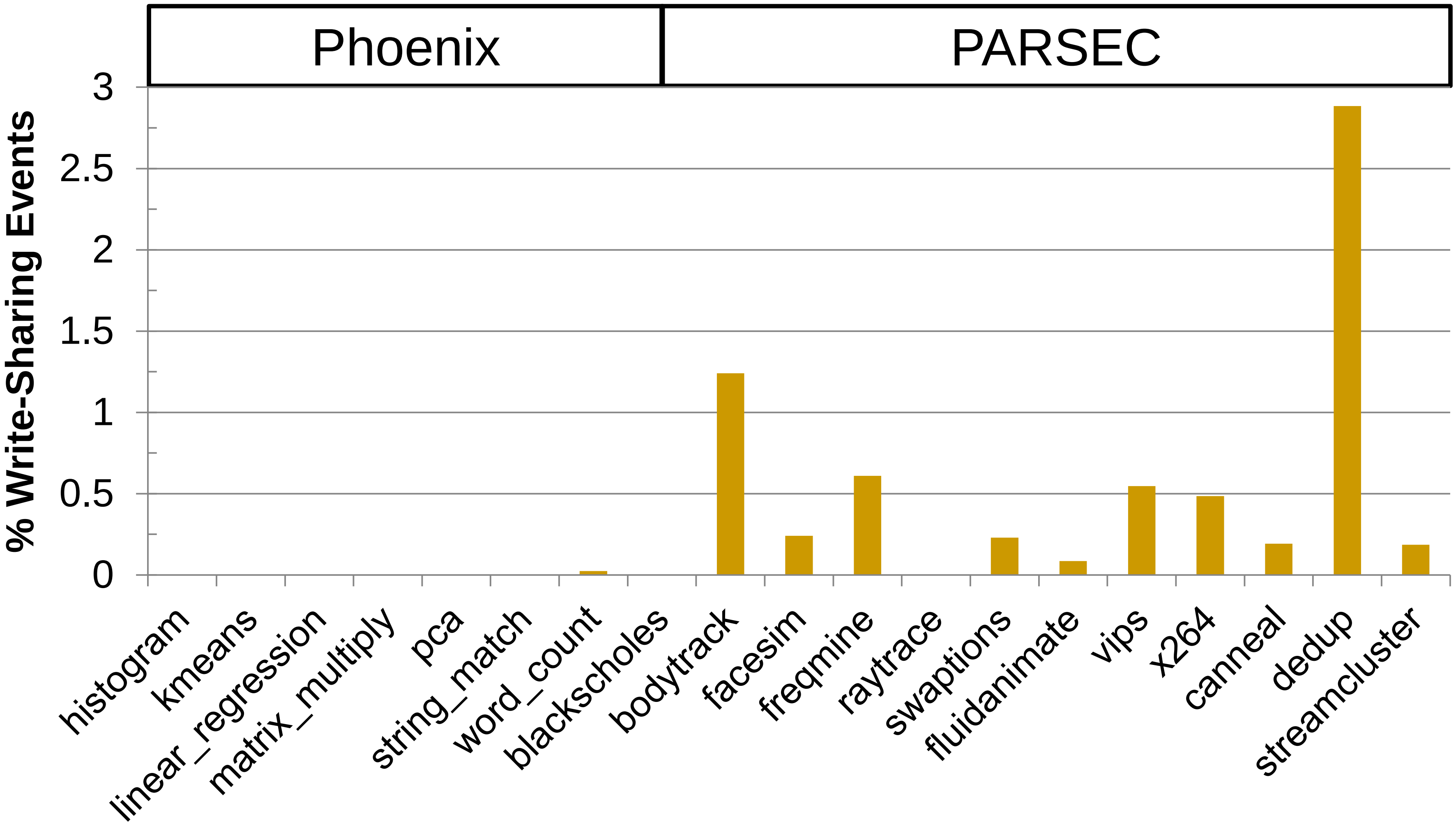
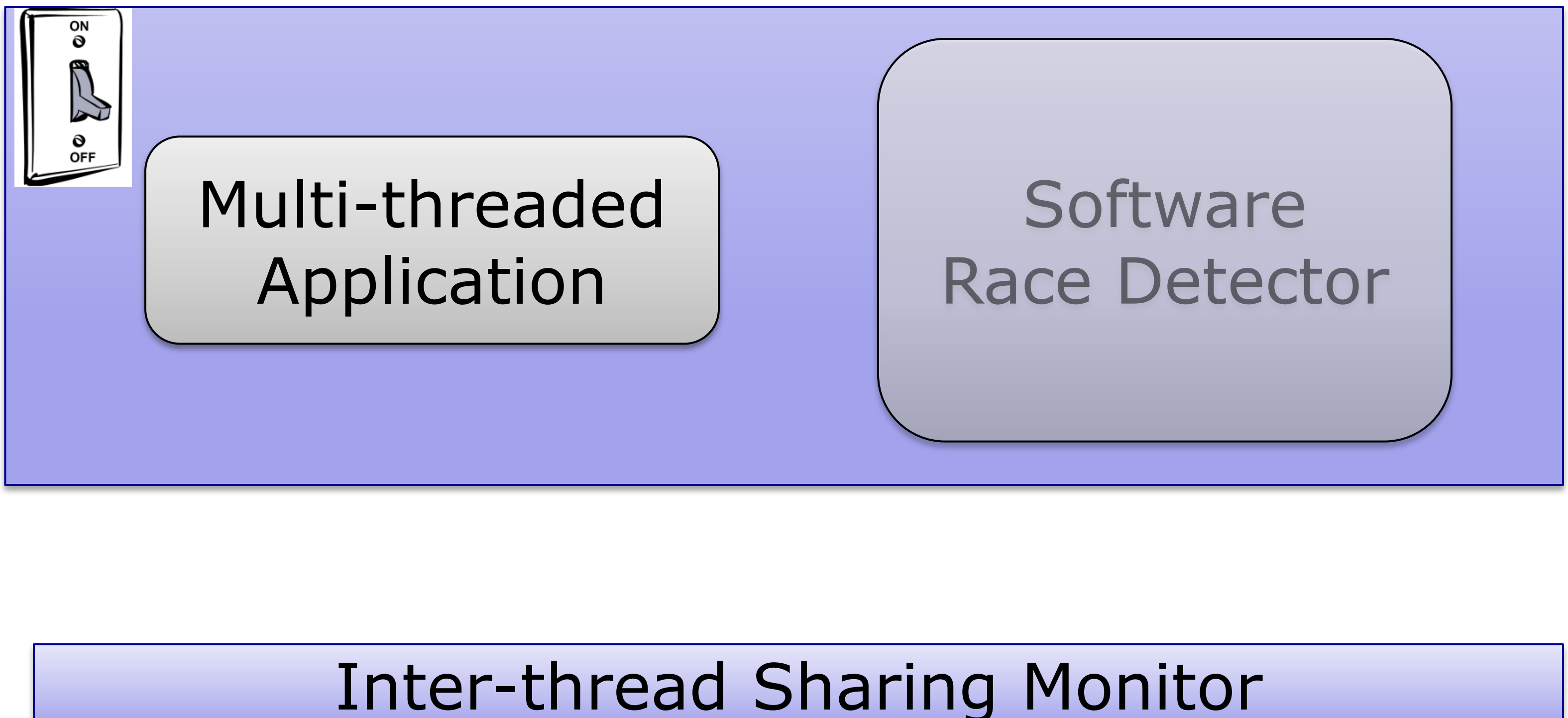


Very Little Inter-Thread Sharing



Use Demand-Driven Analysis!



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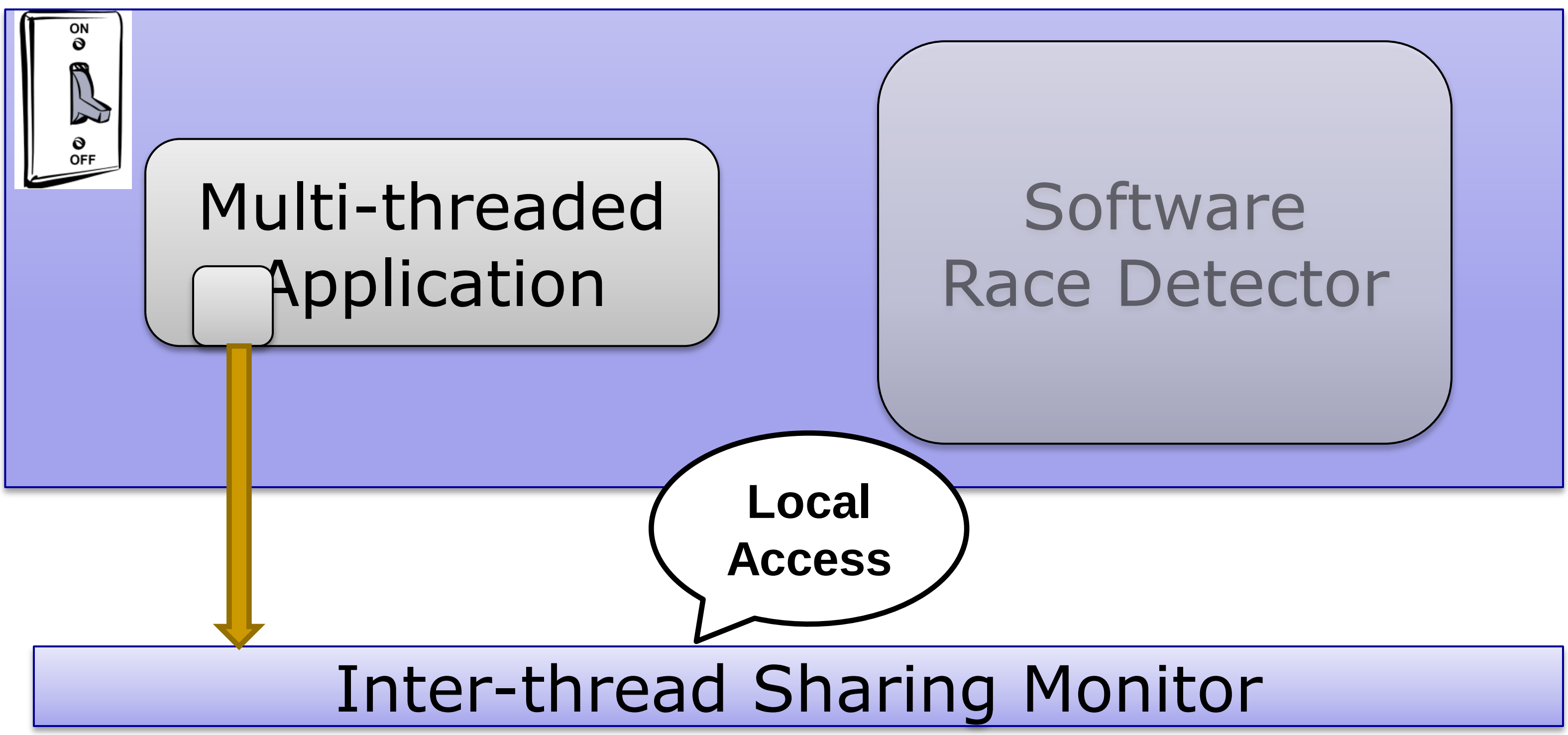

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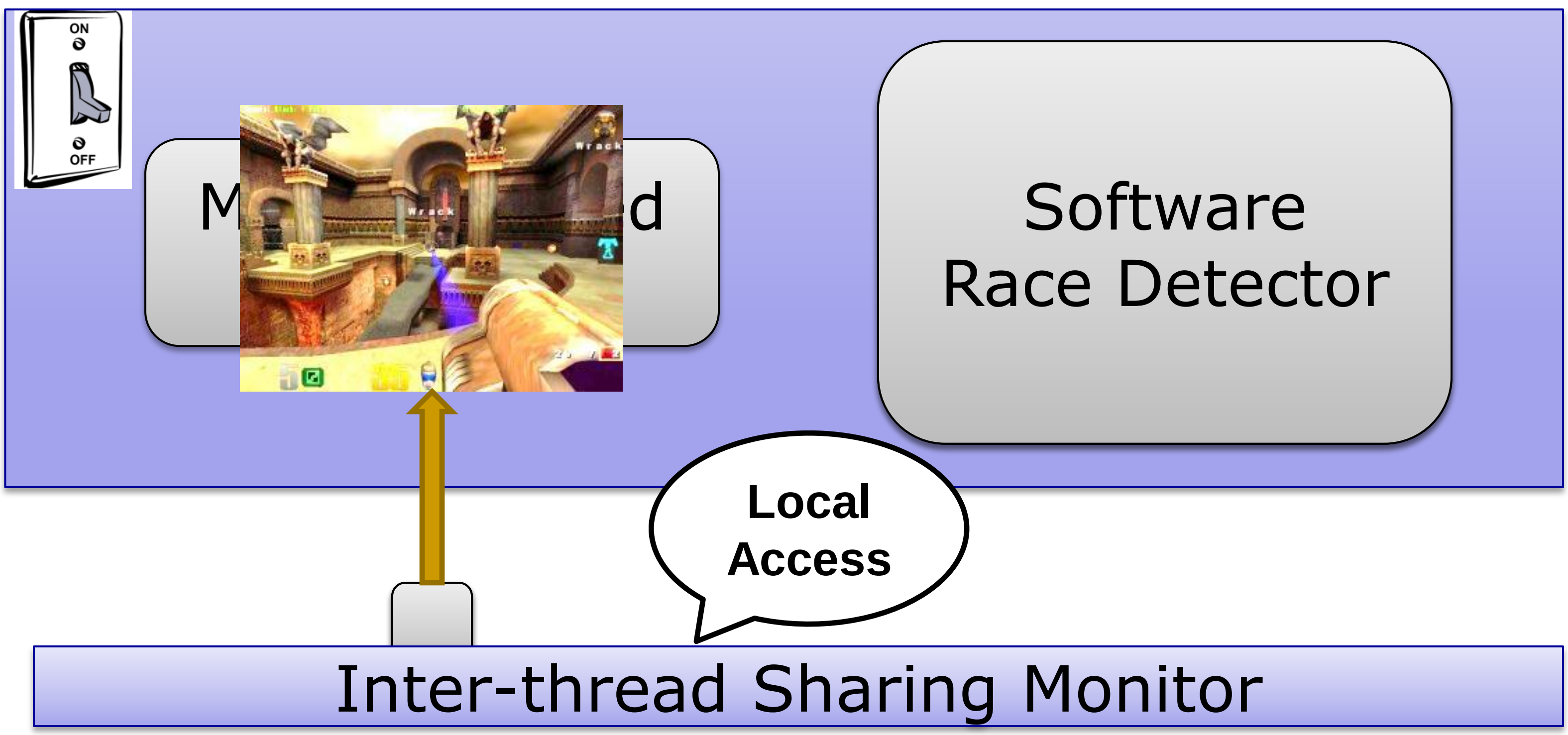

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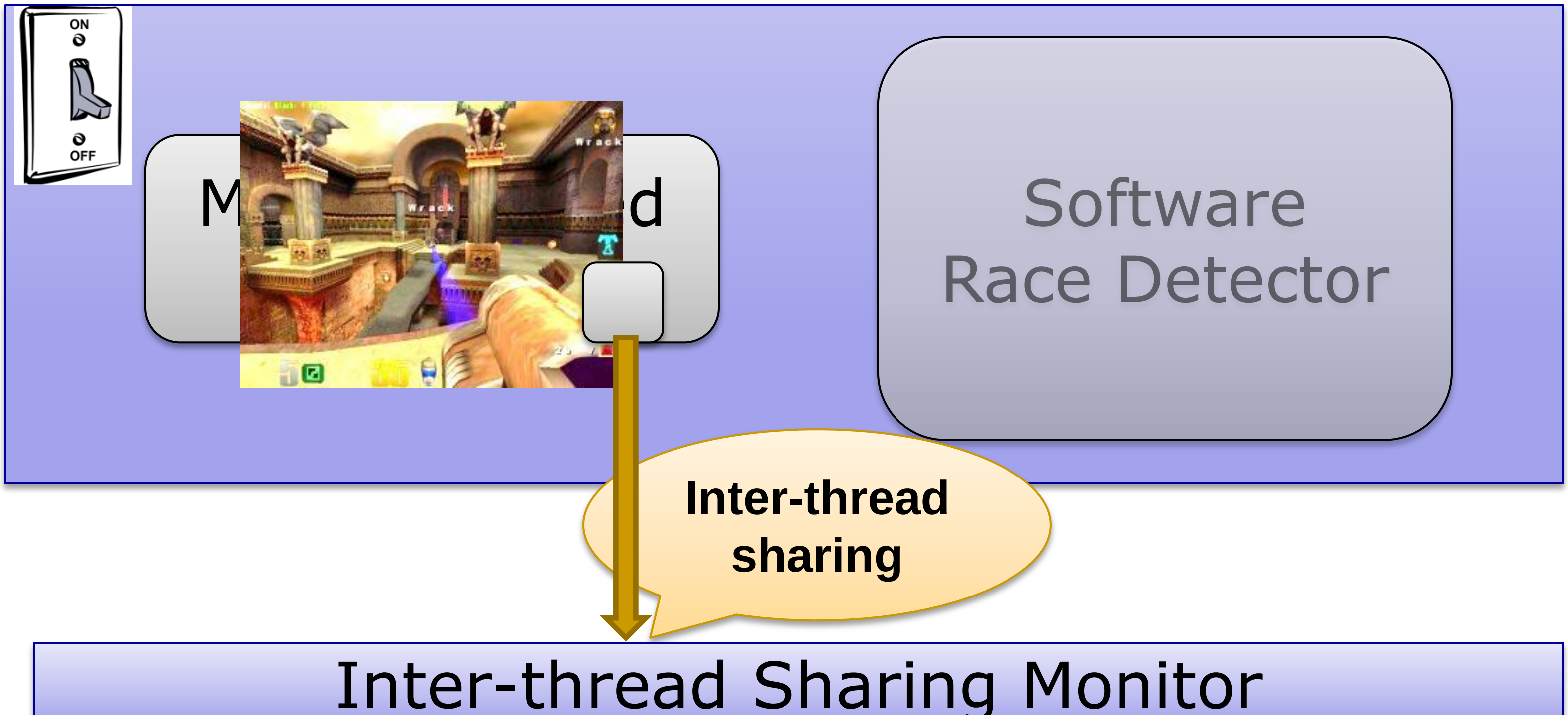

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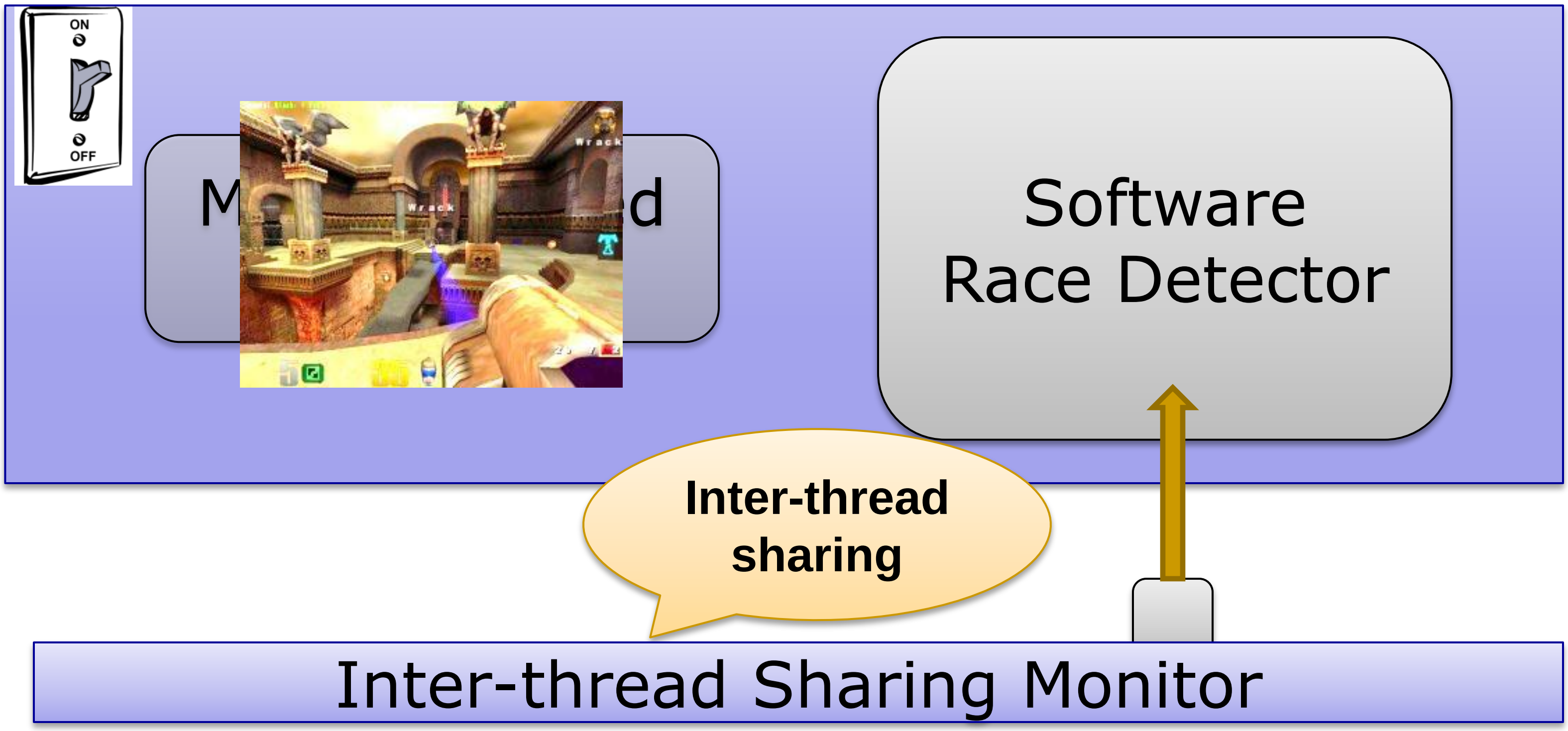

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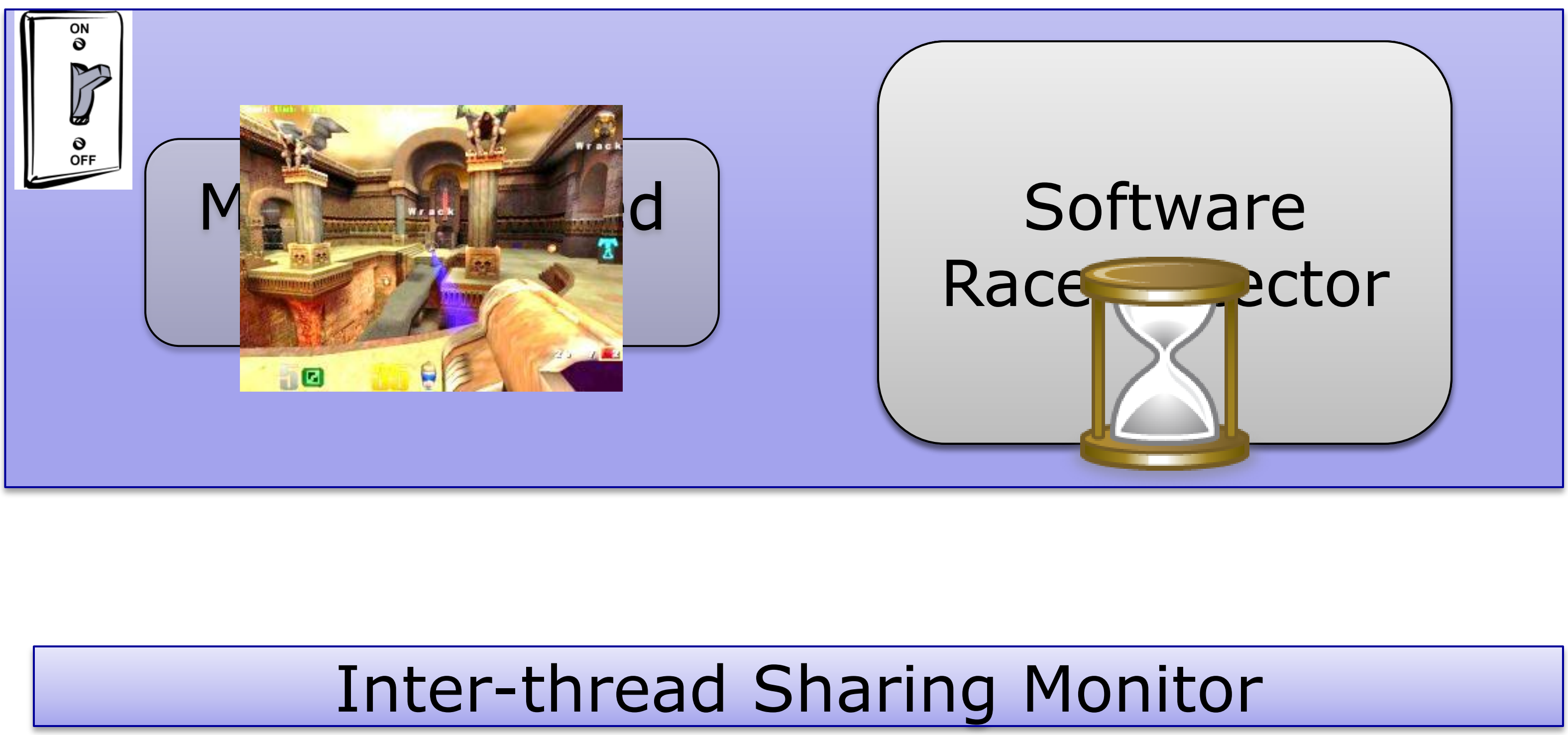

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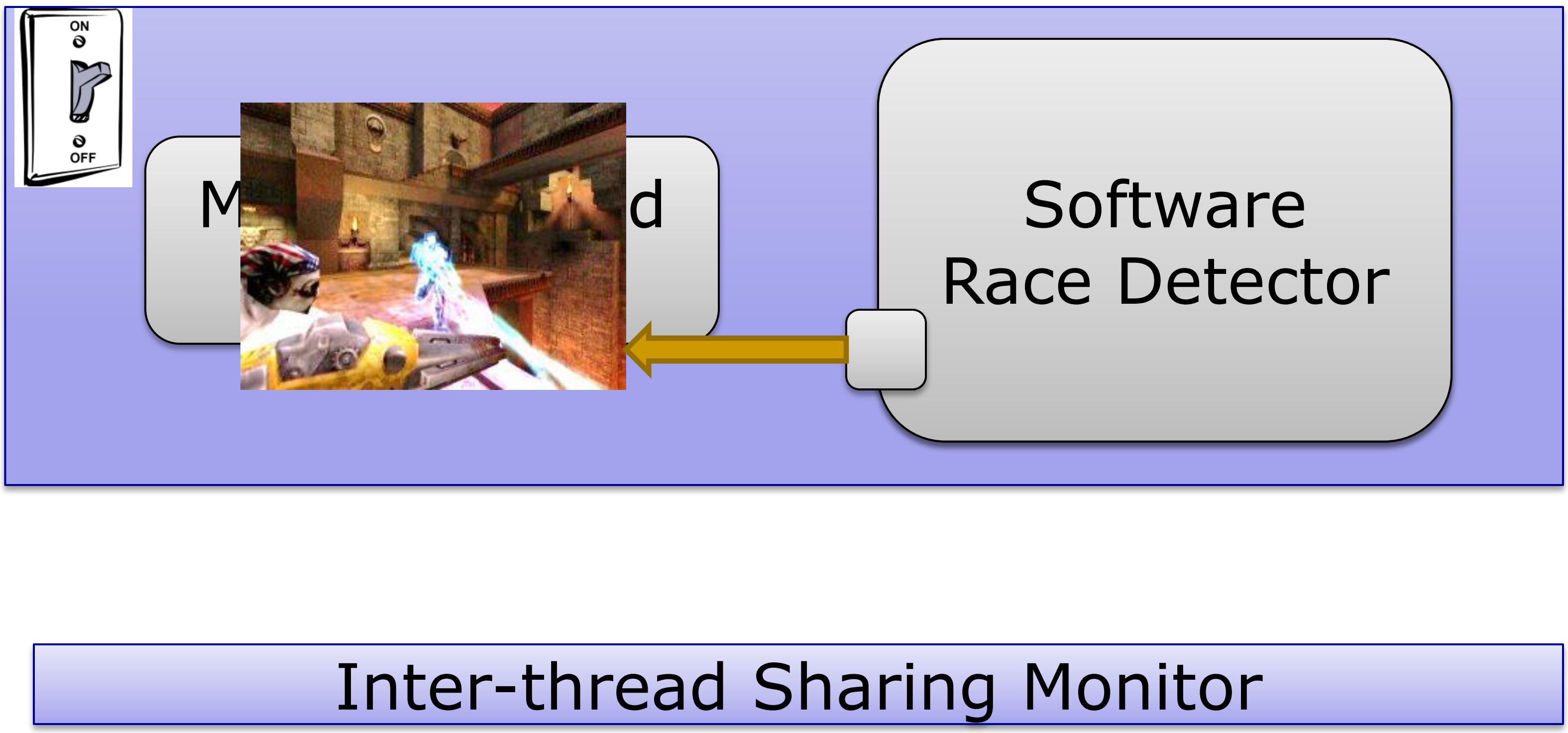

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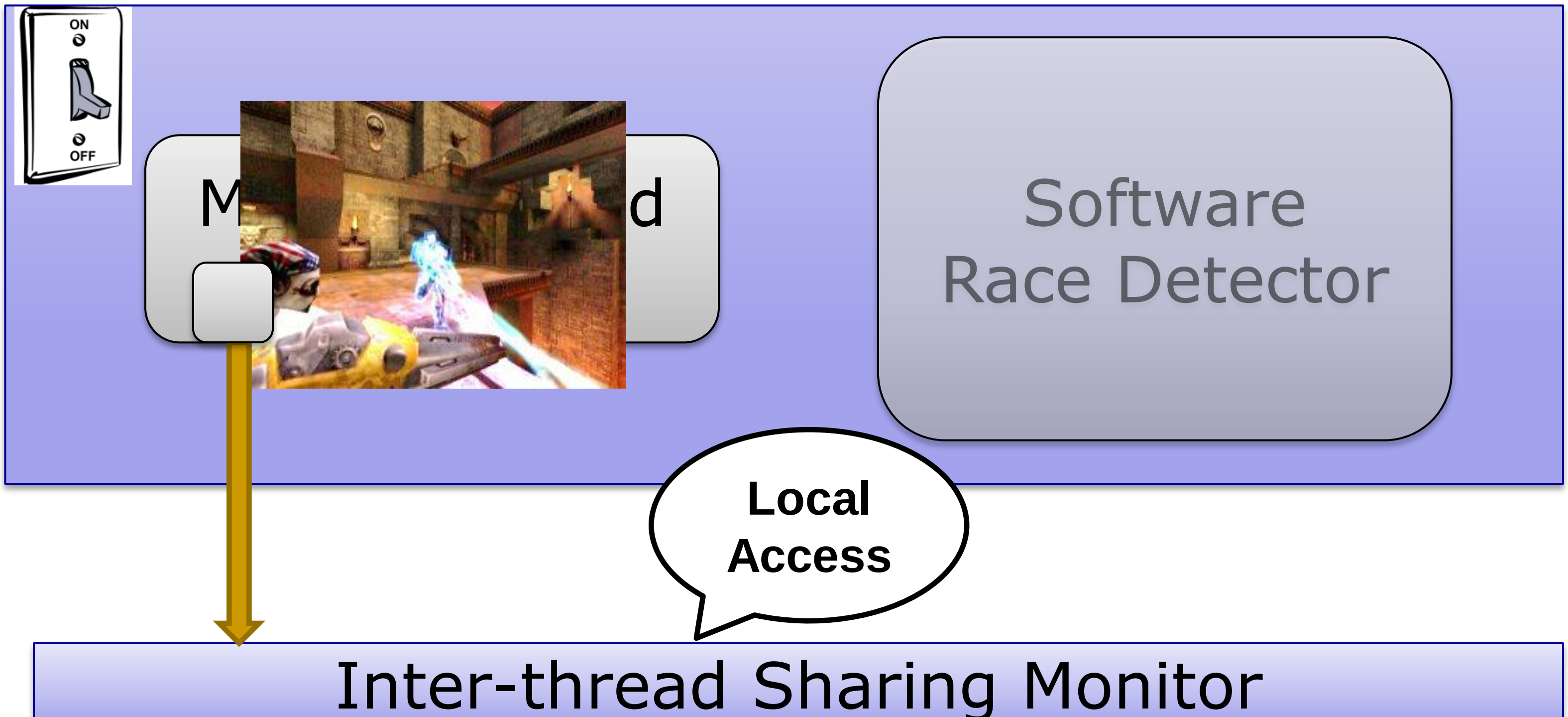

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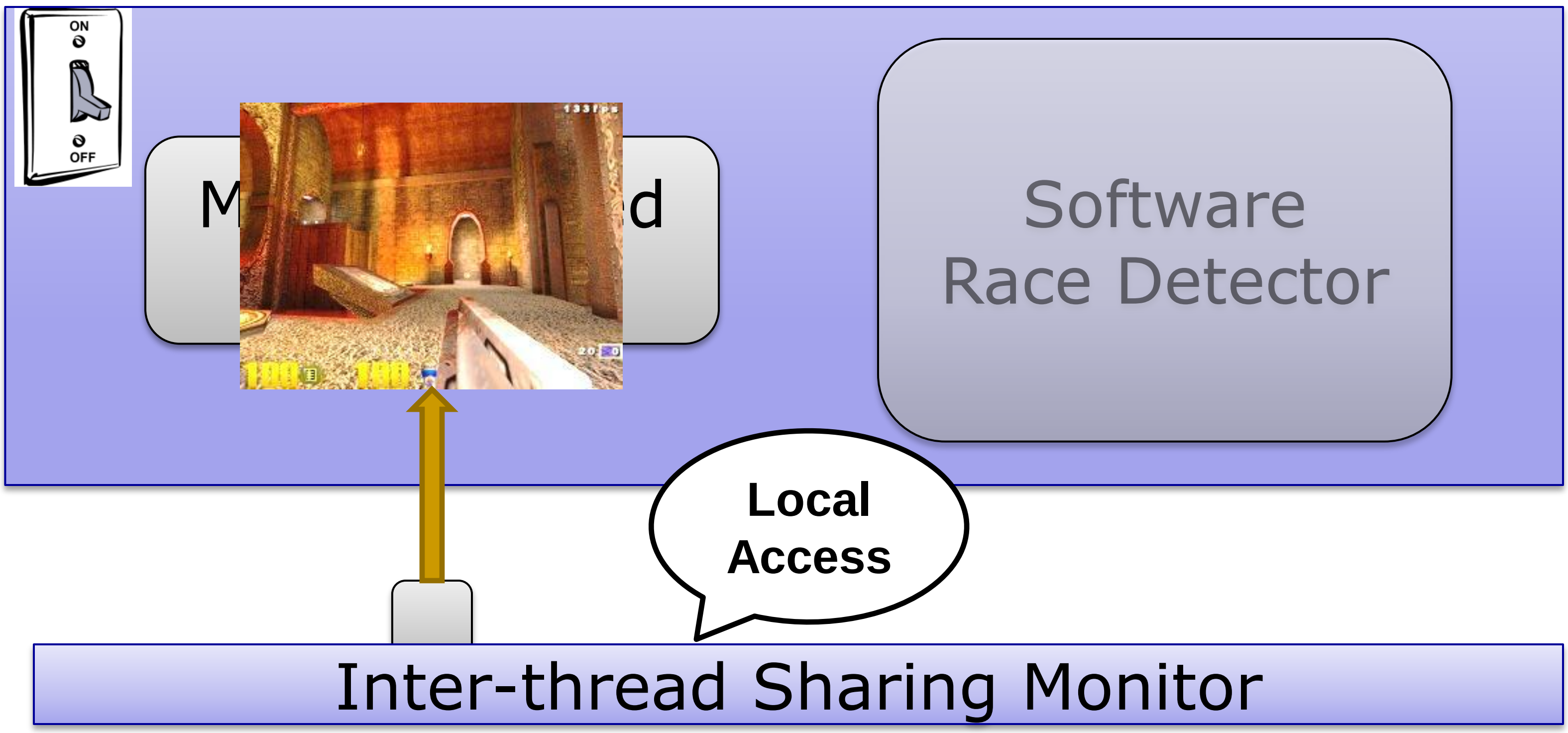

Finding Inter-thread Sharing

- Virtual Memory Watchpoints?

Finding Inter-thread Sharing

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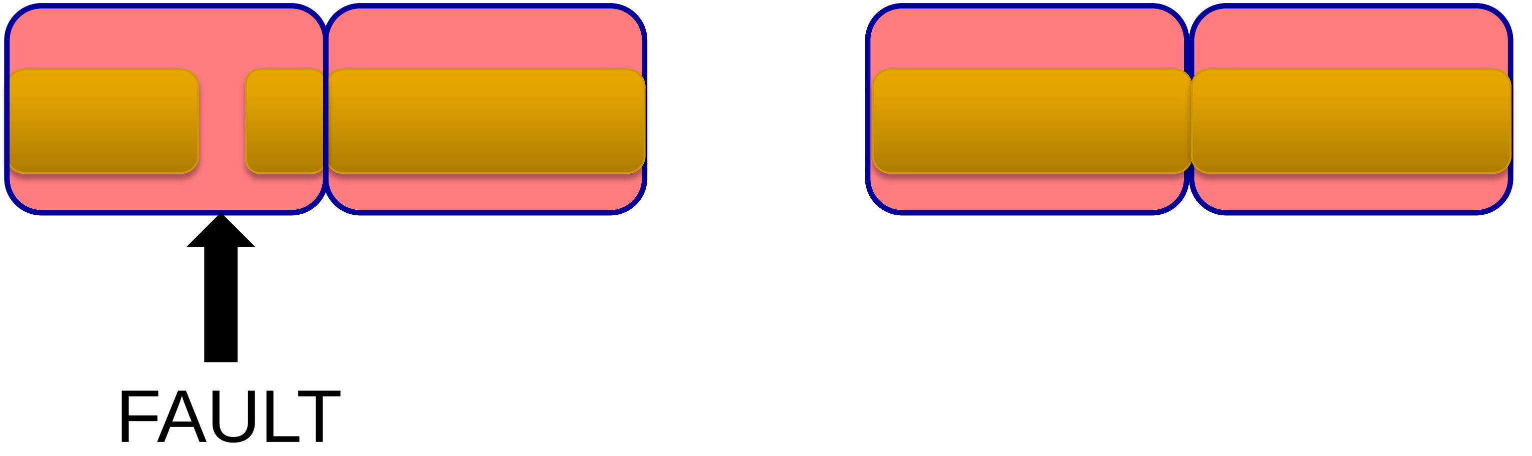

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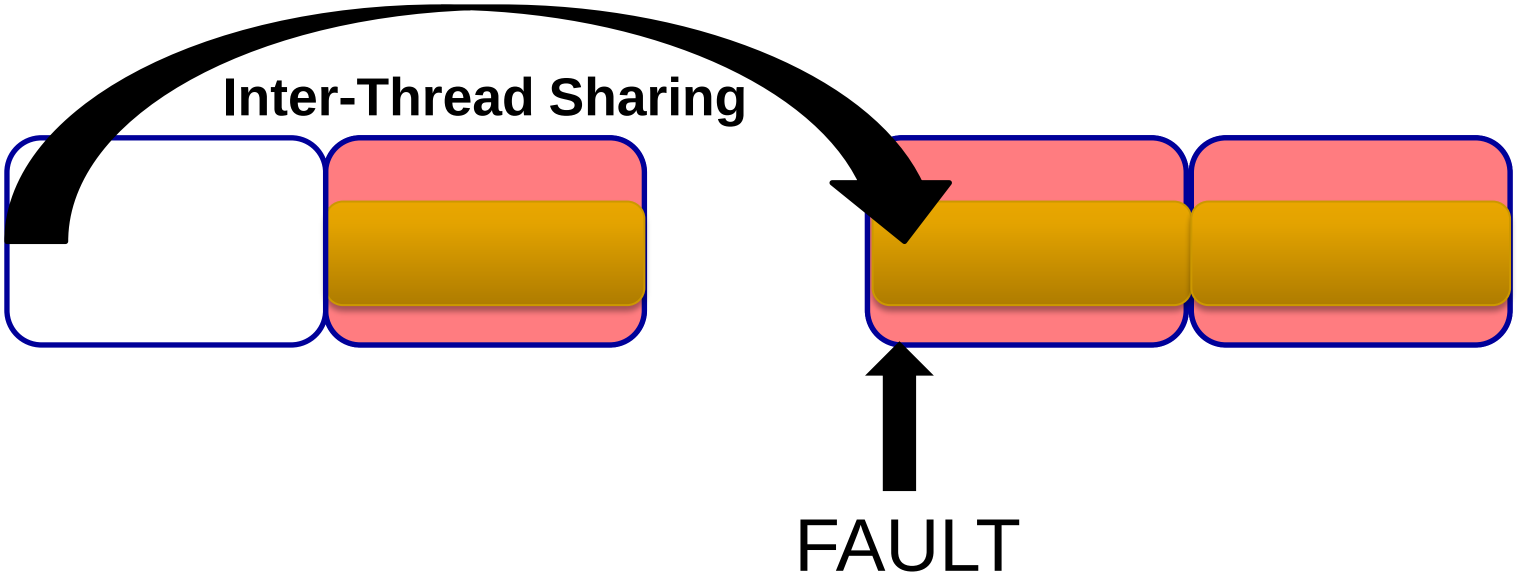

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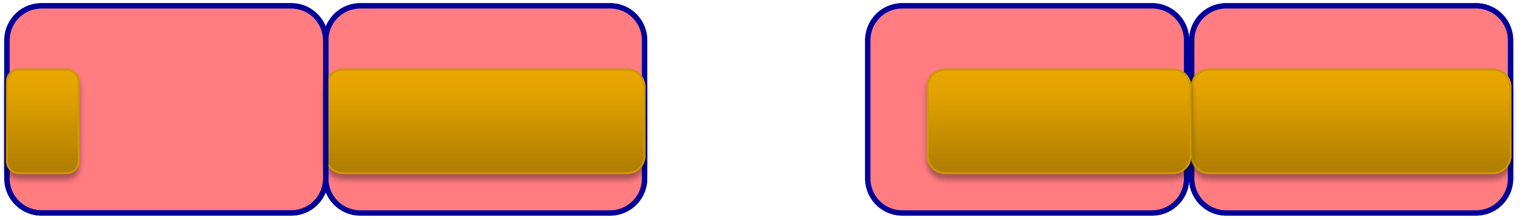
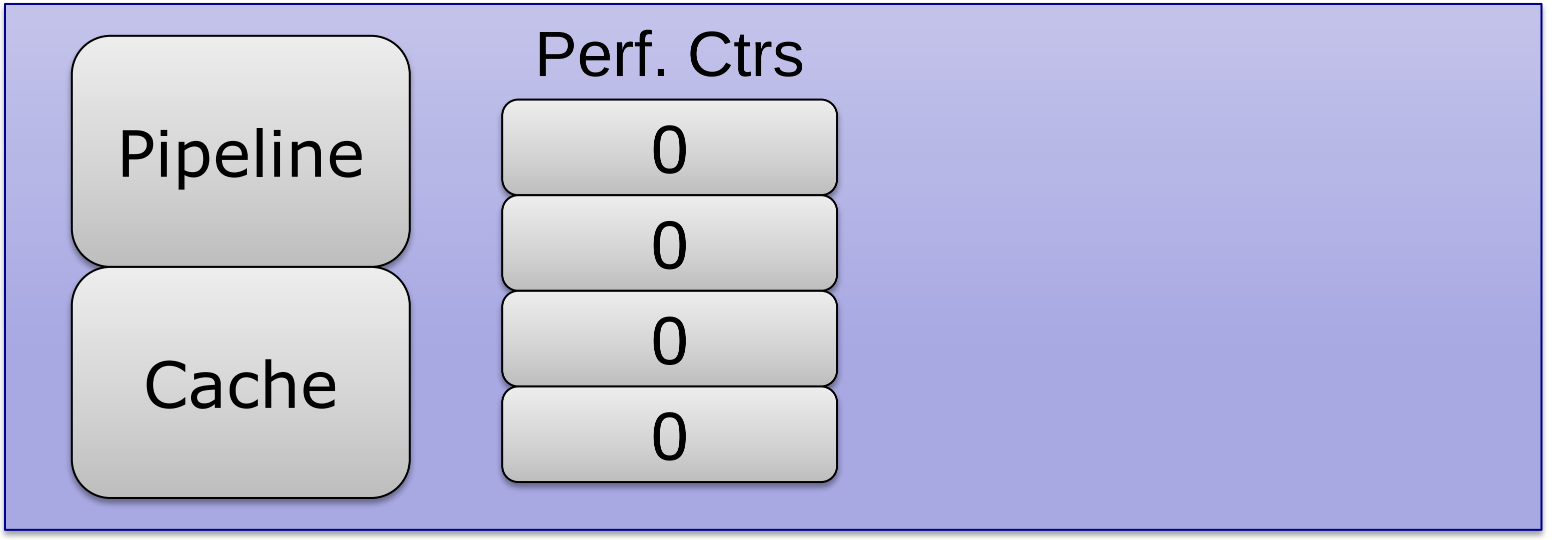


  – ~100% of accesses cause page faults
- Granularity Gap
- Per-process not per-thread
- Must go through the kernel on faults
- Syscalls for setting/removing meta-data

Hardware Sharing Detector

- Hardware Performance Counters



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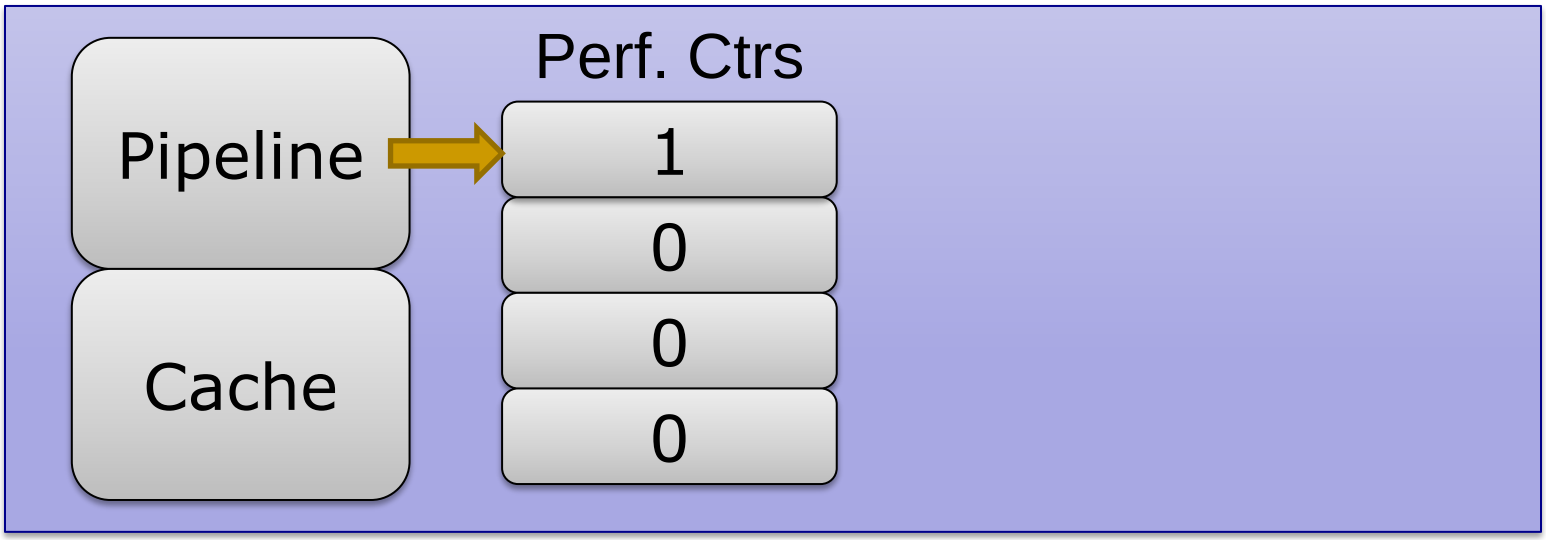

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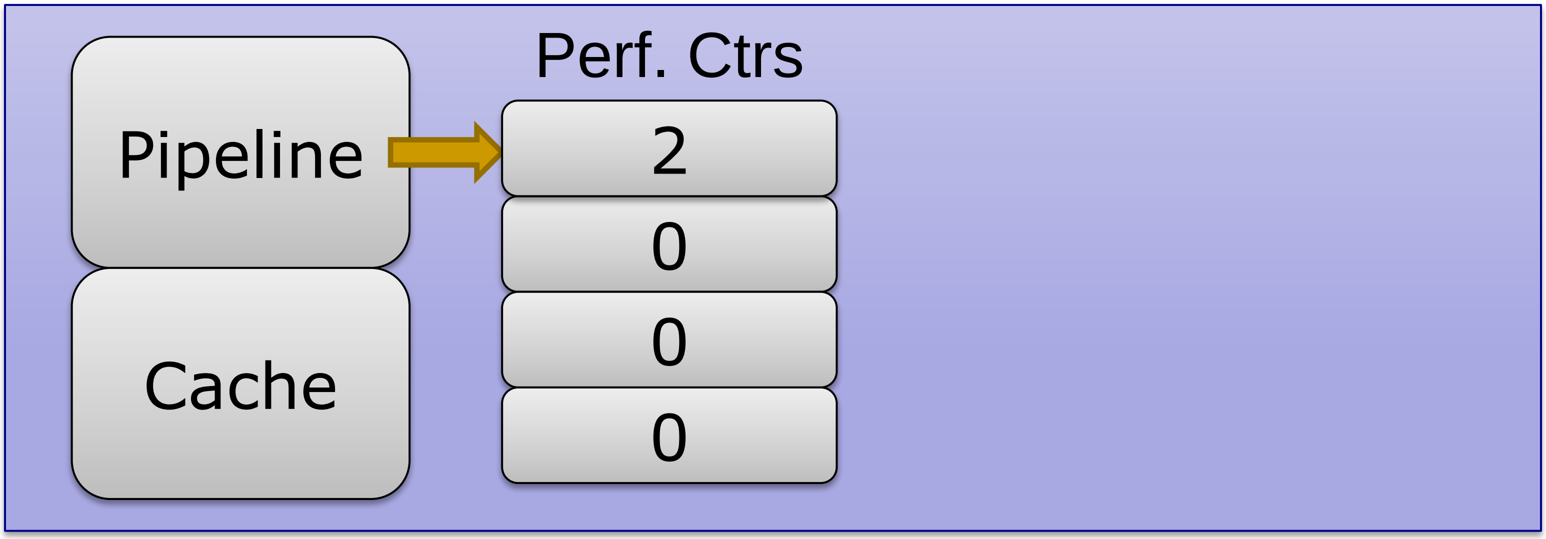

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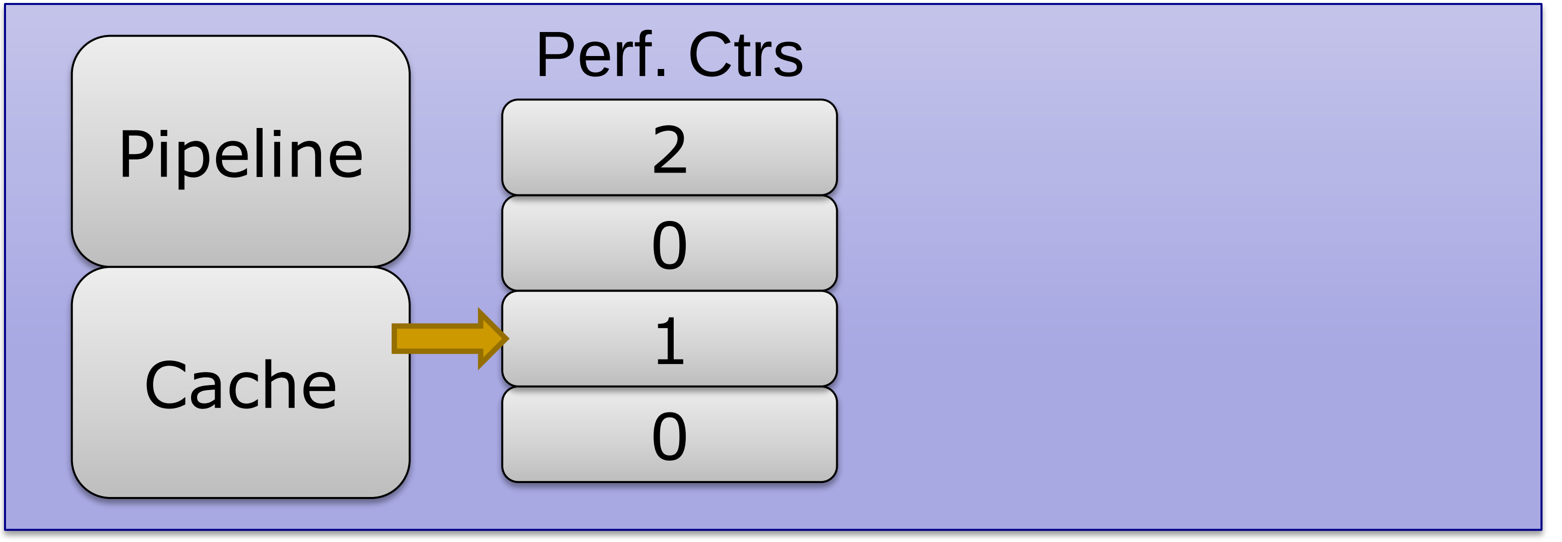

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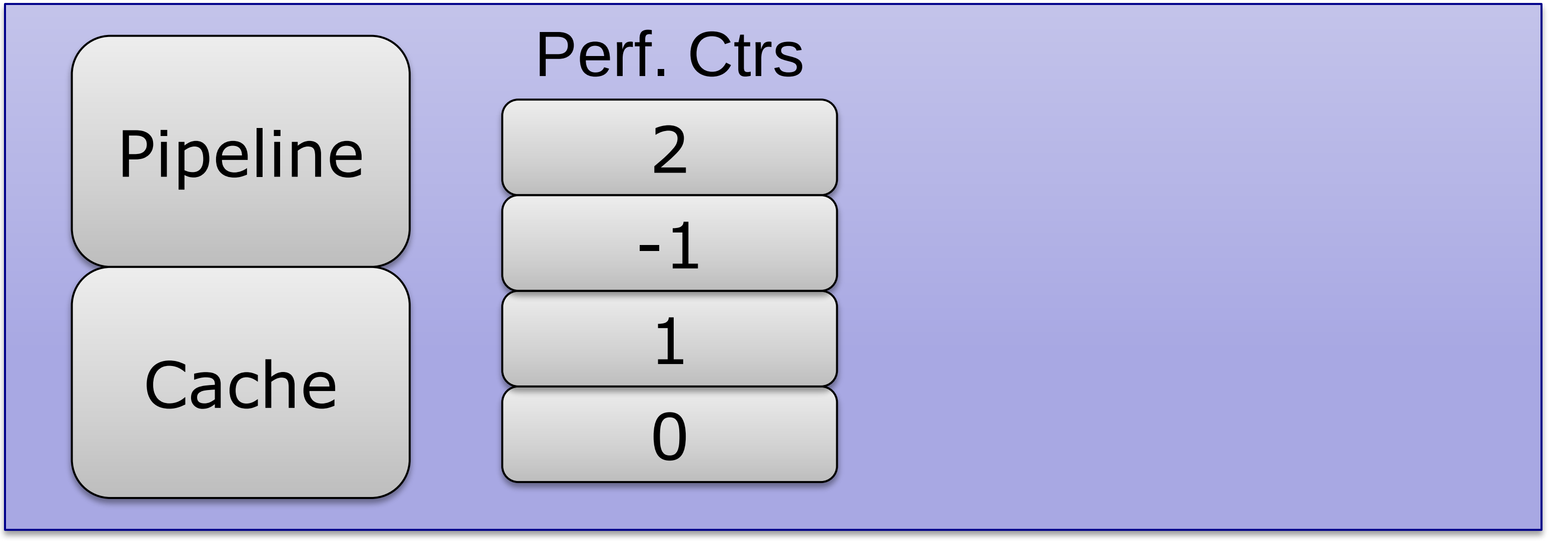

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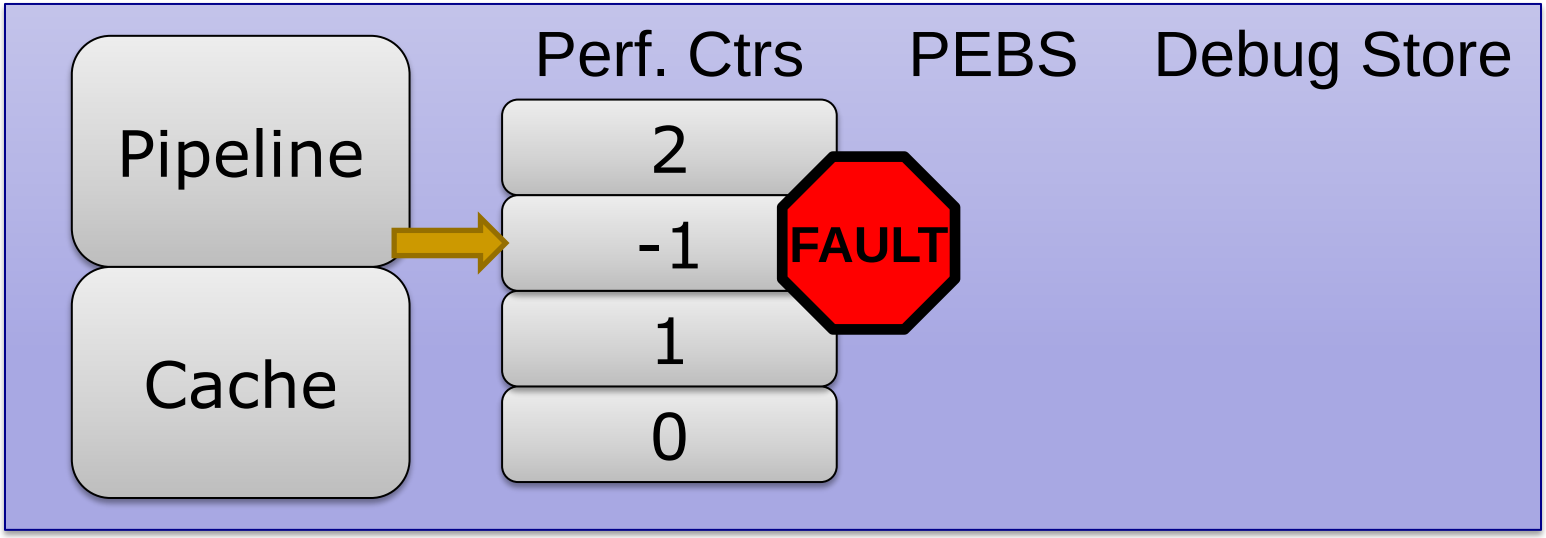

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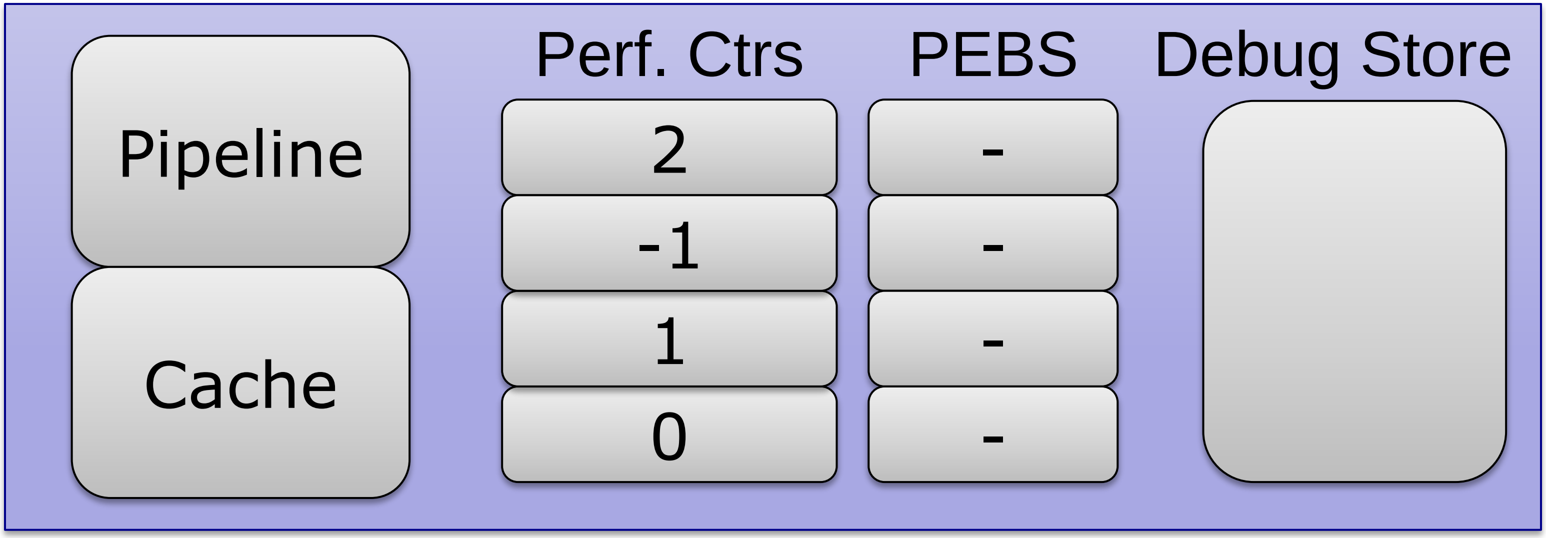

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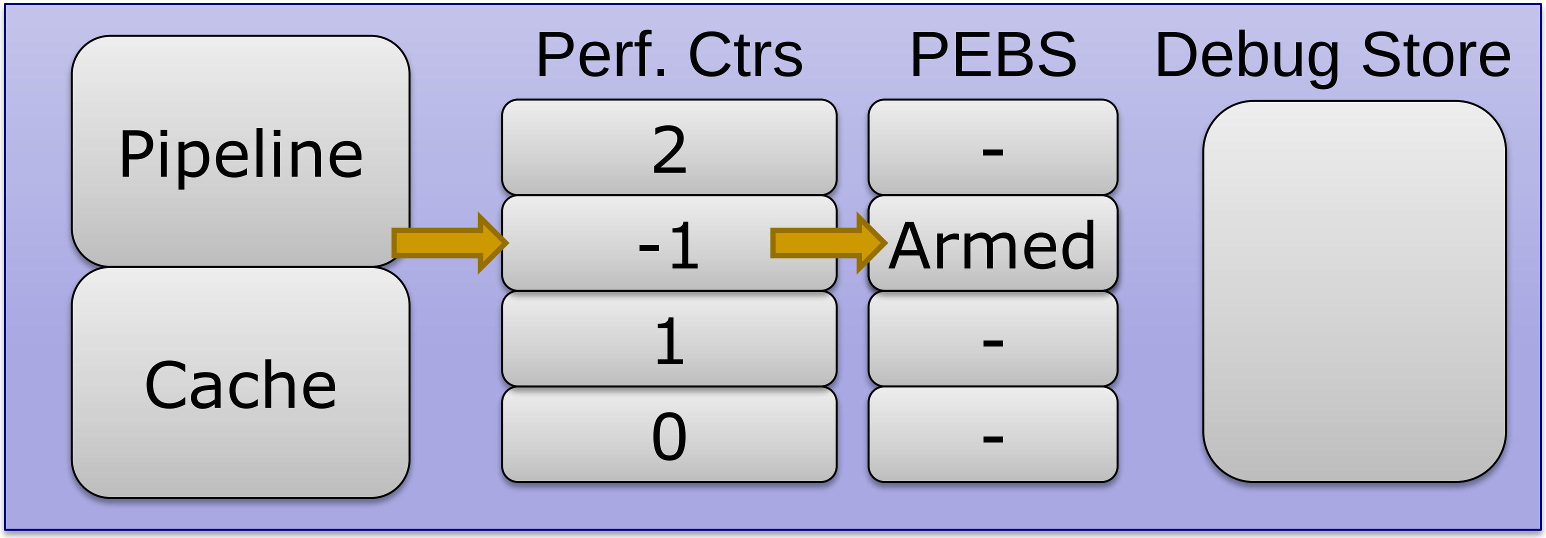

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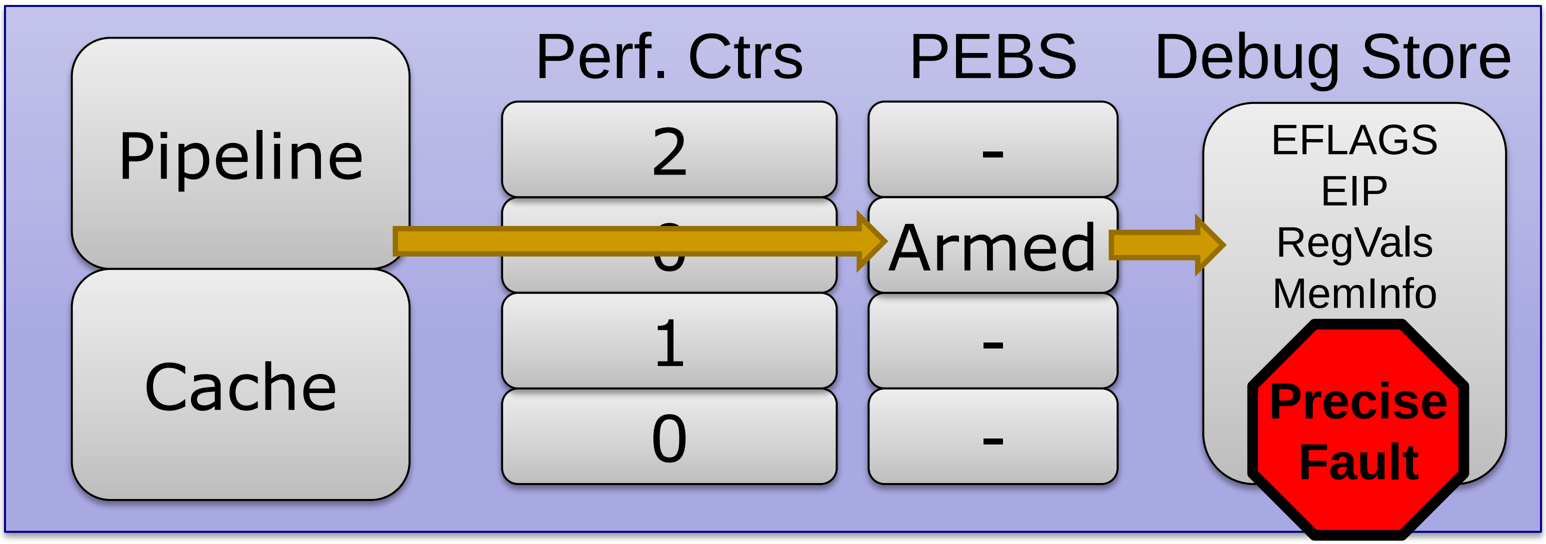

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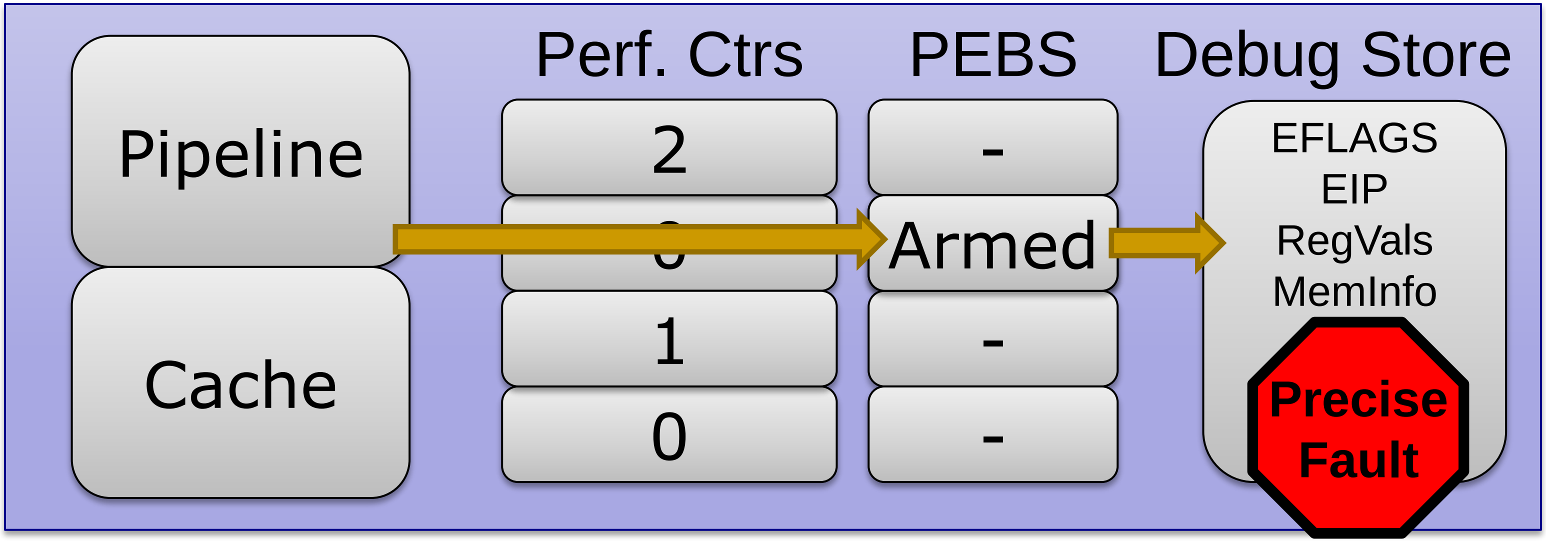
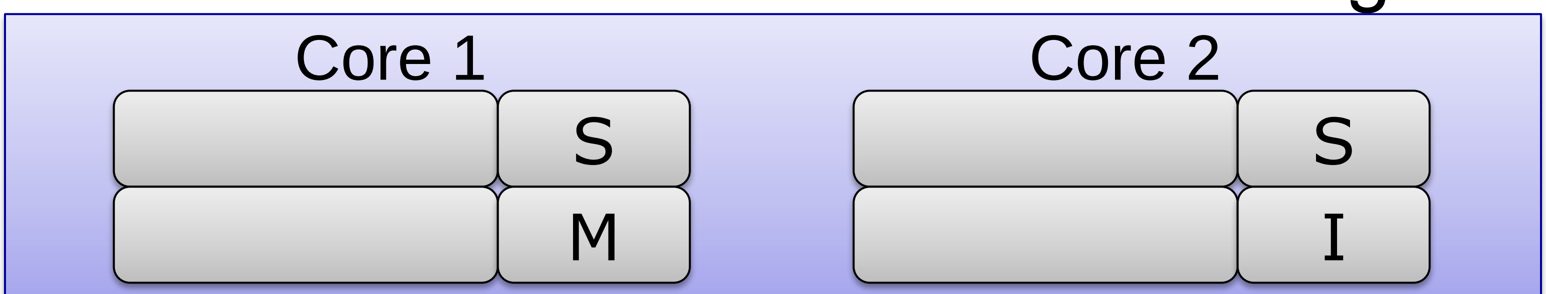


- Intel's HITM event: W→R Data Sharing



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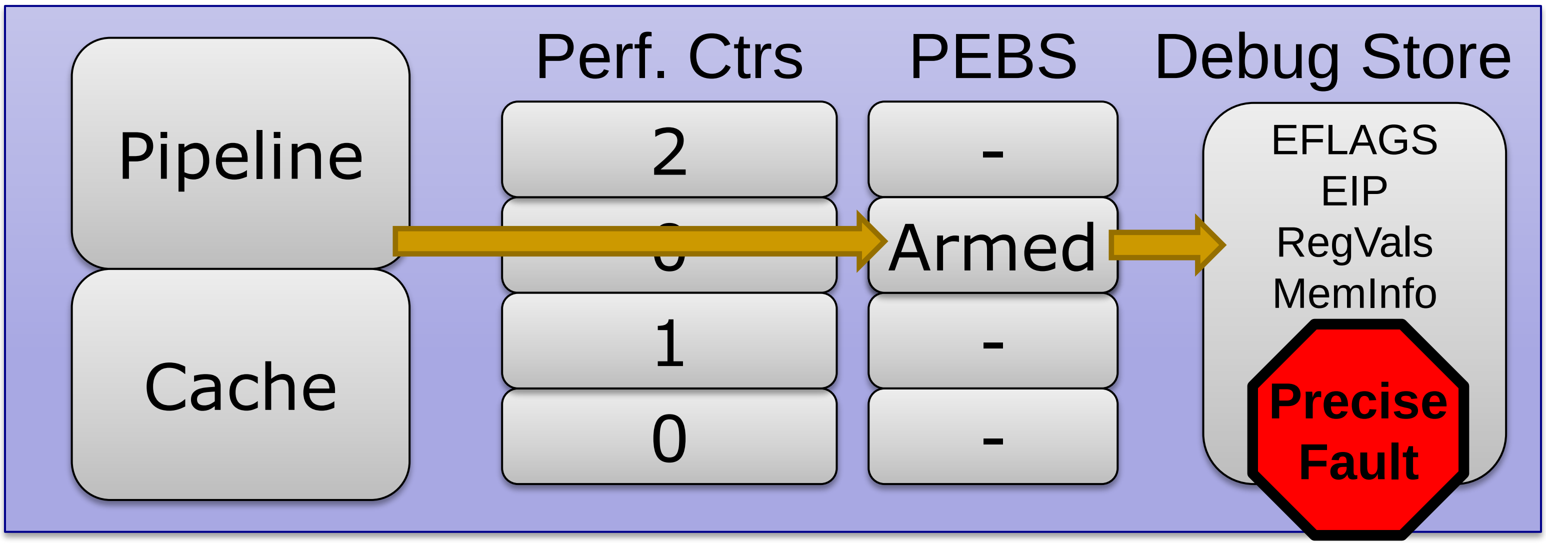

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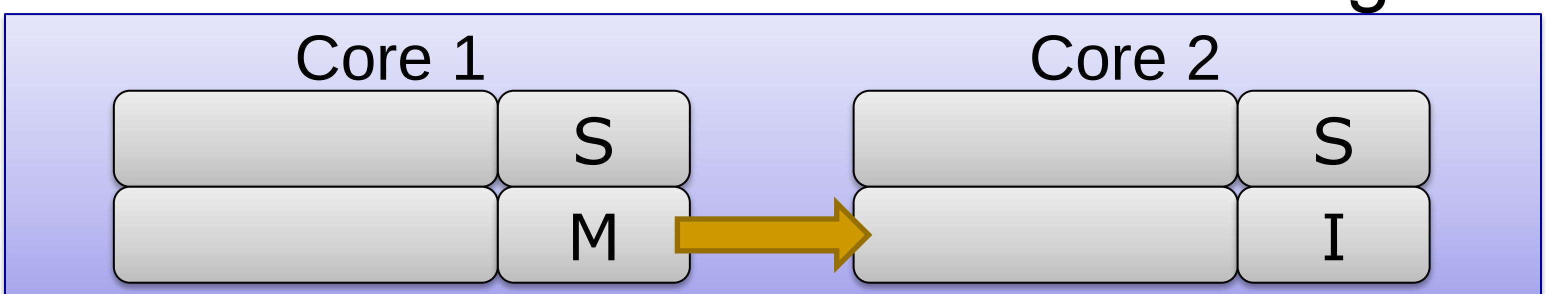

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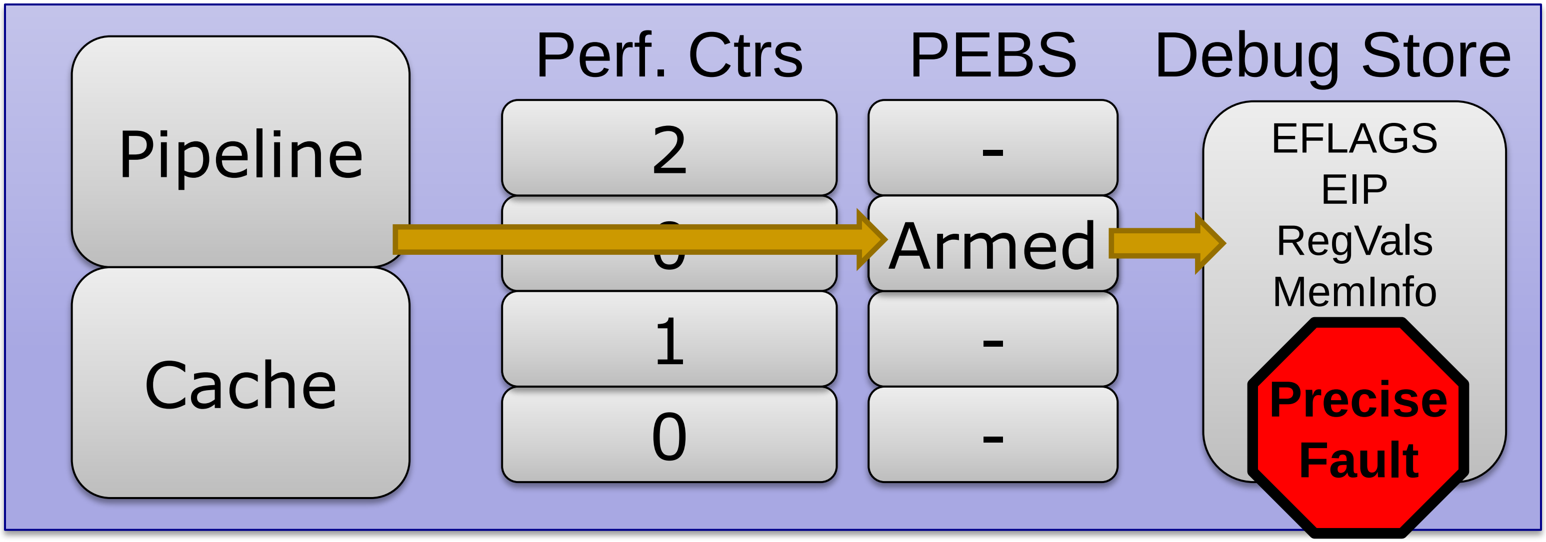

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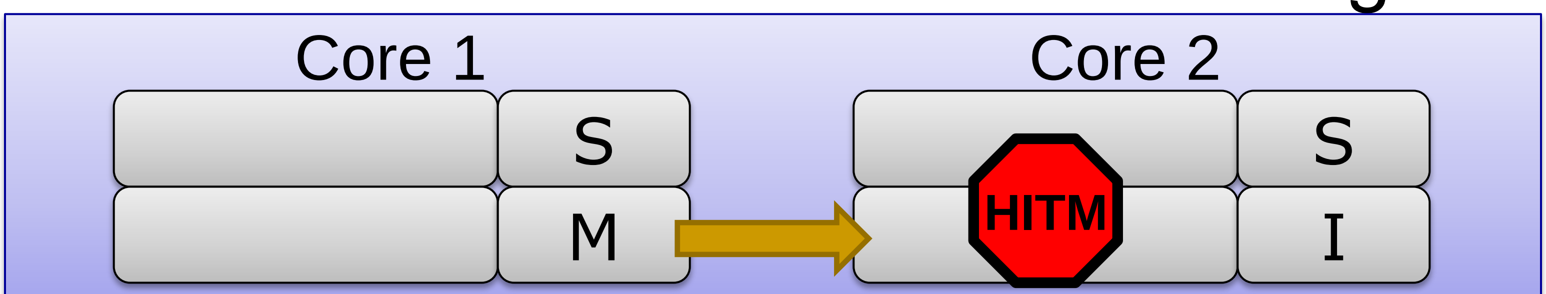


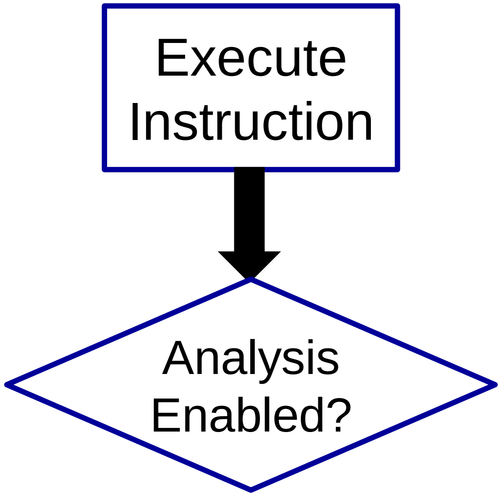
Potential Accuracy & Perf. Problems

- 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

Demand-Driven Analysis on Real HW

Execute
Instruction

Demand-Driven Analysis on Real HW



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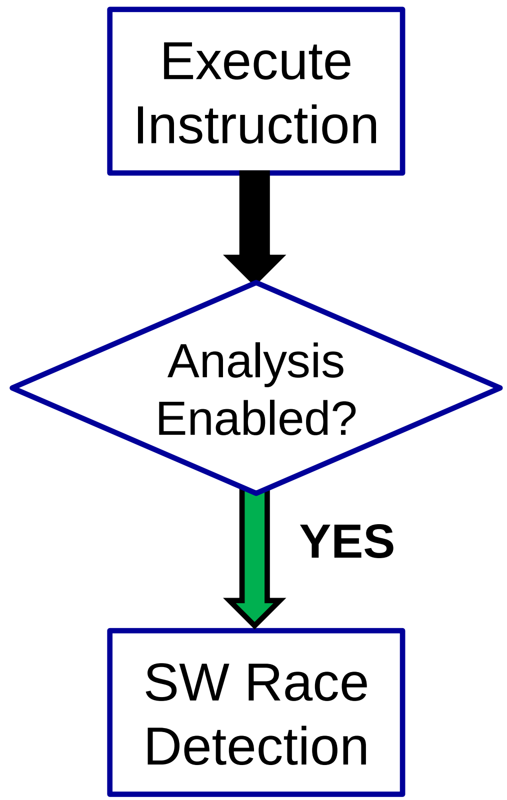

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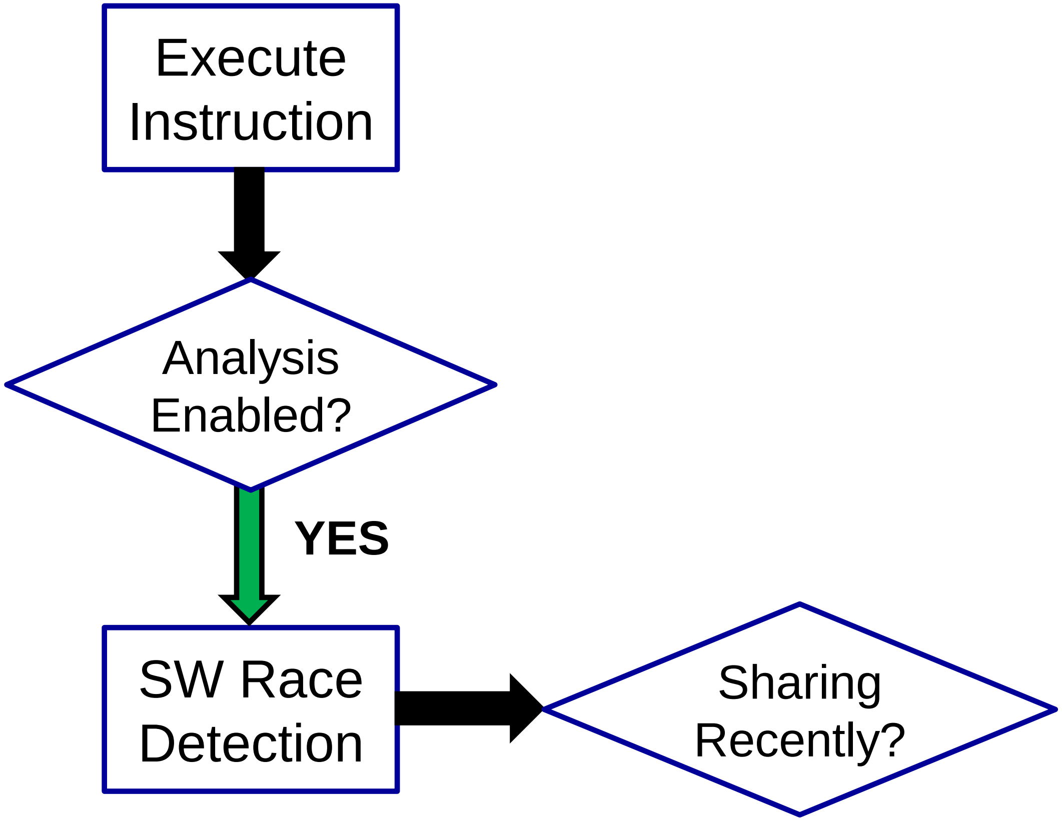

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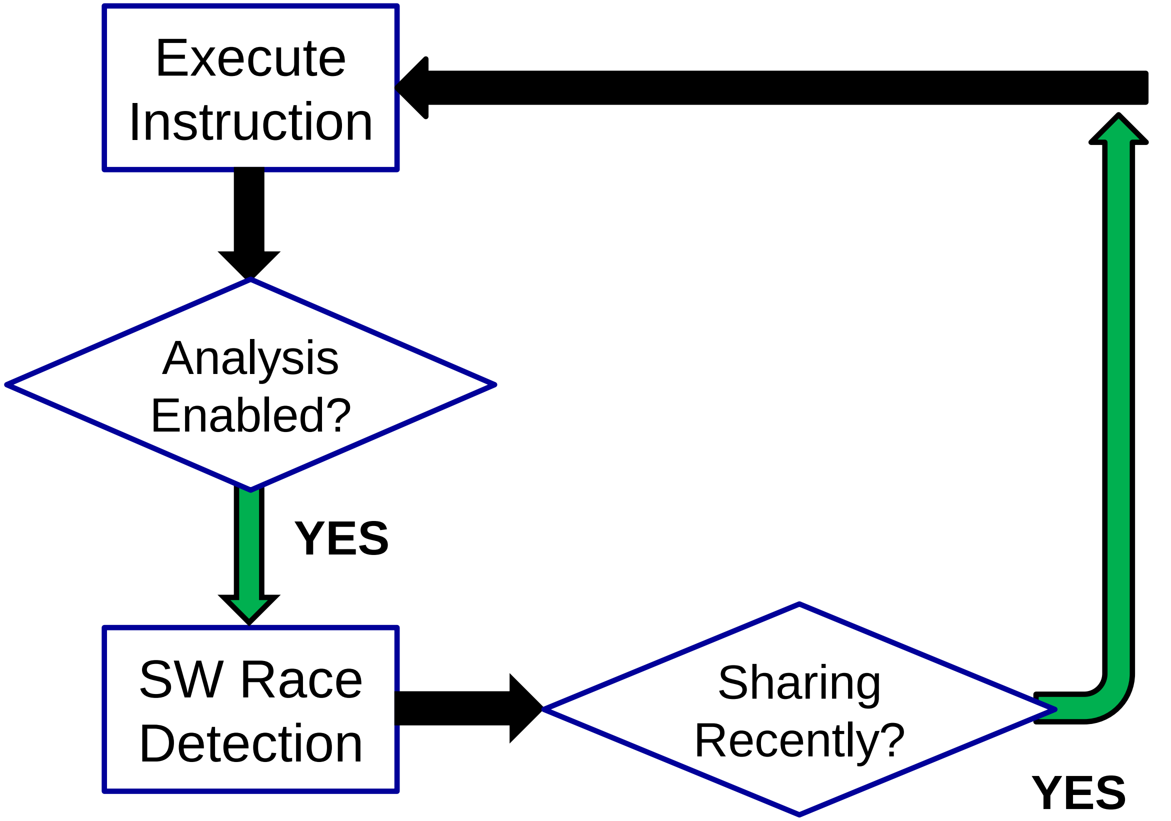

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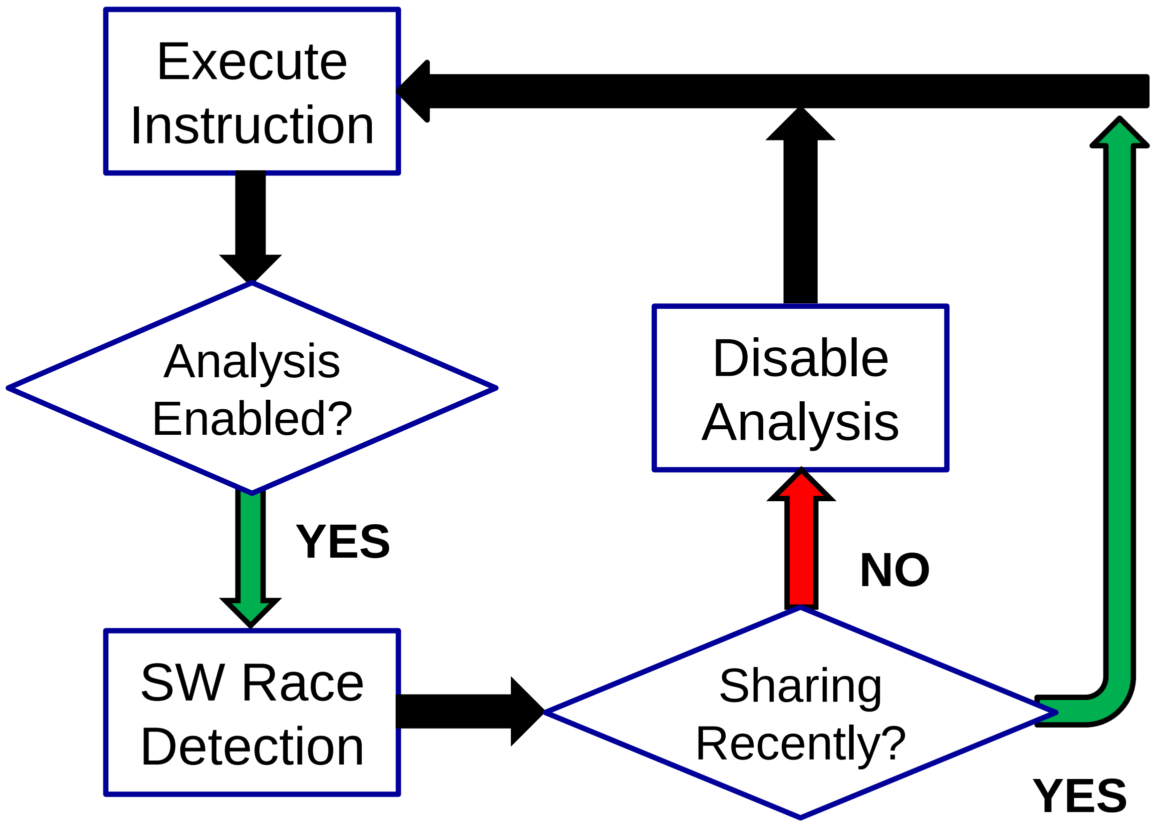

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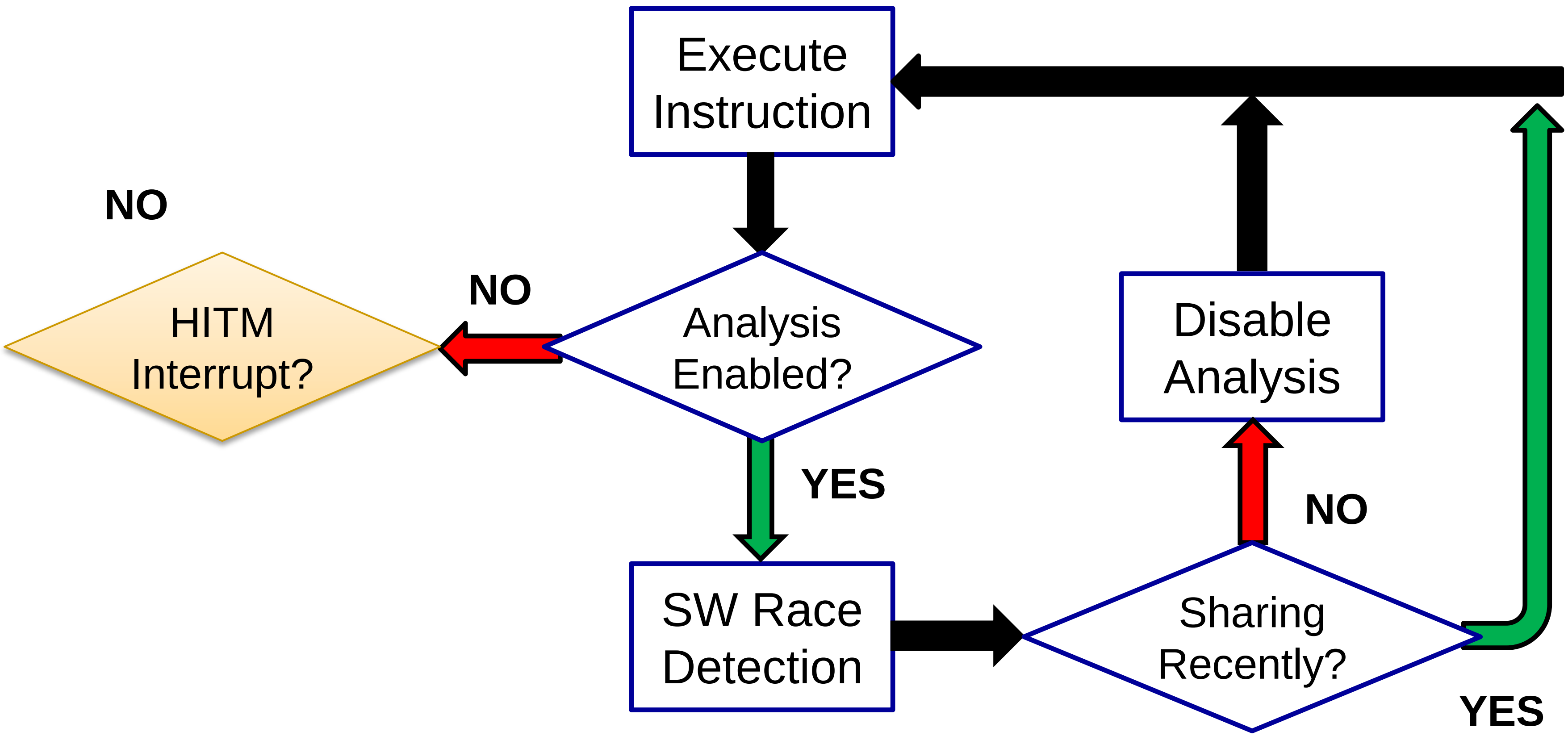

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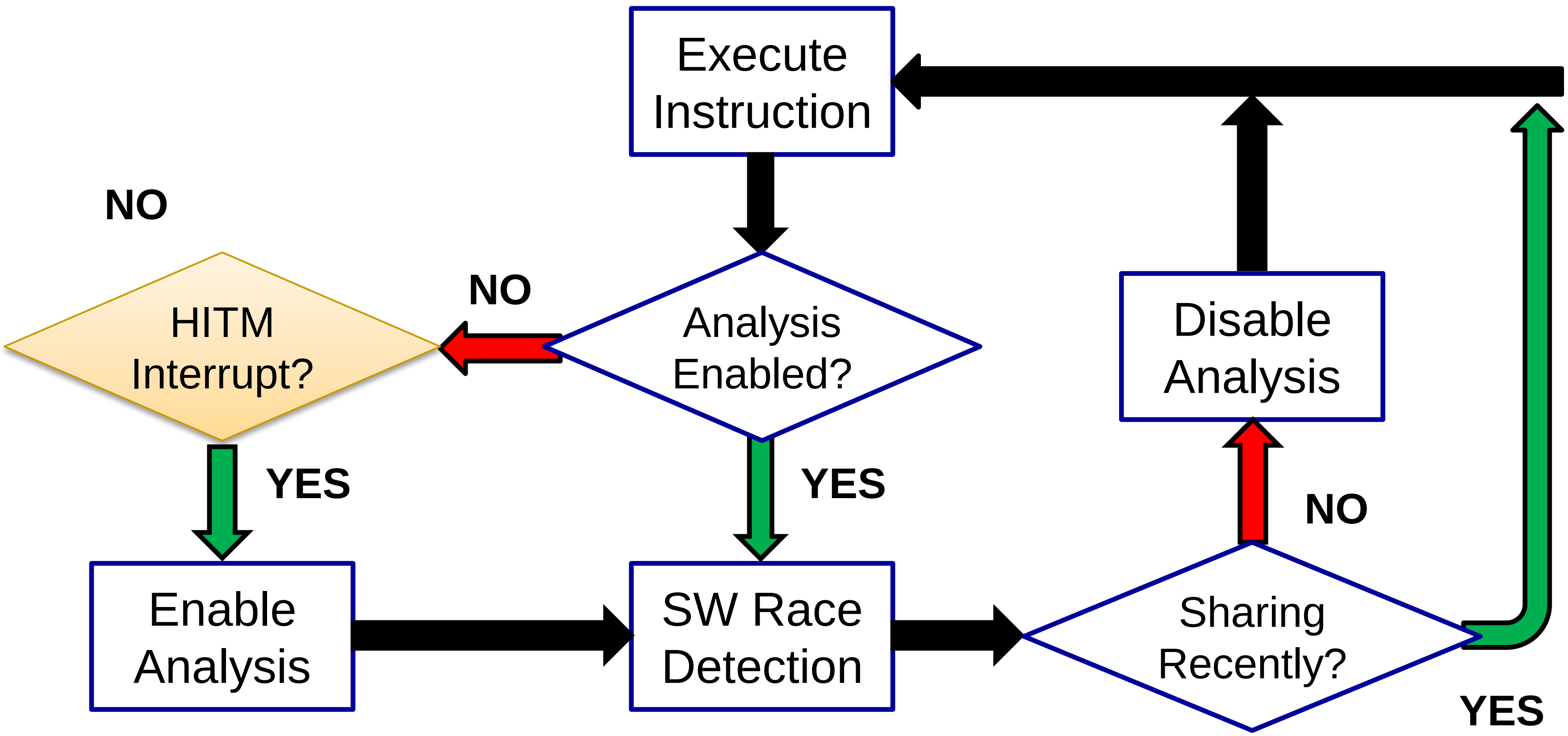

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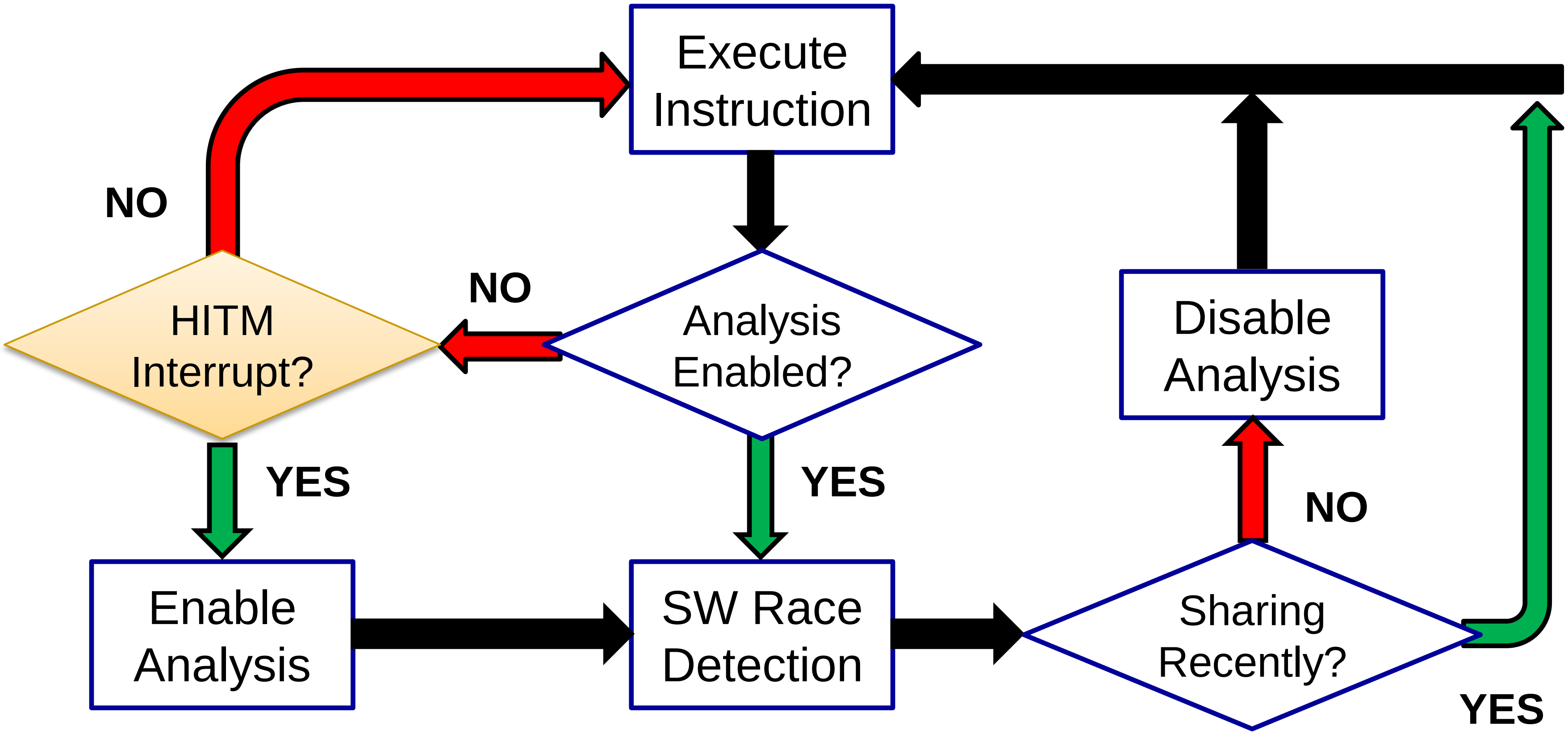

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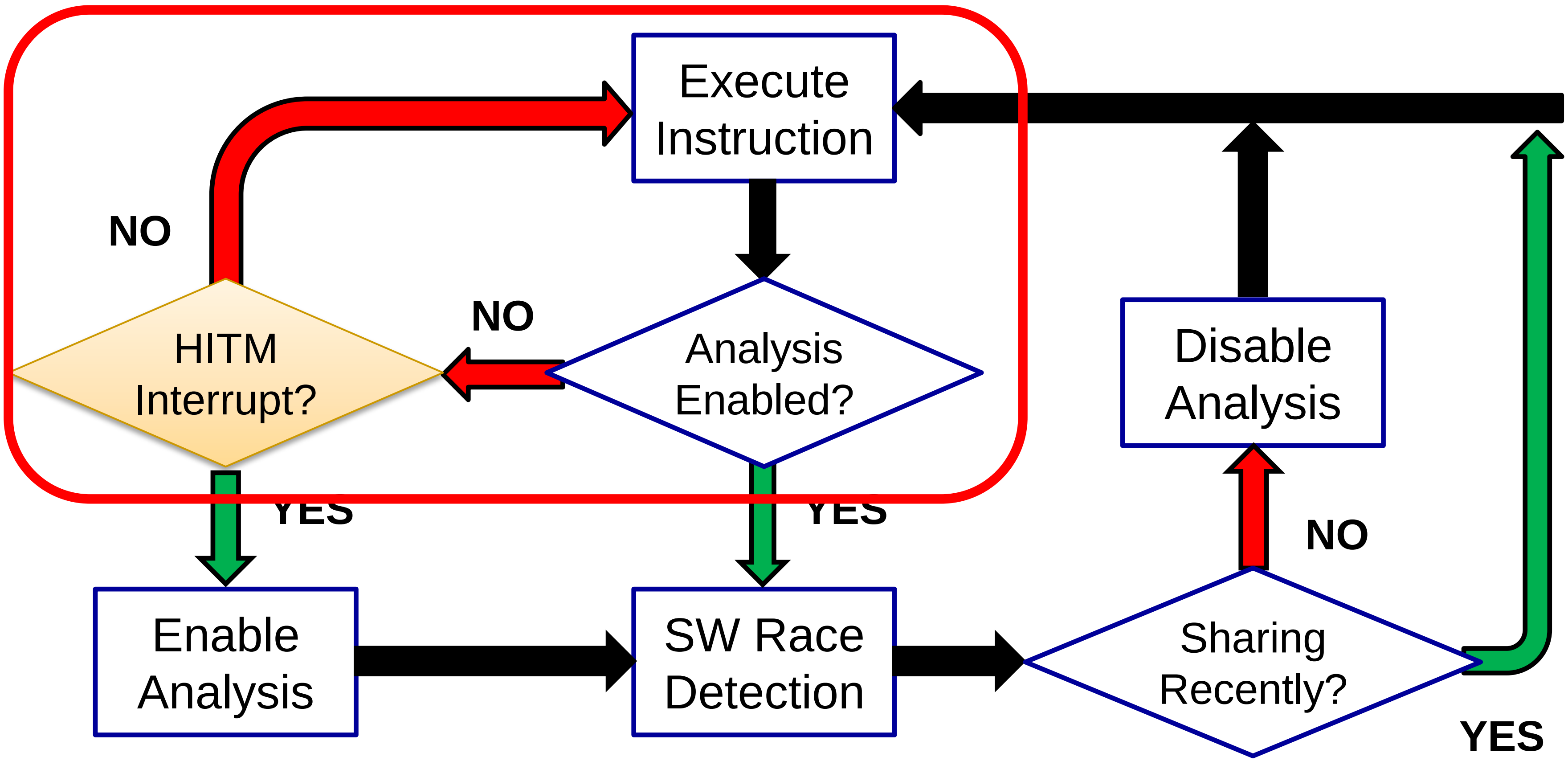
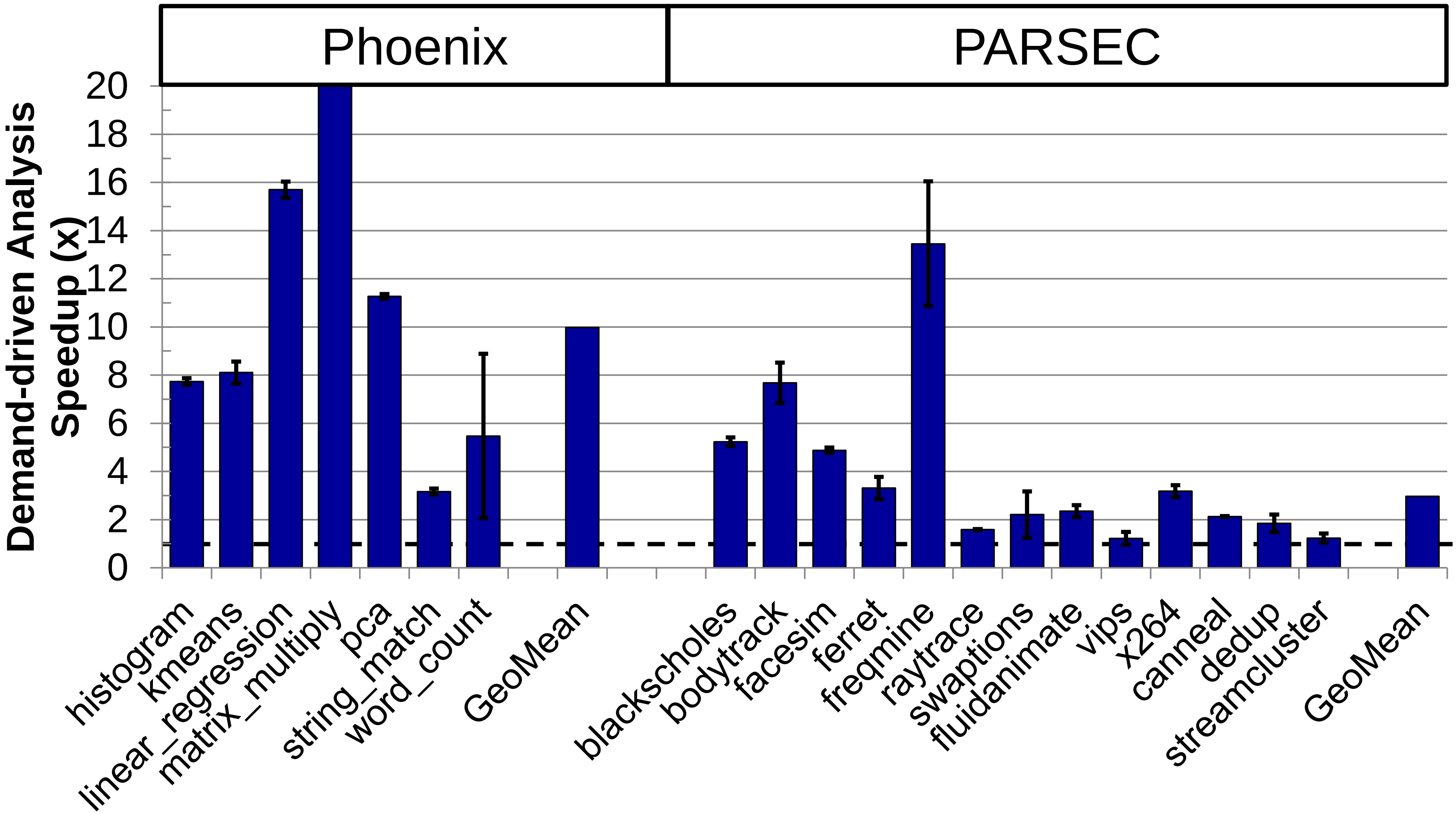


Performance Increases



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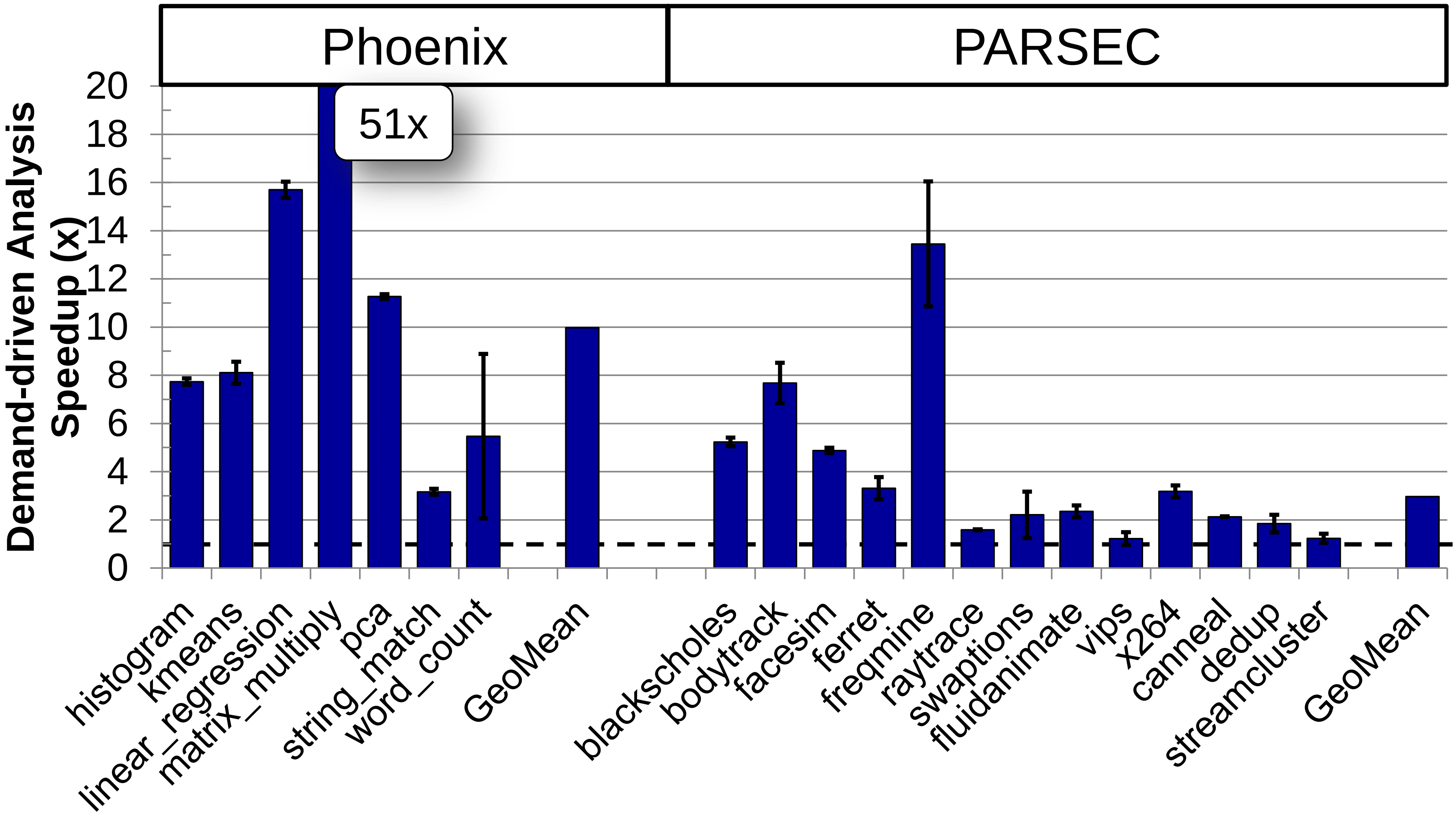
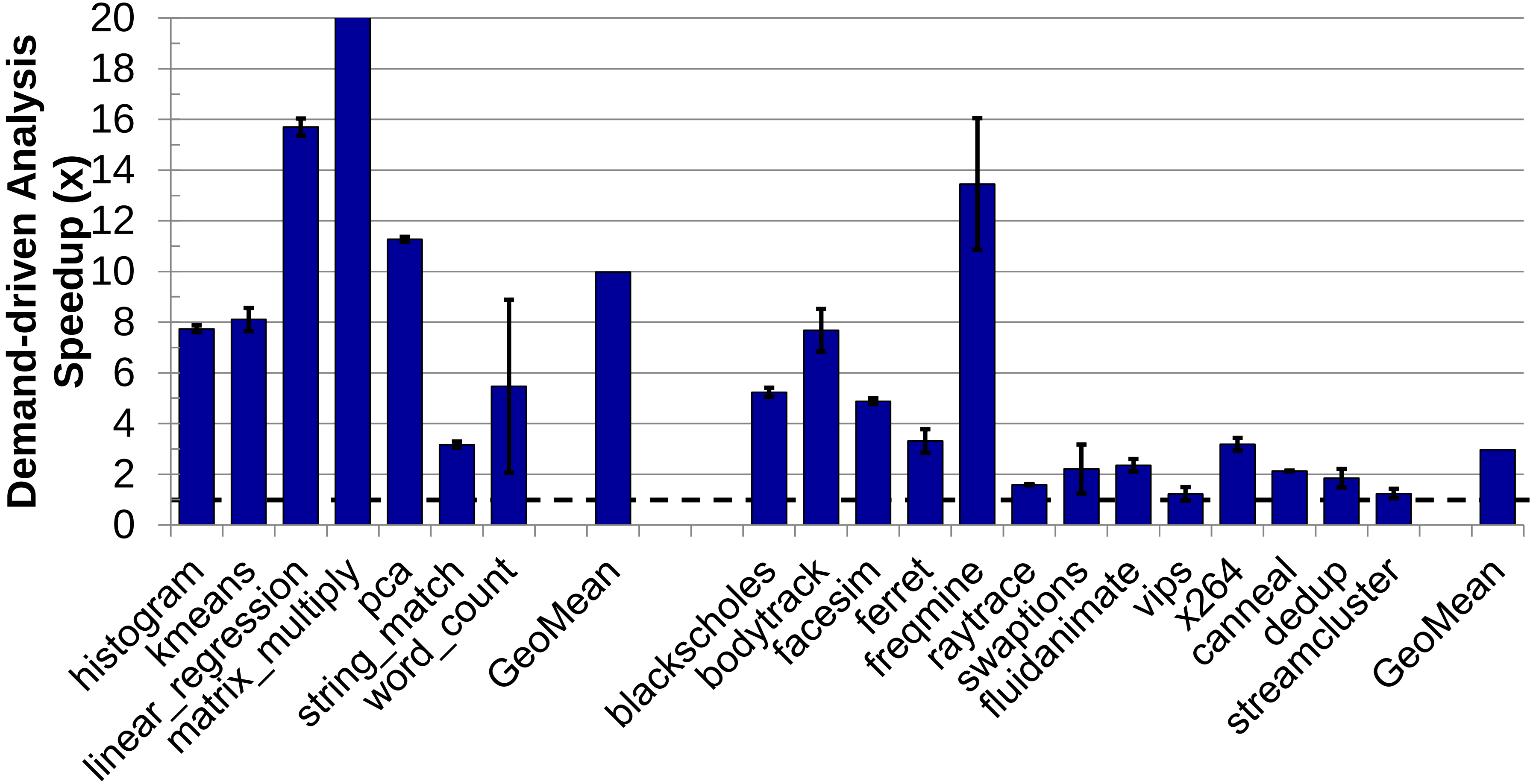


Demand-Driven Analysis Accuracy



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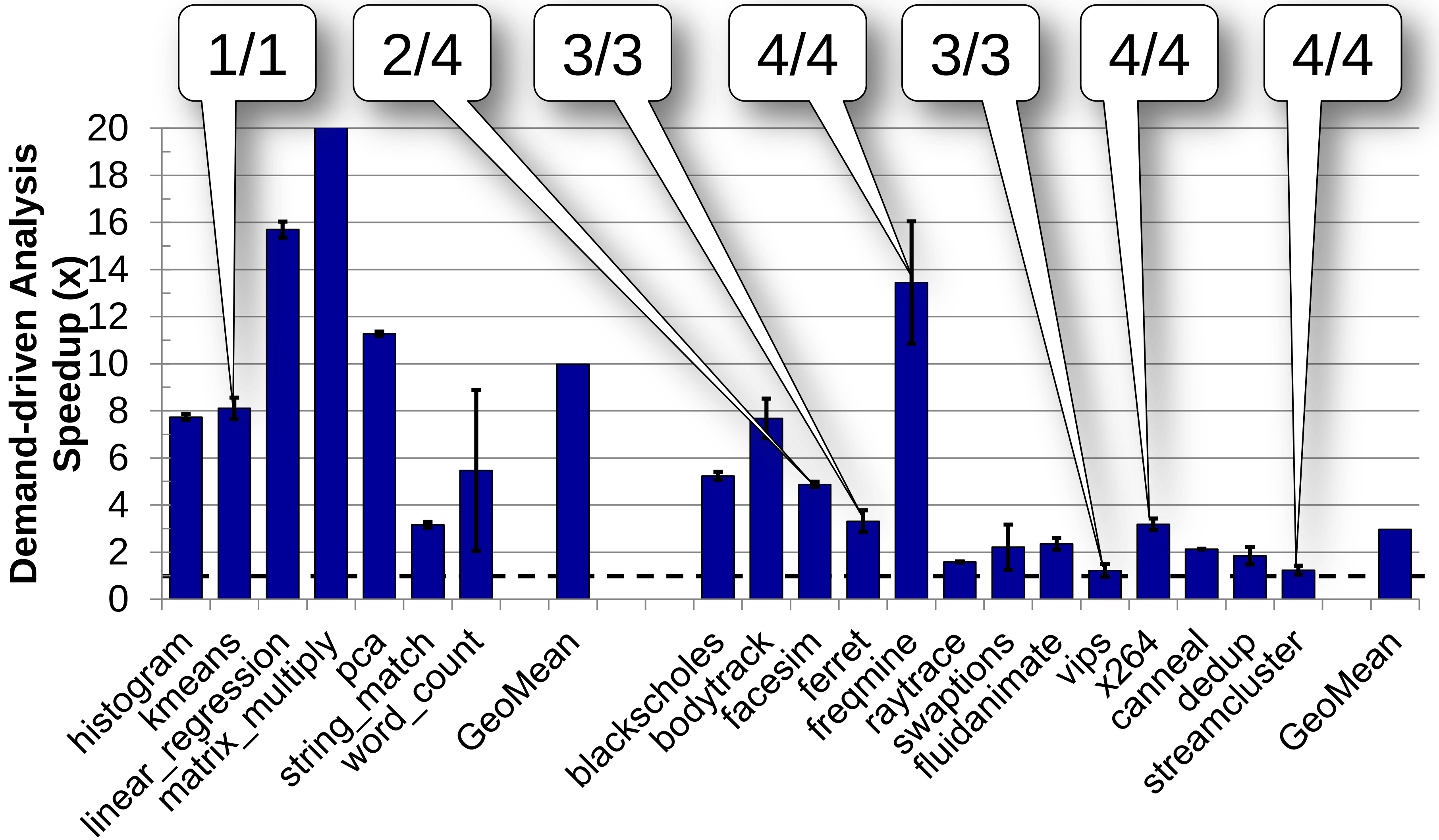

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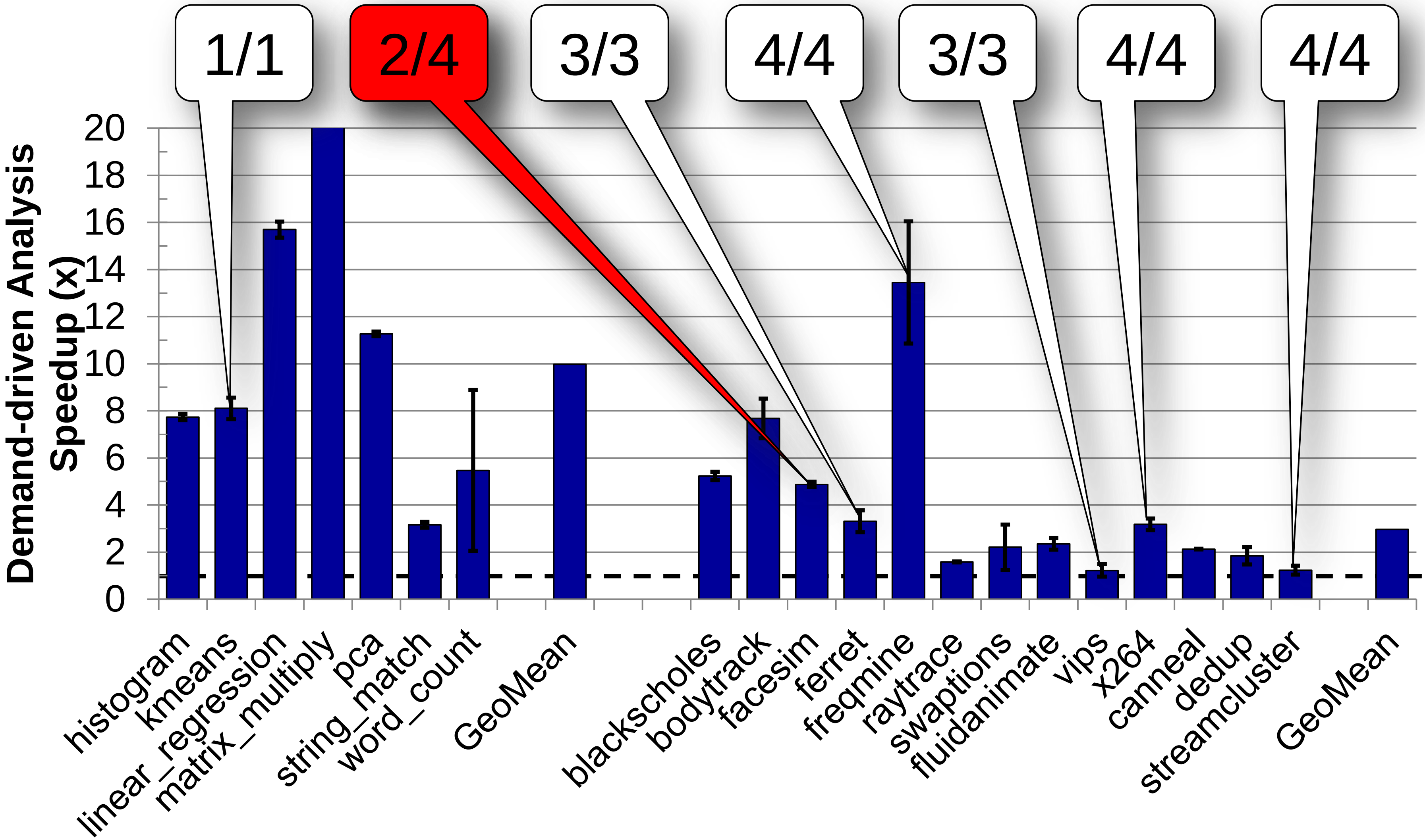

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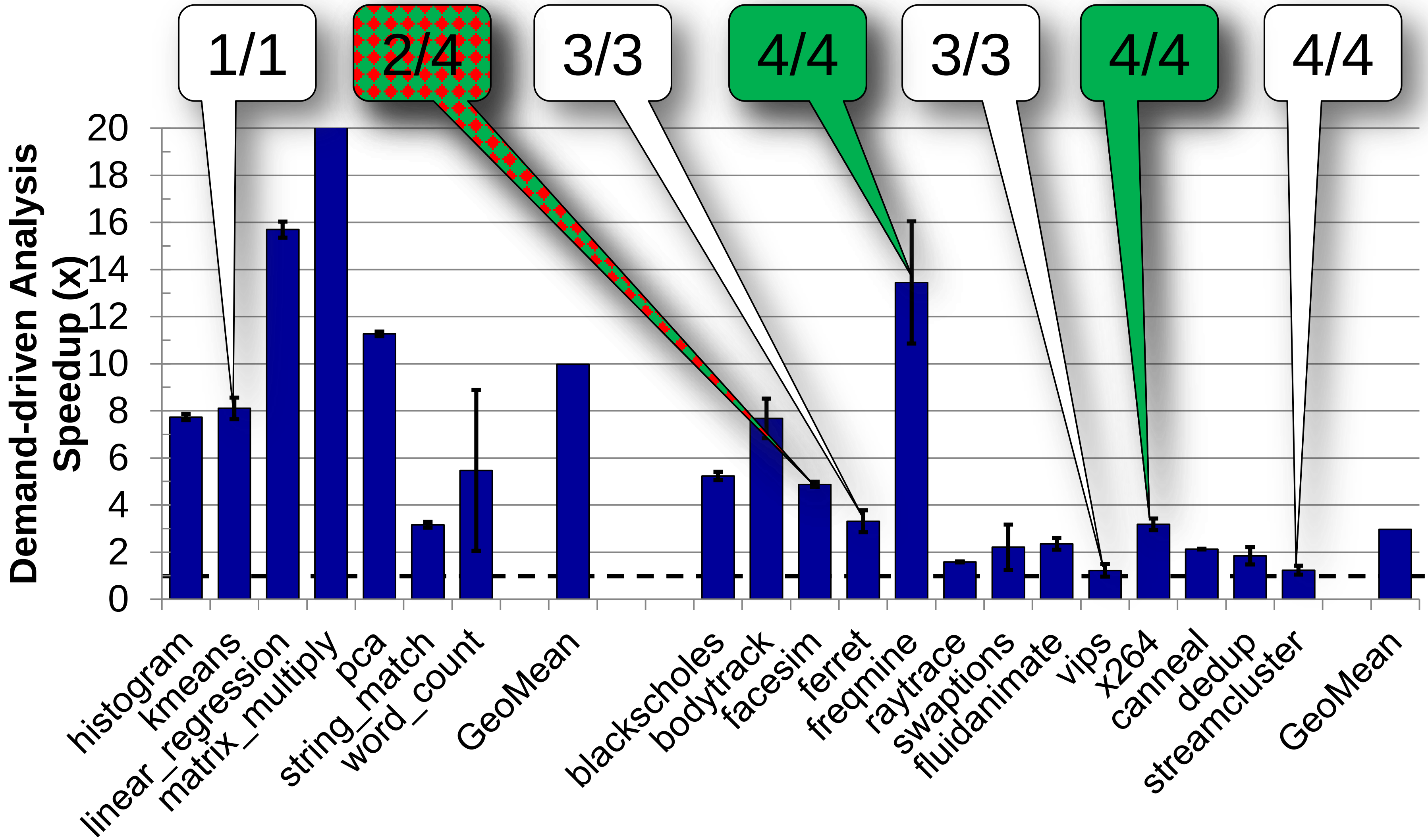

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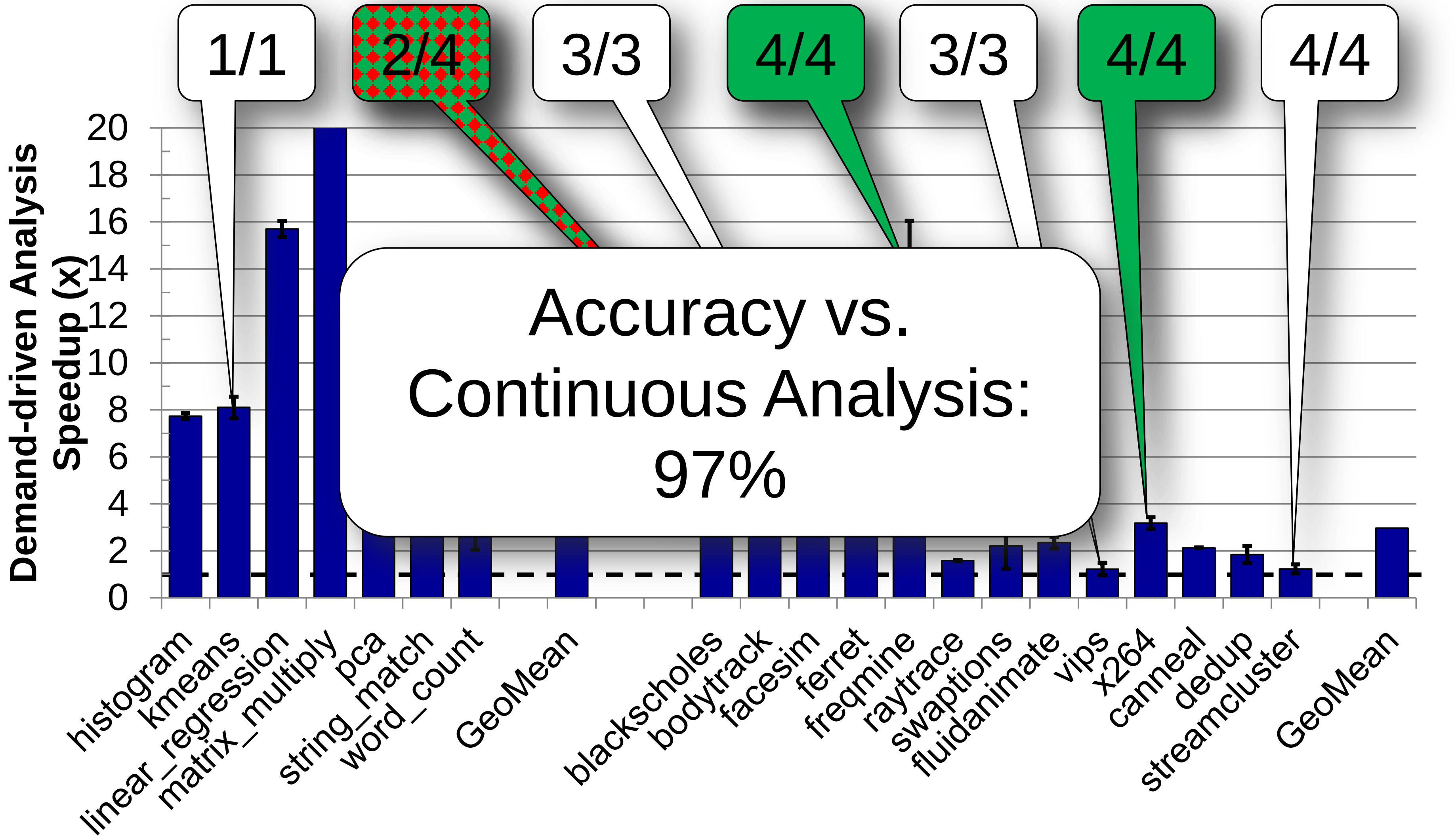

Outline

- 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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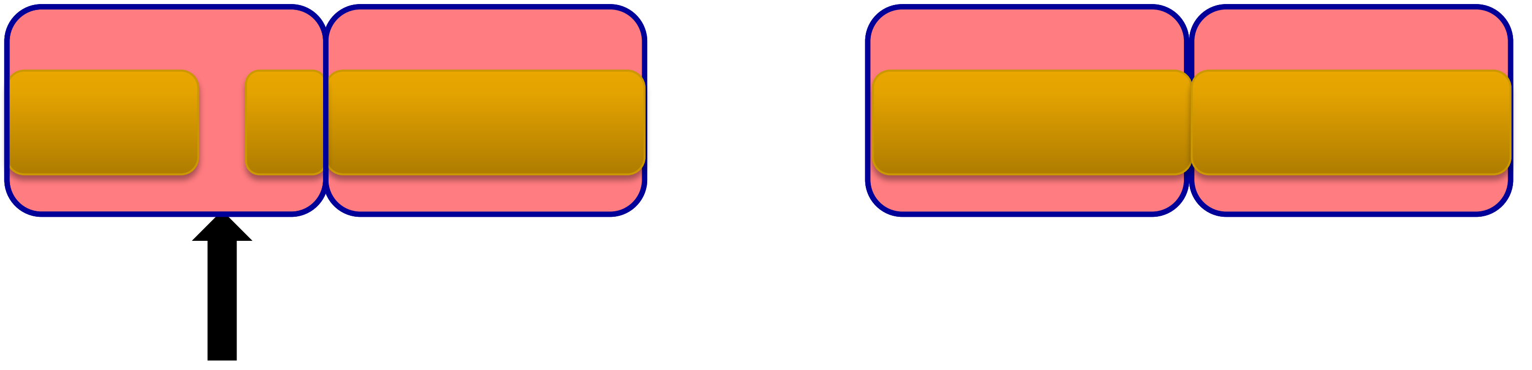

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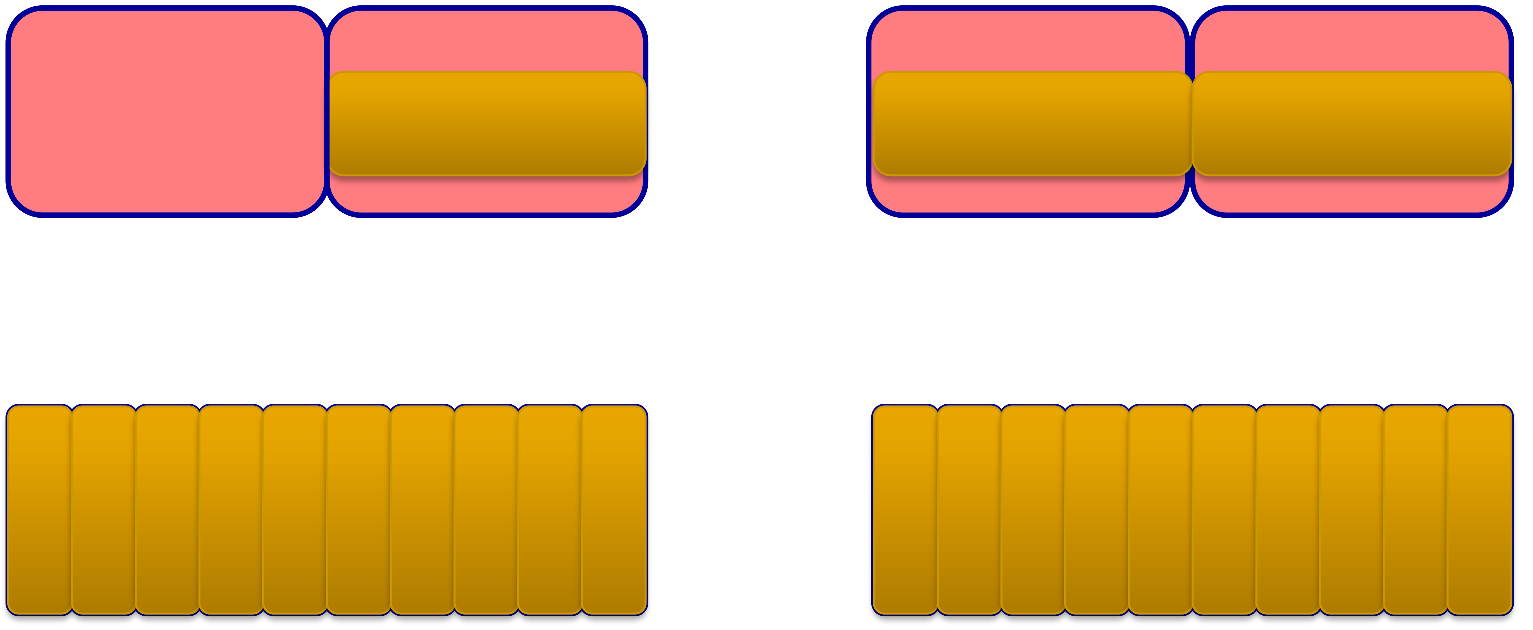

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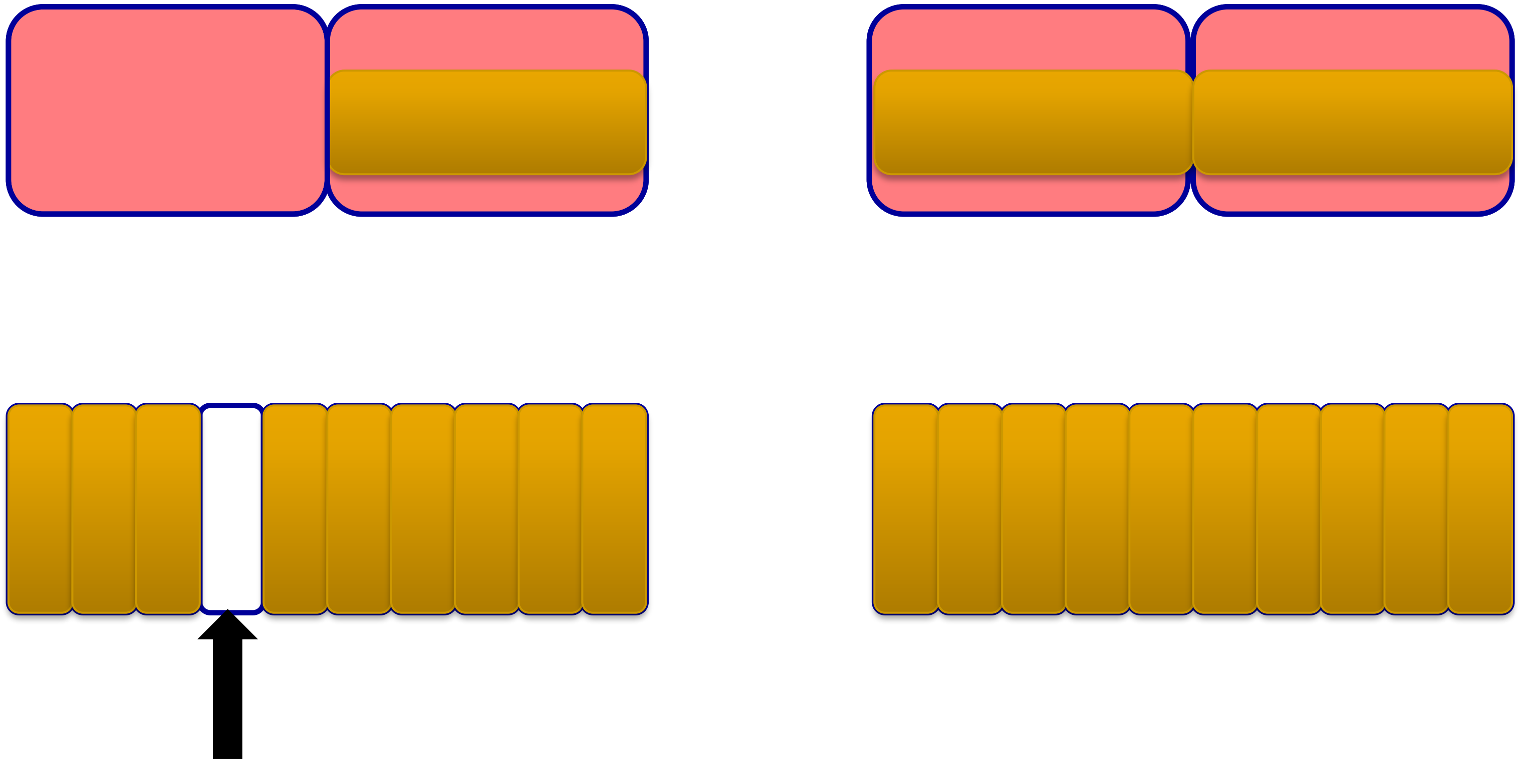

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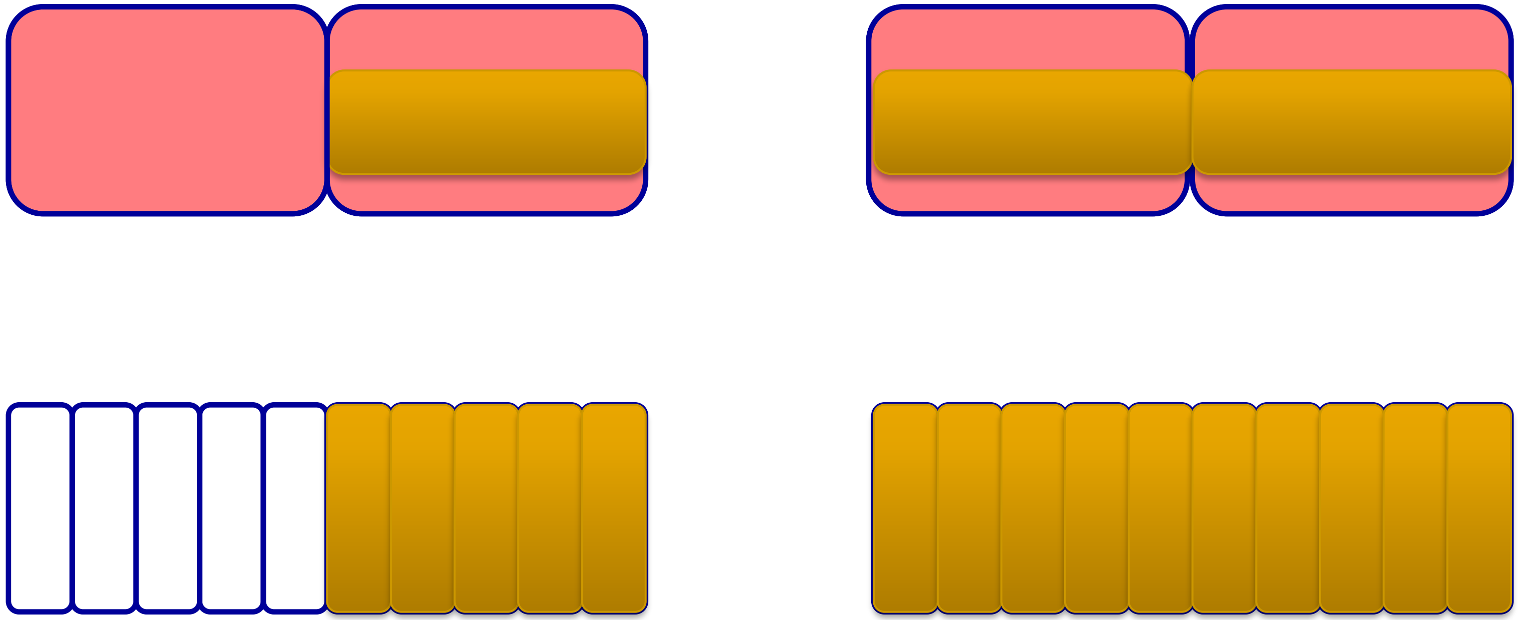

Watchpoint-Based Software Analyses

- Taint analysis / Dynamic dataflow 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

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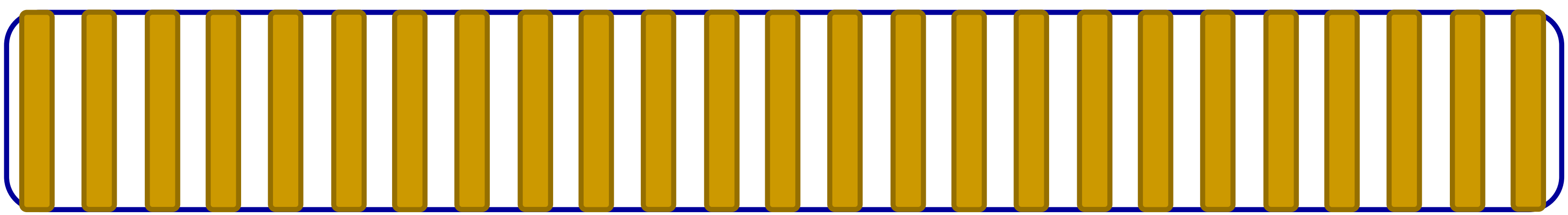

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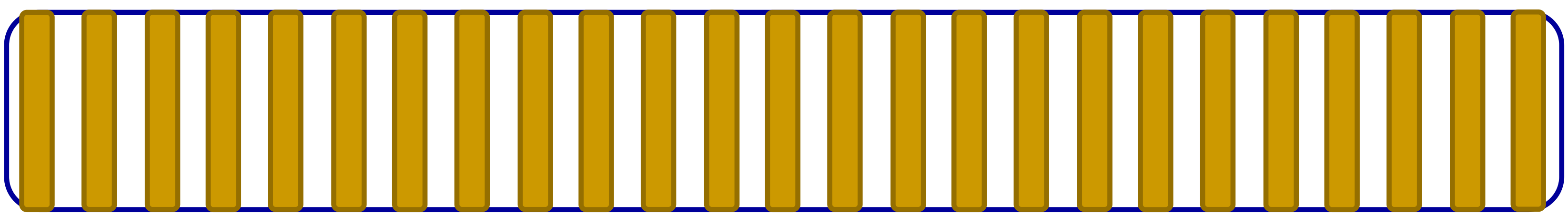
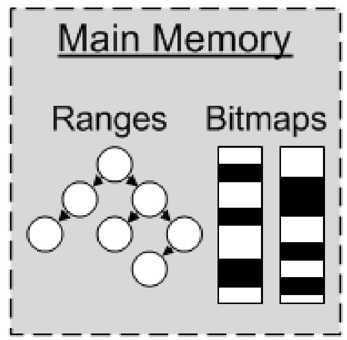


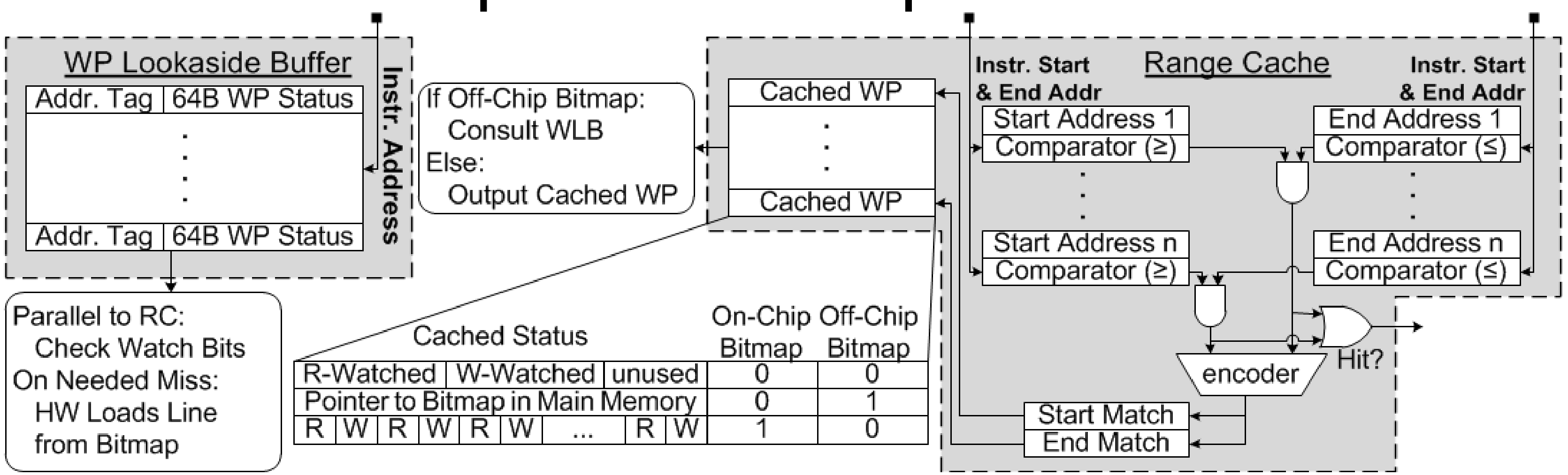
  - Better stored as bitmaps
- Need a large number

The Best of Both Worlds

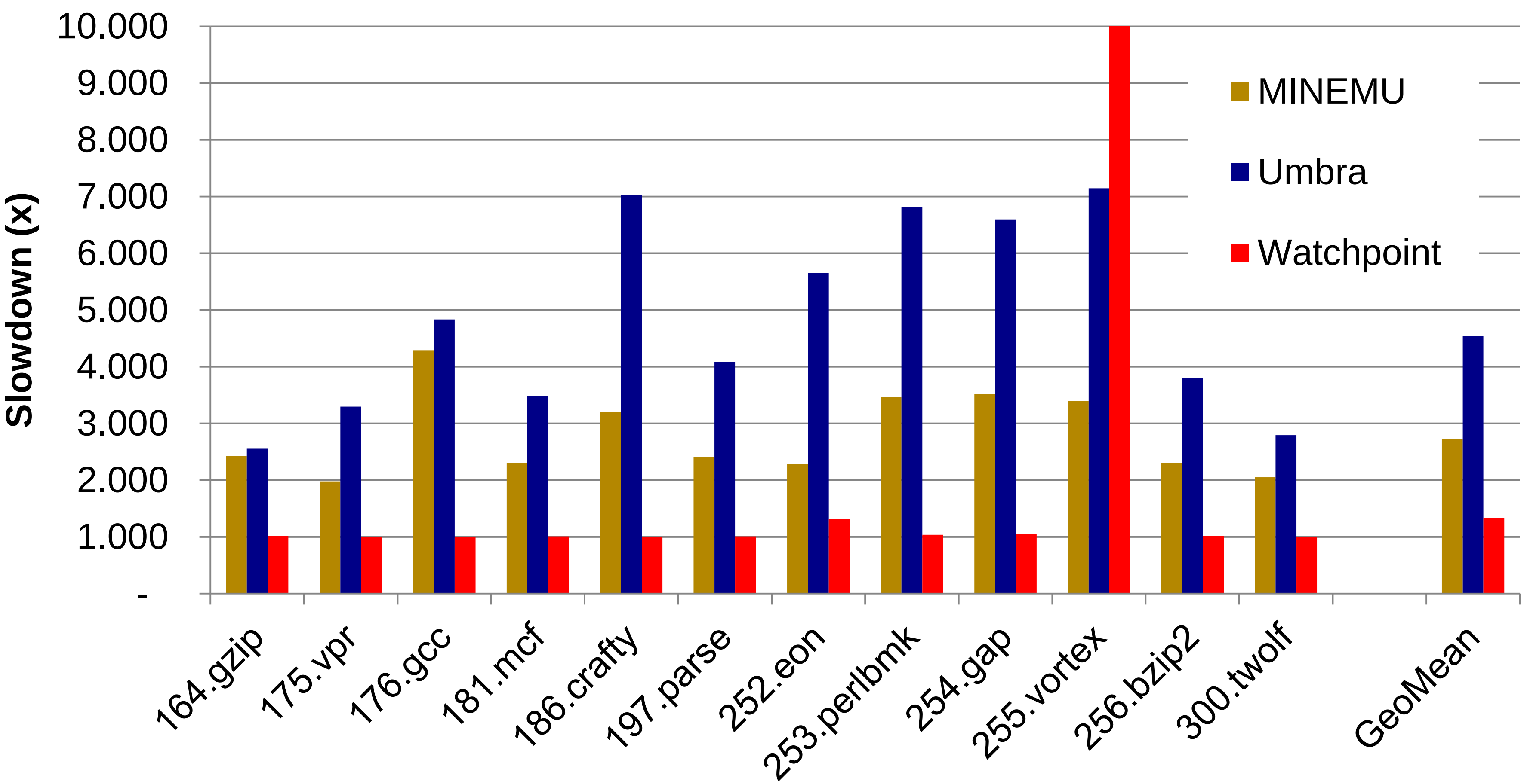
- Store Watchpoints in Main Memory



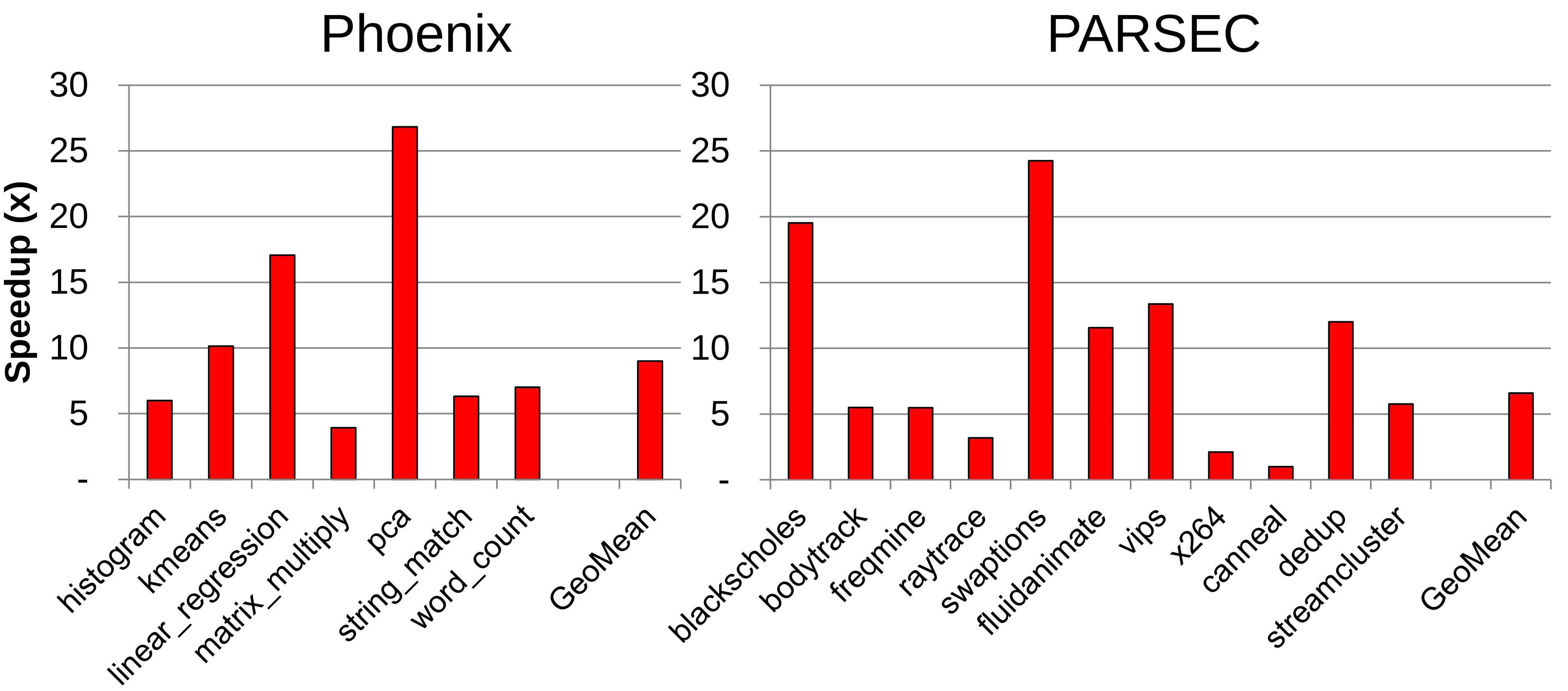
- Cache watchpoints on-chip



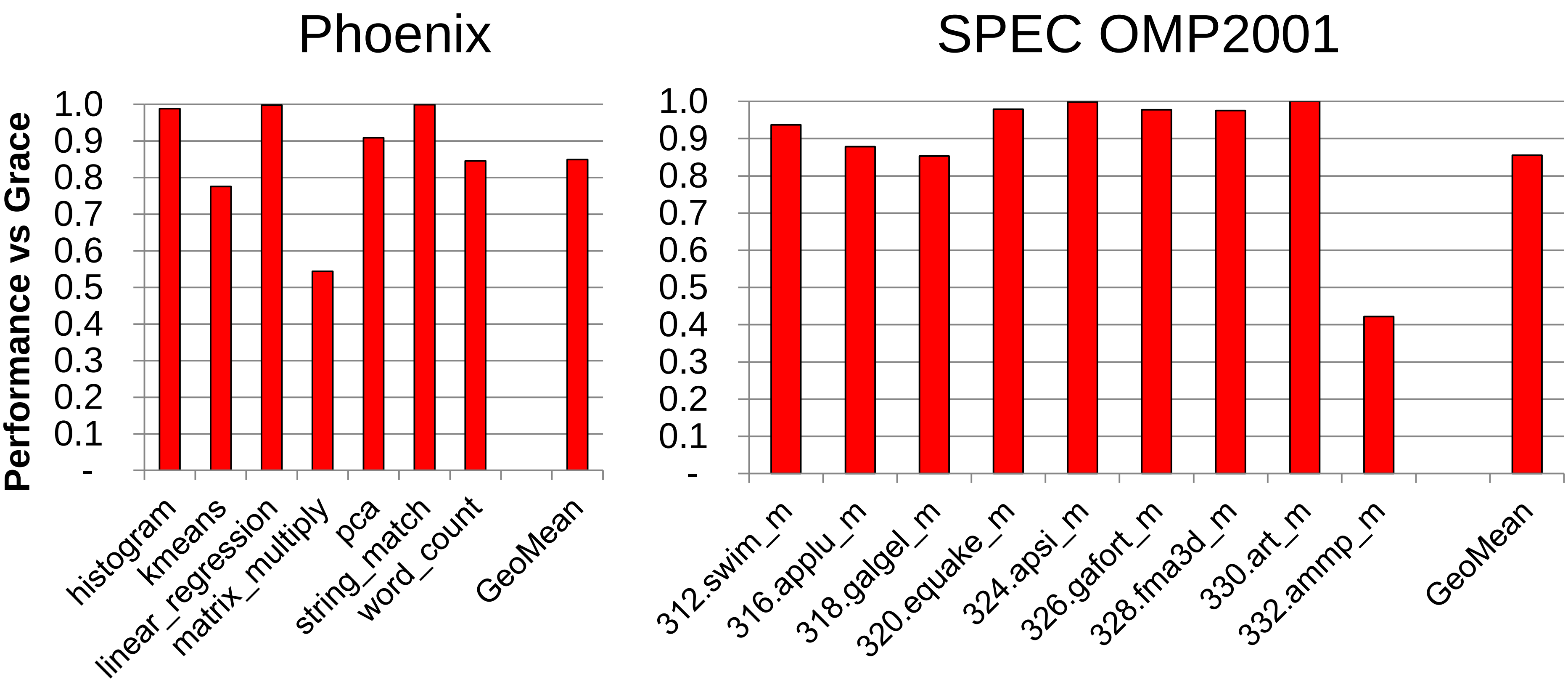
Demand-Driven Taint Analysis



Watchpoint-Based Data Race Detection

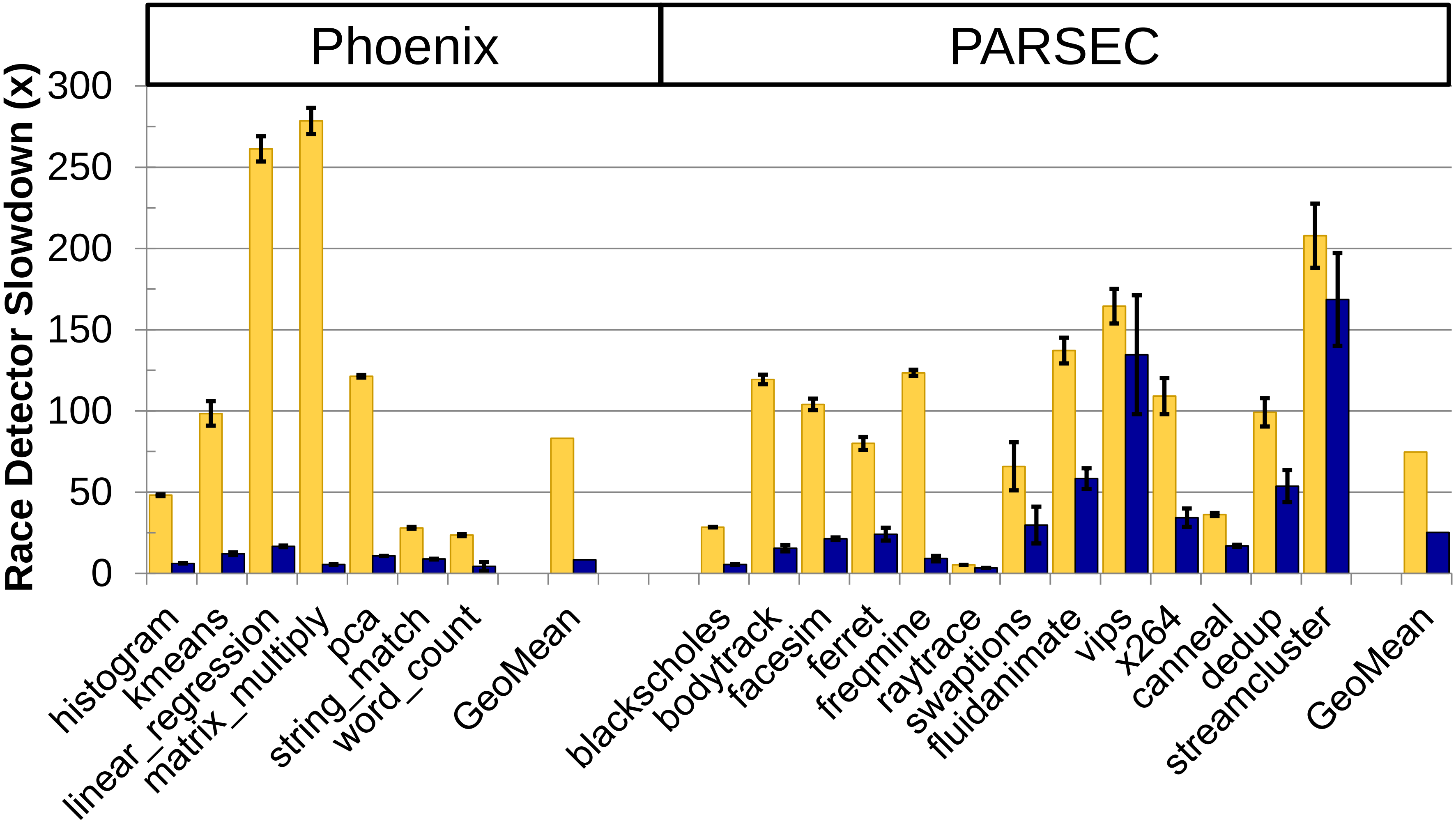


Watchpoint-Based Grace System



BACKUP SLIDES

Performance Difference



Accuracy on Real Hardware

	kmeans	facesim	ferret	freqmine	vips	x264	streamcluster
W→W	1/1 (100%)	0/1 (0%)	-	-	1/1 (100%)	-	1/1 (100%)
R→W	-	0/1 (0%)	2/2 (100%)	2/2 (100%)	1/1 (100%)	3/3 (100%)	1/1 (100%)
W→R	-	2/2 (100%)	1/1 (100%)	2/2 (100%)	1/1 (100%)	3/3/ (100%)	1/1 (100%)

	Spider Monkey-0	Spider Monkey-1	Spider Monkey-2	NSPR-1	Memcached-1	Apache-1
W→W	9/9 (100%)	1/1 (100%)	1/1 (100%)	3/3 (100%)	-	1/1 (100%)
R→W	3/3 (100%)	-	1/1 (100%)	1/1 (100%)	1/1 (100%)	7/7 (100%)
W→R	8/8 (100%)	1/1 (100%)	2/2 (100%)	4/4 (100%)	-	2/2 (100%)

Width Test