Accelerating Dynamic Software Analyses

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Software Errors Abound

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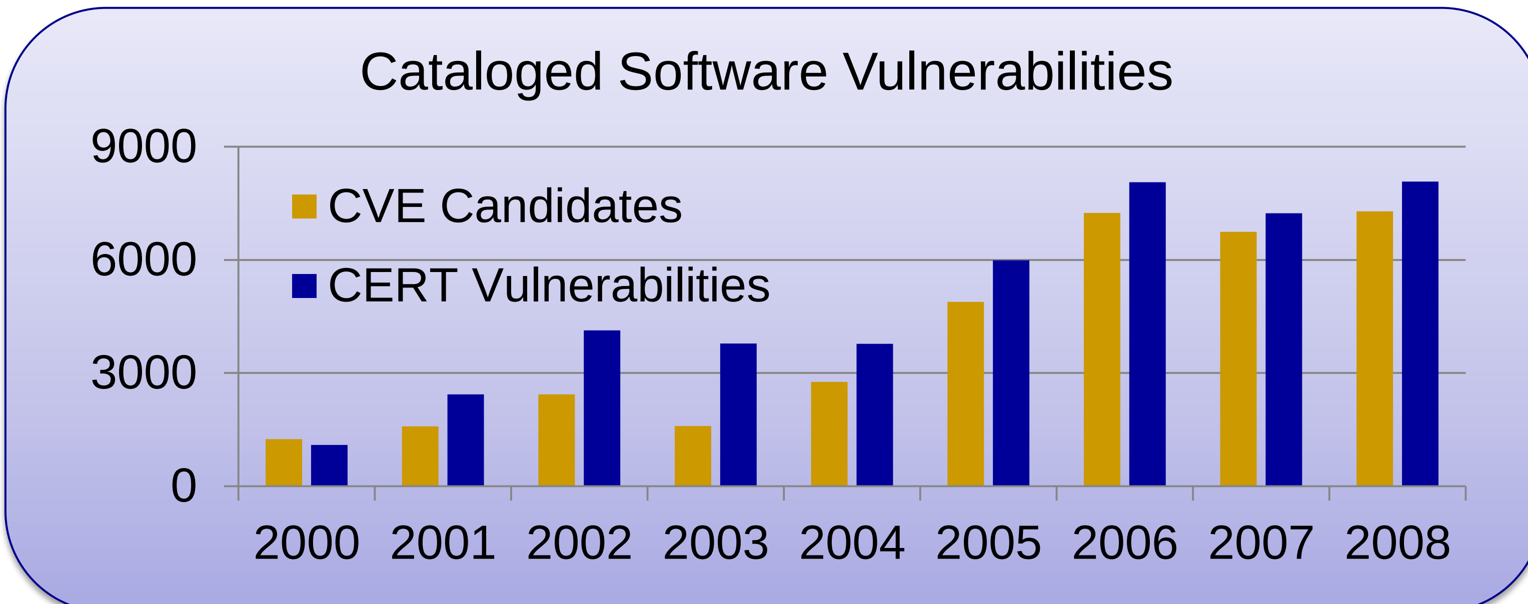

Example of Modern Bug

Nov. 2010 OpenSSL Security Flaw

Example of Modern Bug

TIME

Thread 1 mylen=small	Thread 2 mylen=large
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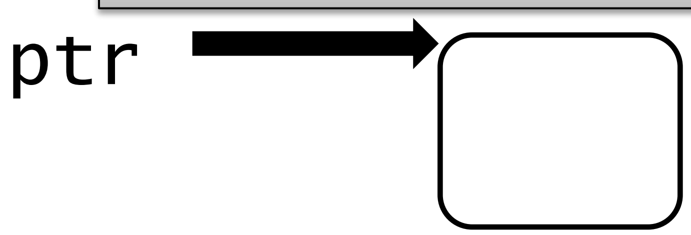

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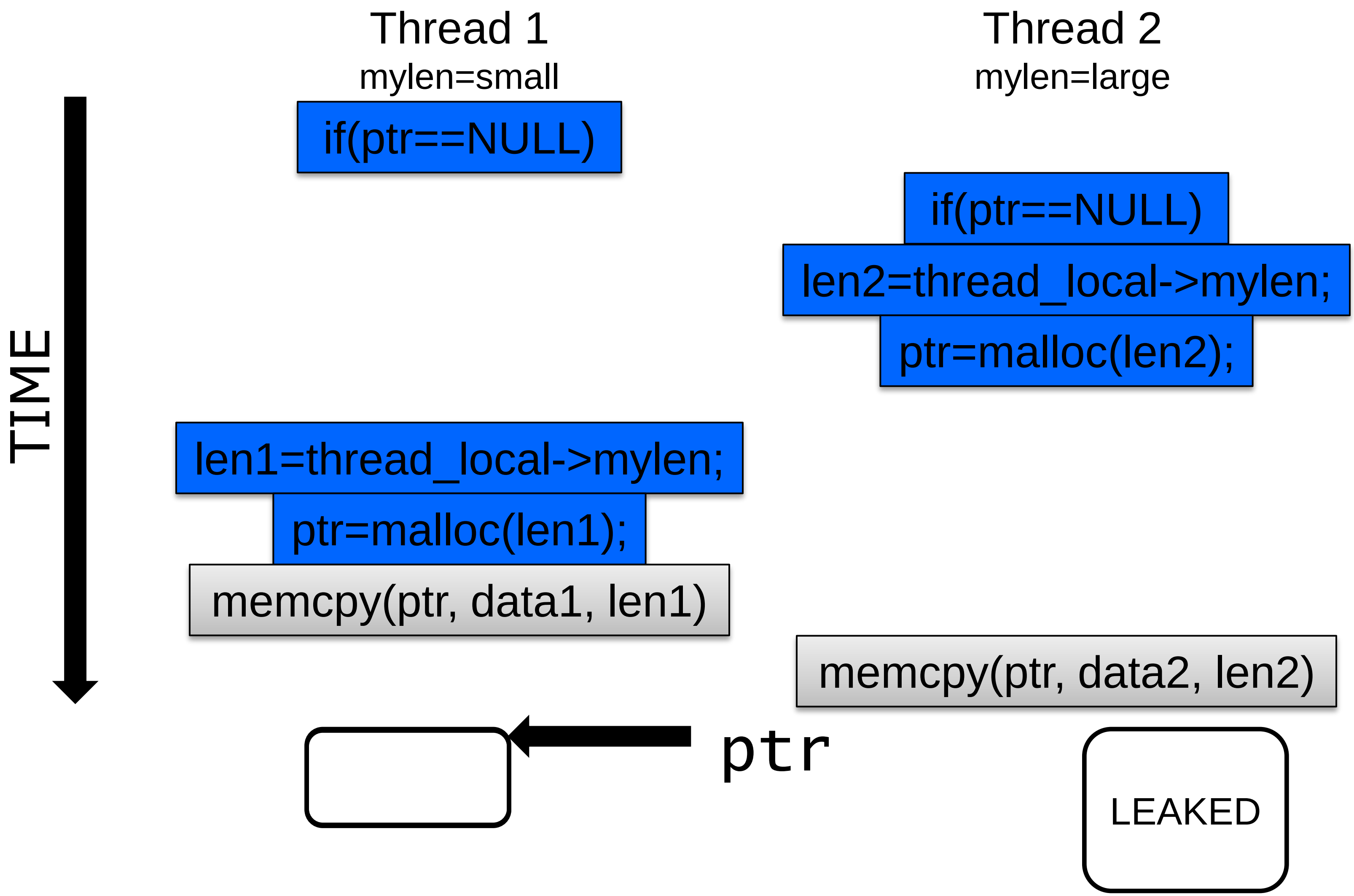

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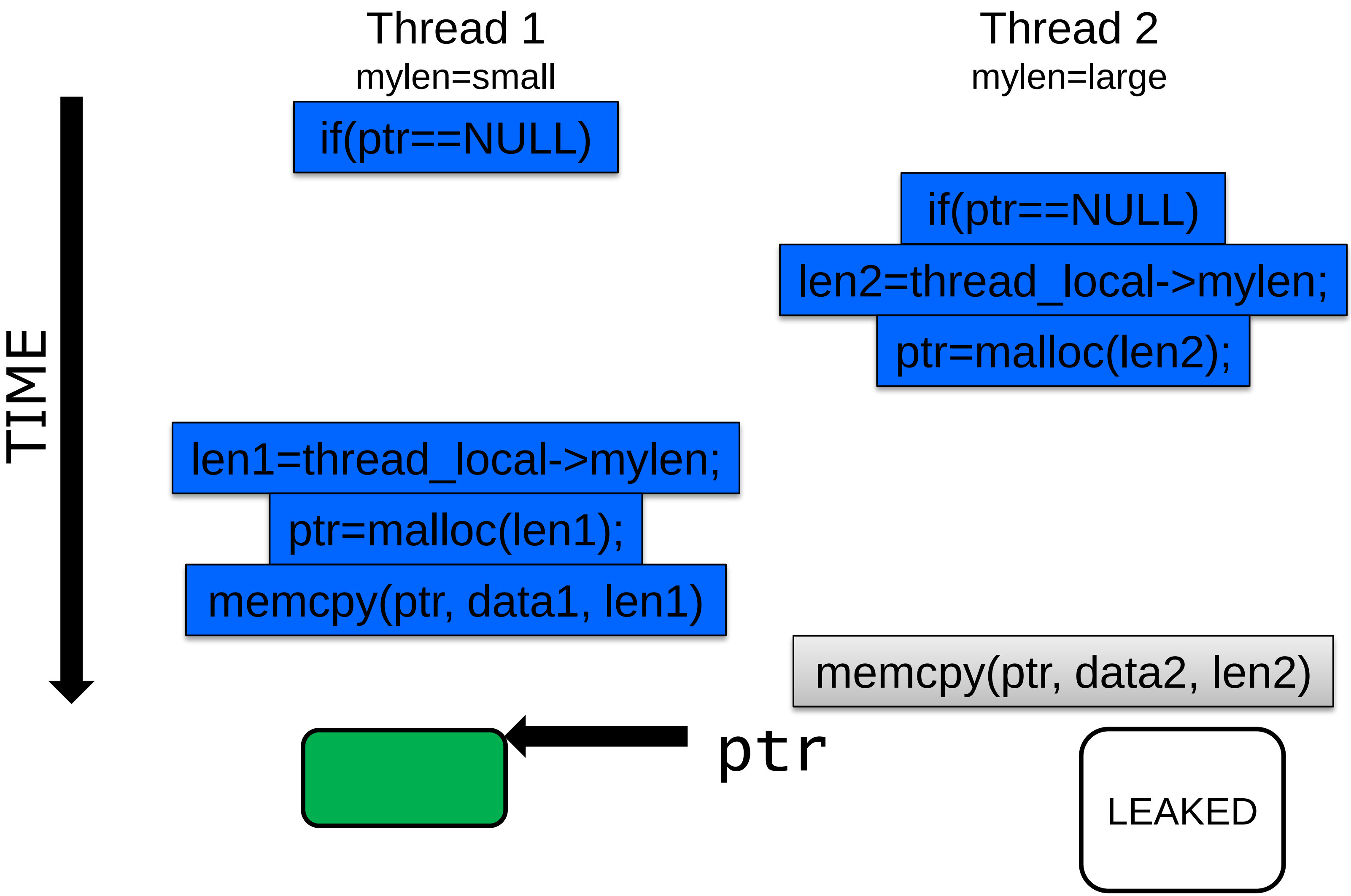

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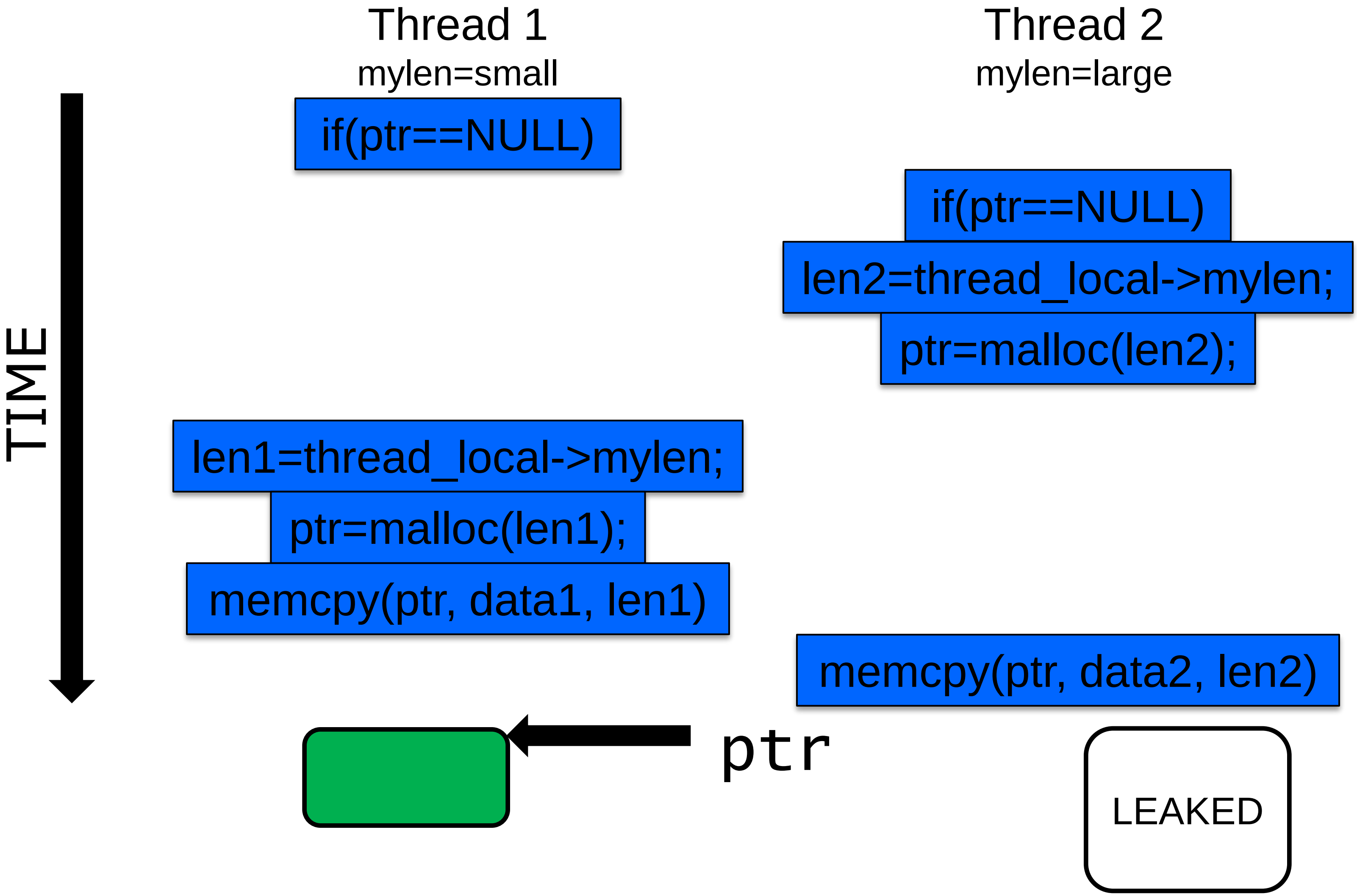

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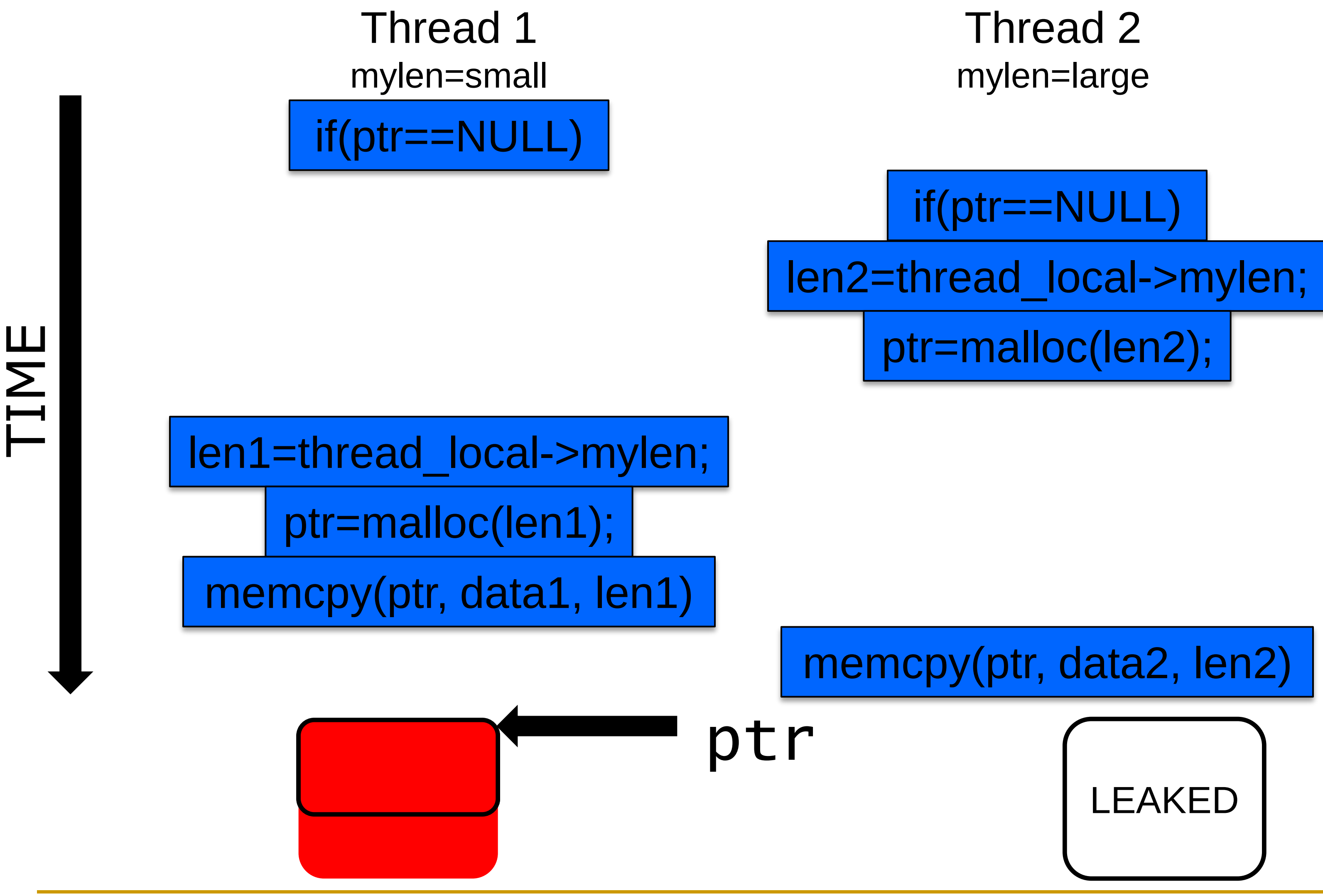
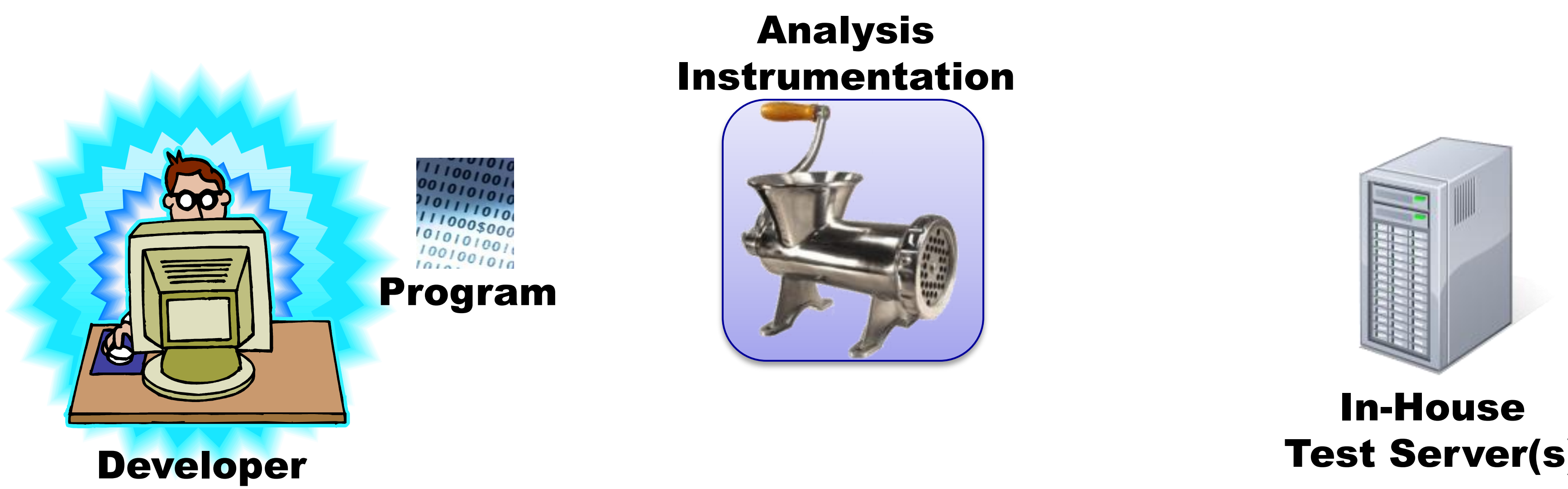


Dynamic Software Analysis

- 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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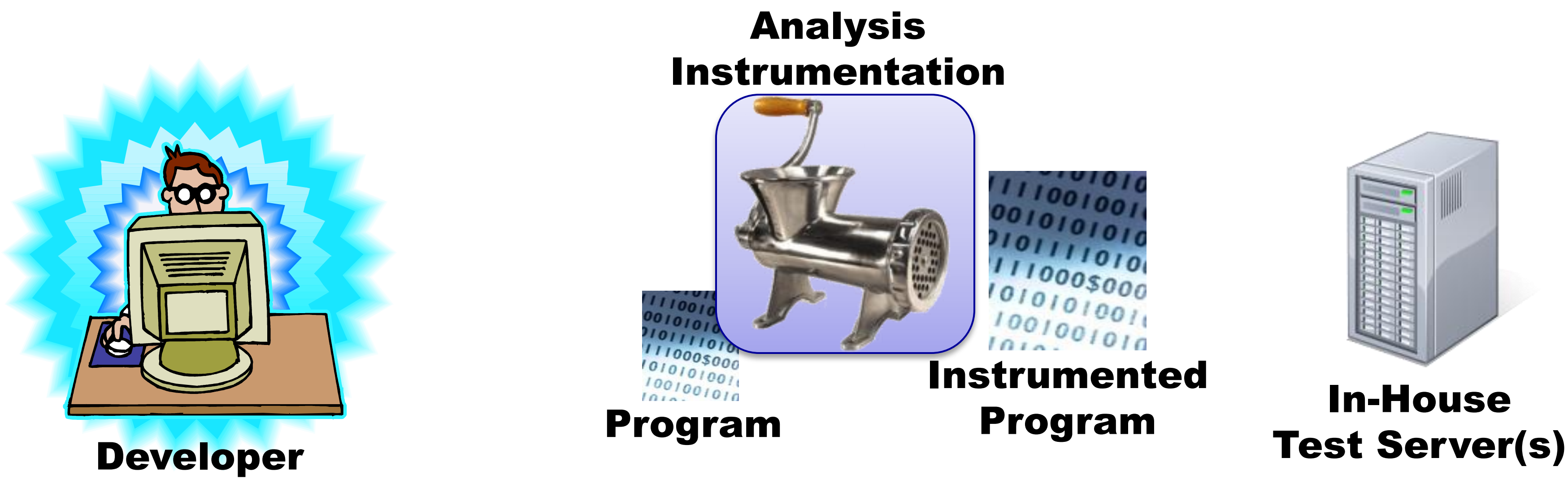

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Analysis Instrumentation

Developer

In-House Test Server(s)

LONG run time

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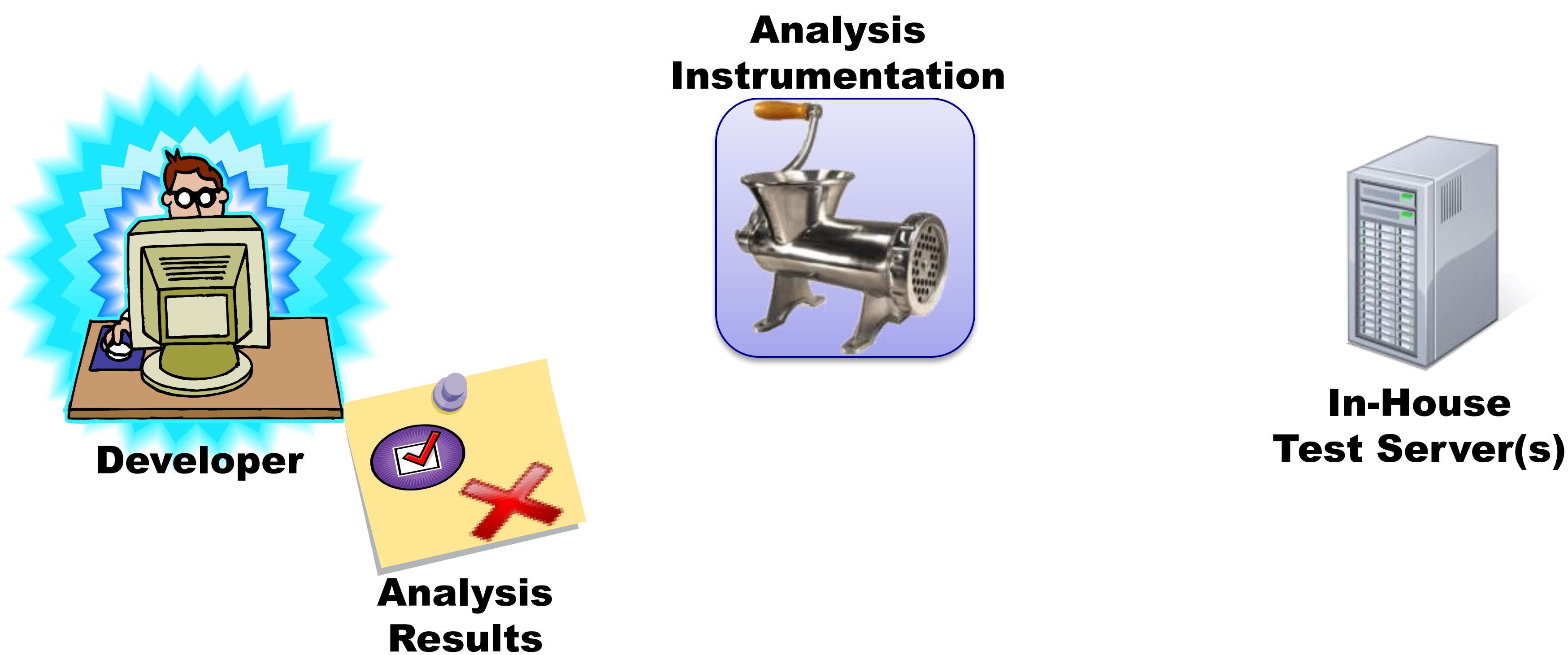


Runtime Overheads: How Large?

- 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

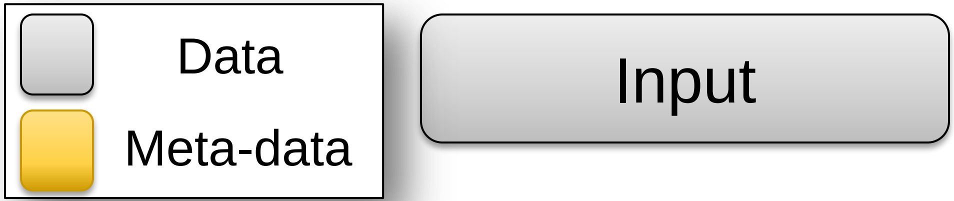
Outline

- Problem Statement
- Background Information
  - Demand-Driven Dynamic Dataflow Analysis
- Proposed Solutions
  - Demand-Driven Data Race Detection
  - Sampling to Cap Maximum Overheads

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



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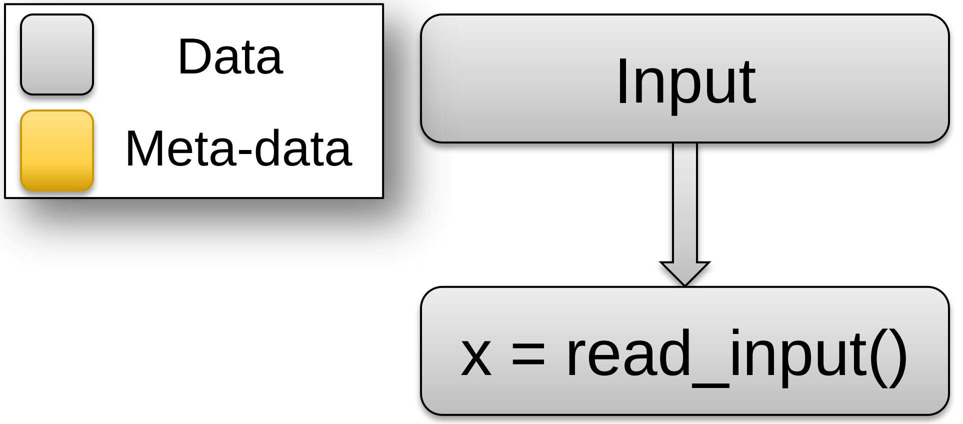

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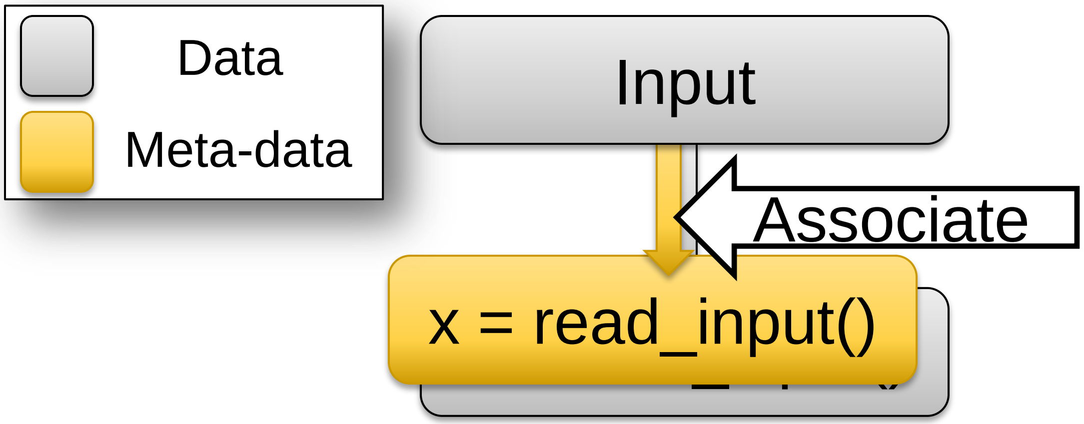

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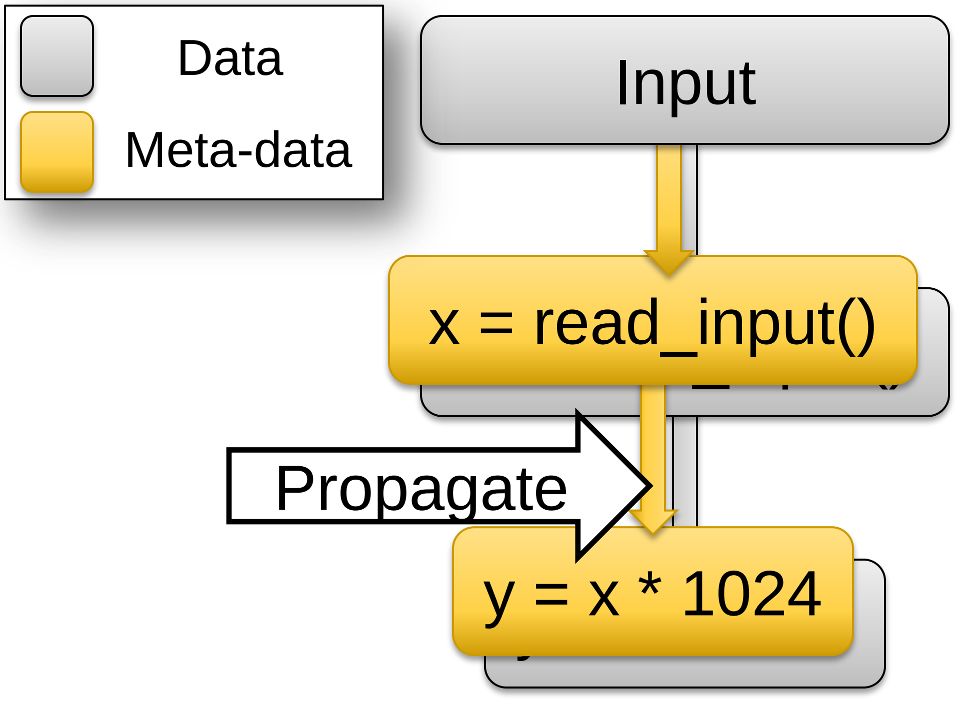

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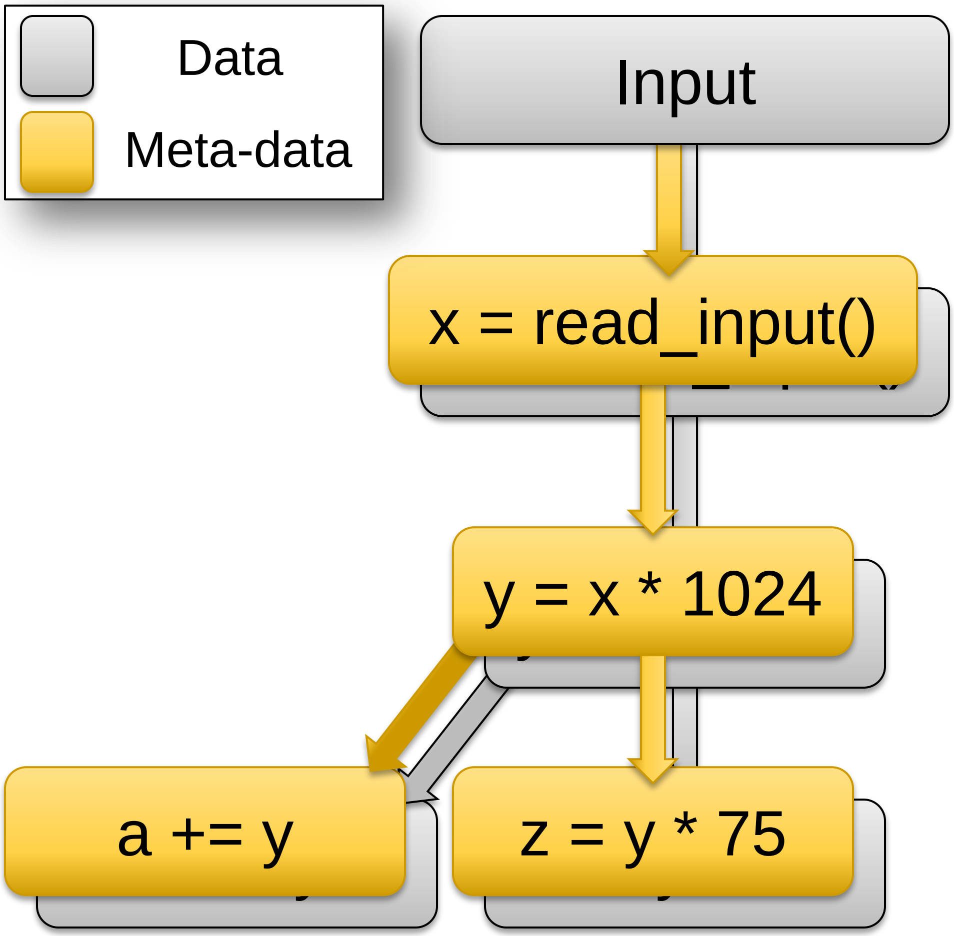

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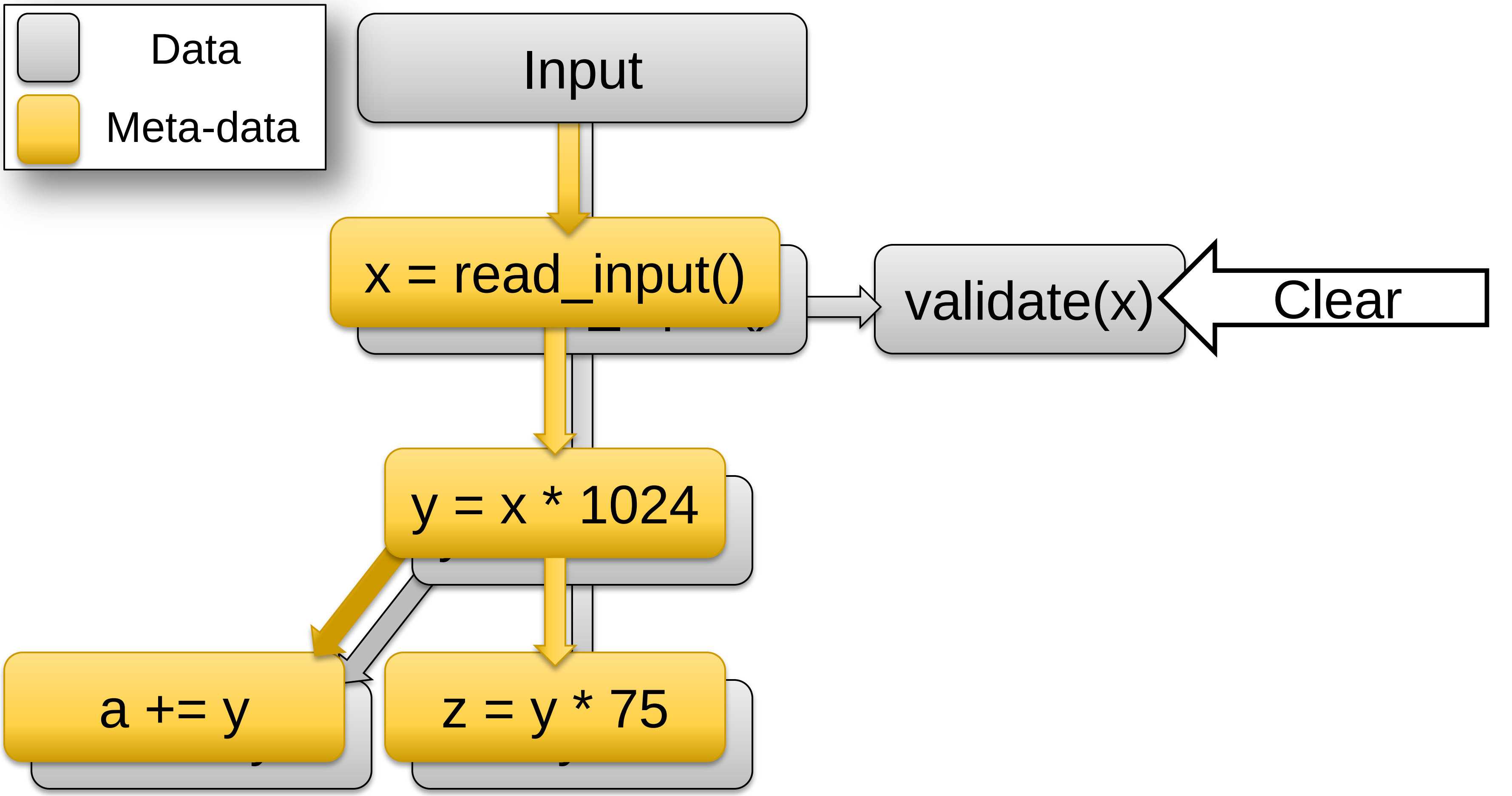

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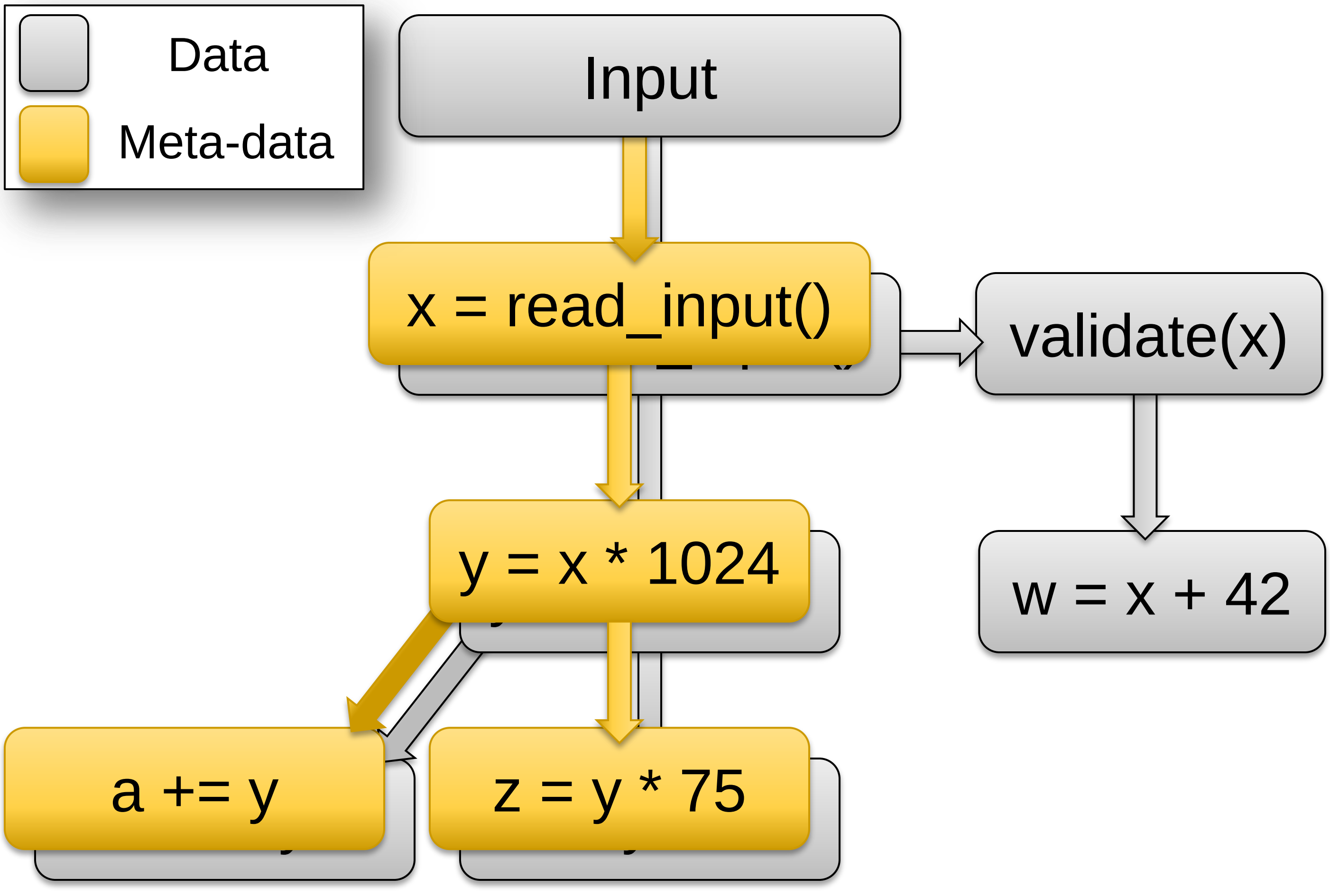

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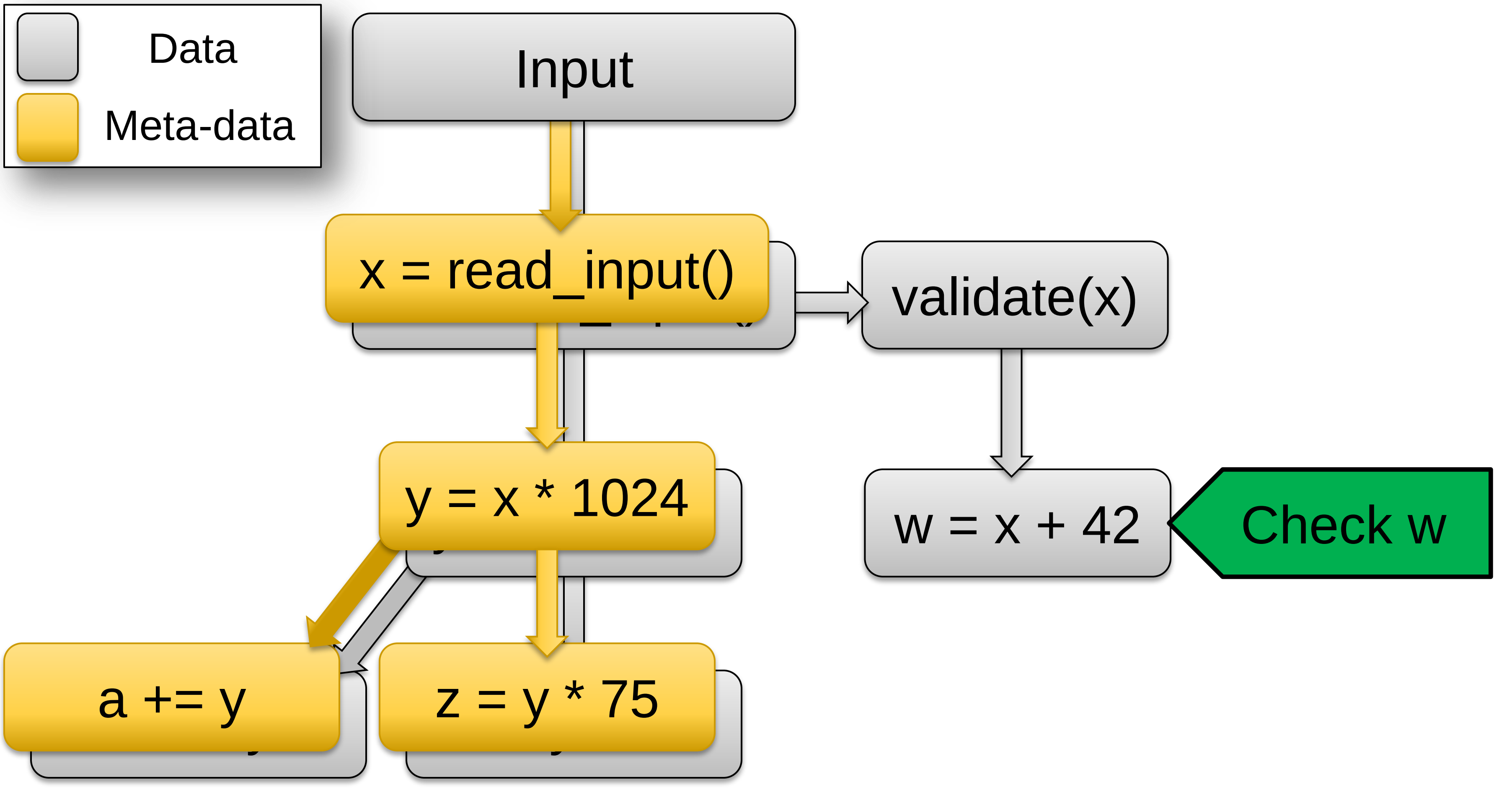

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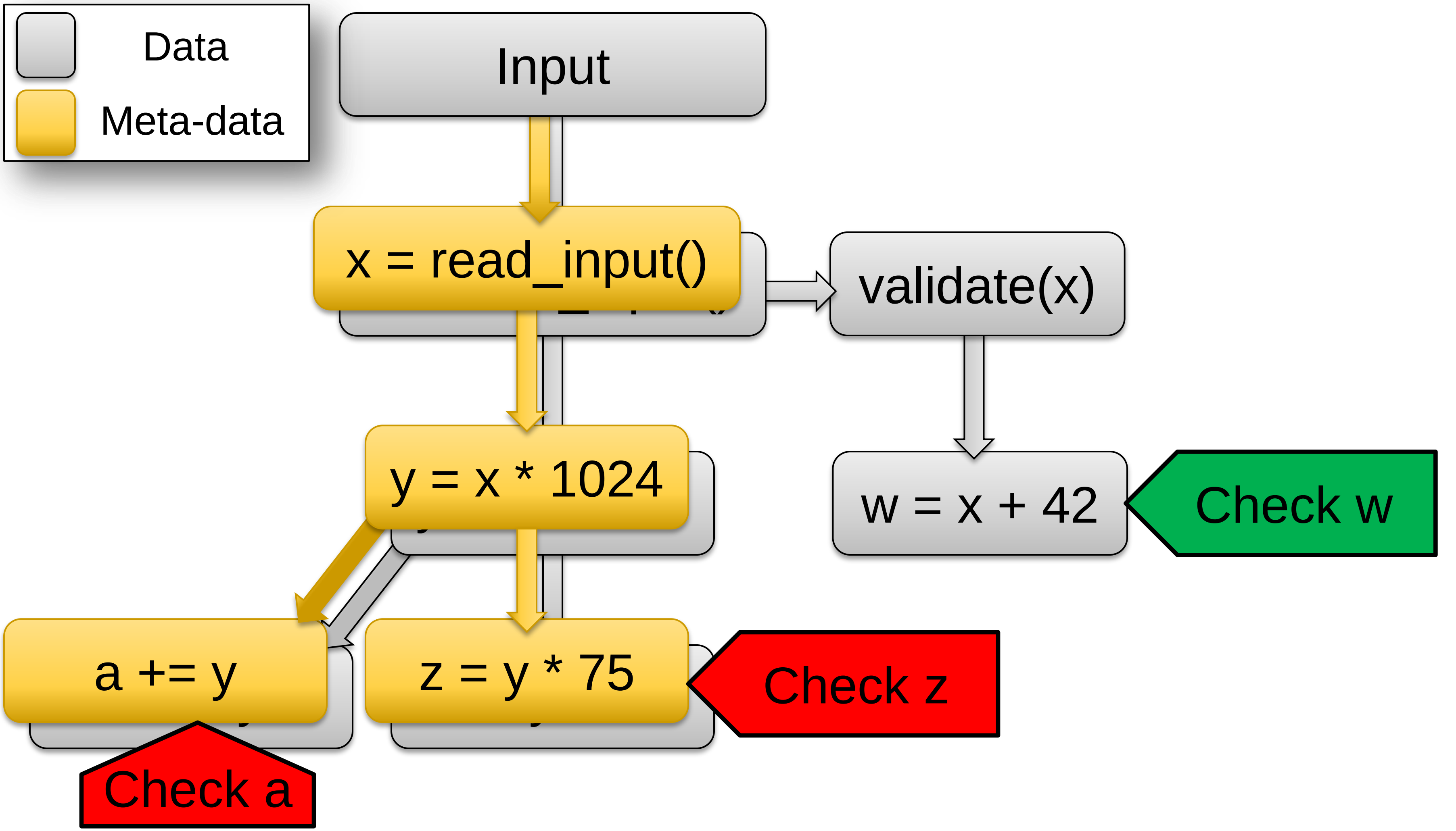

Demand-Driven Dataflow Analysis

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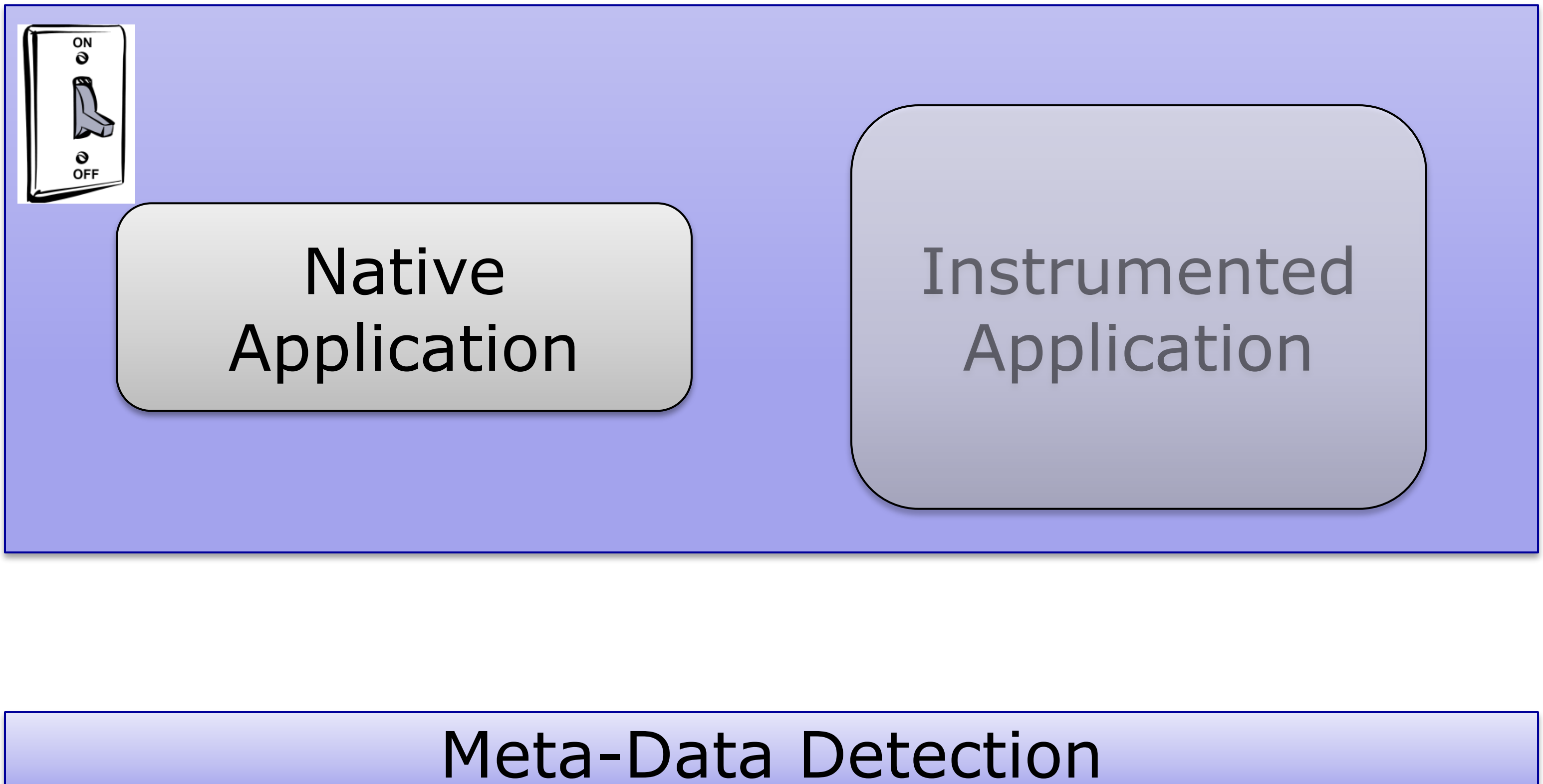

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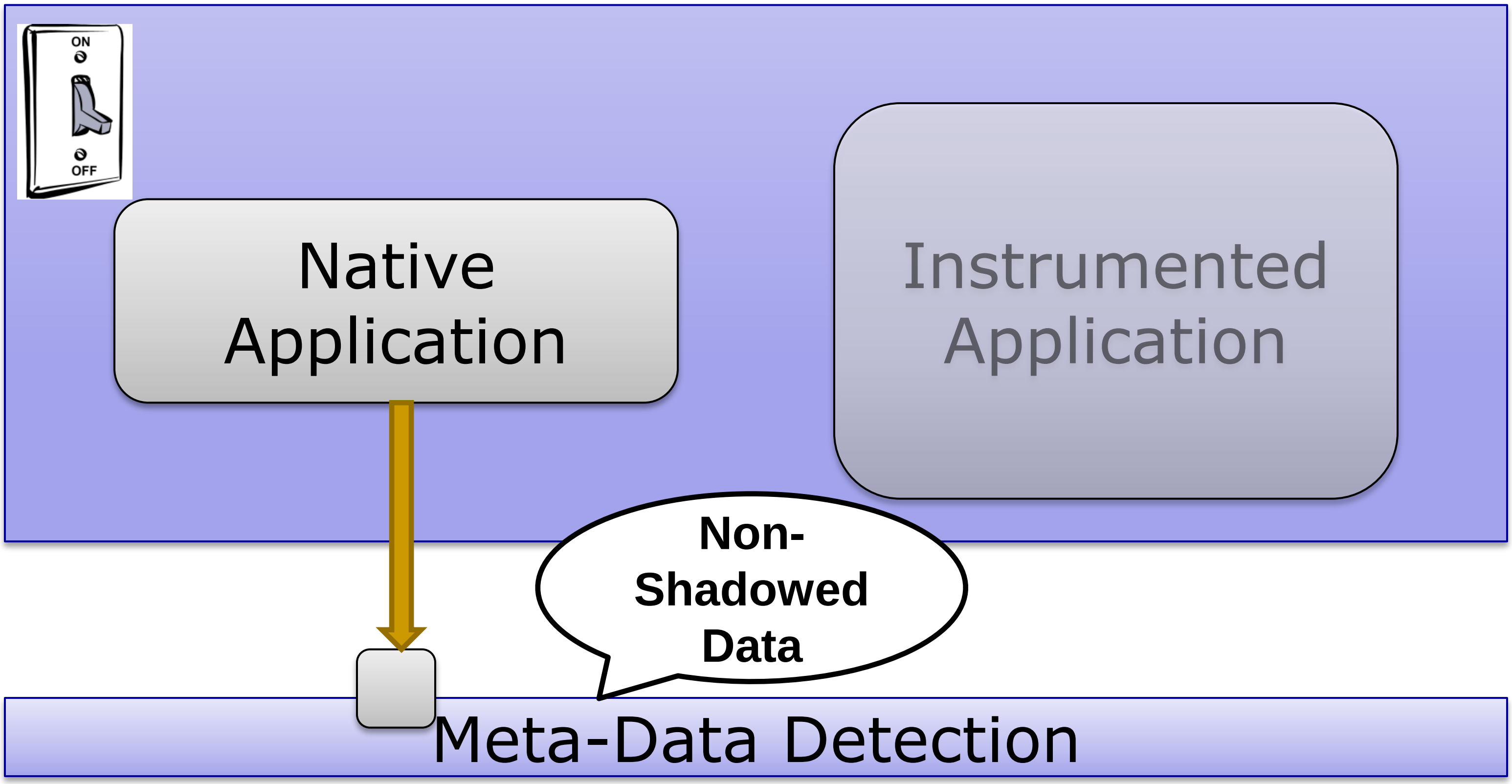

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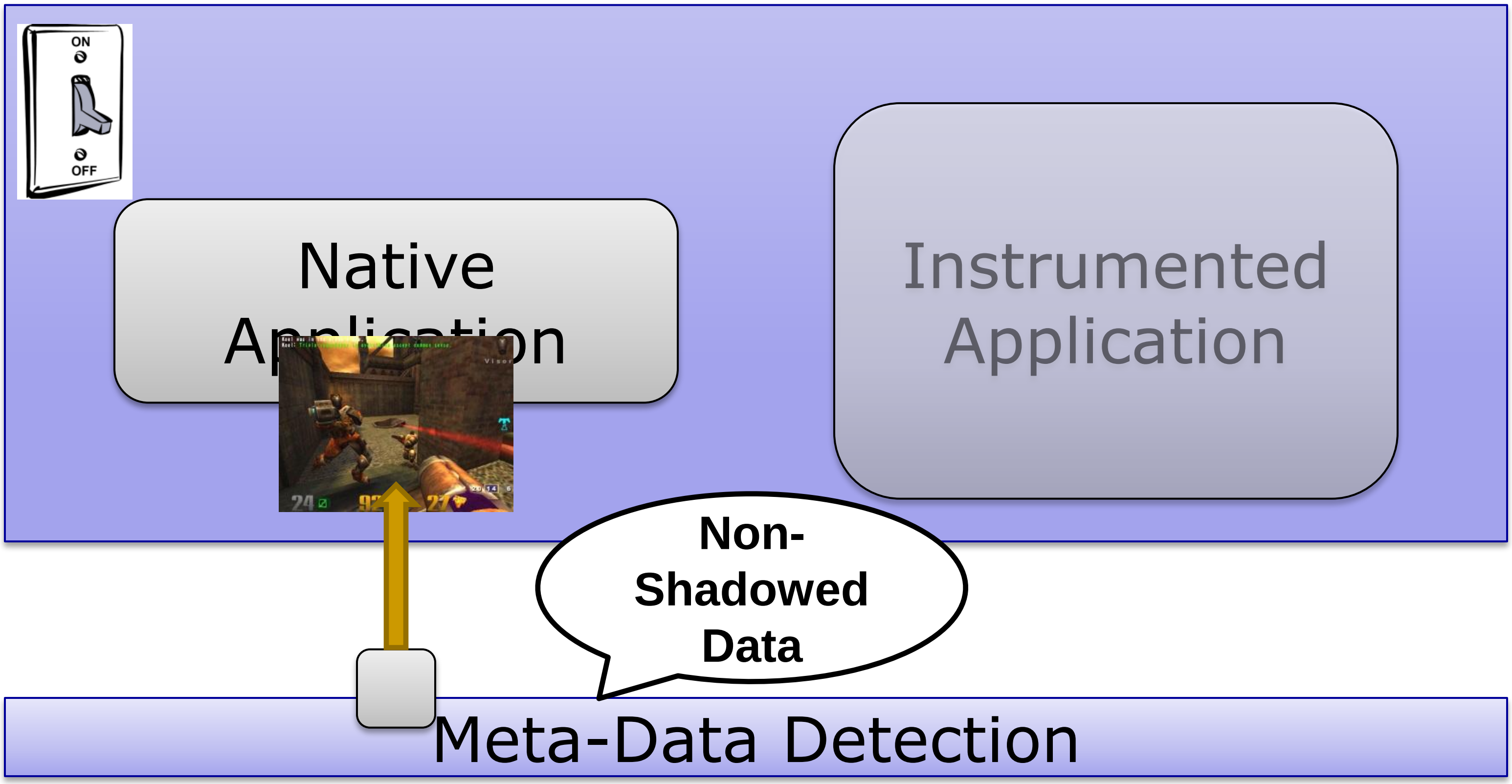

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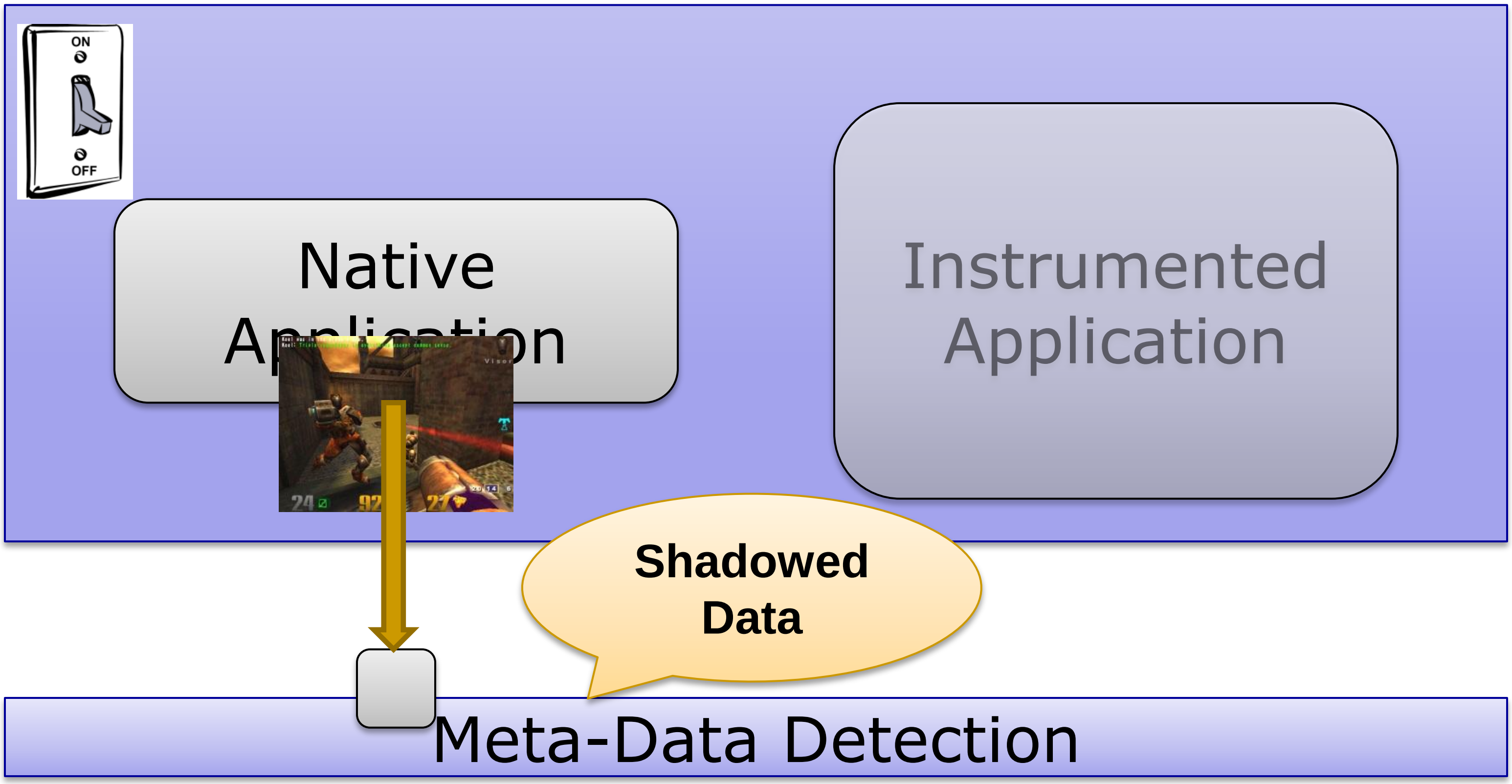

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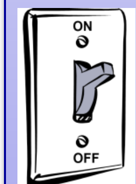

Native Application

Instrumented Application

Meta-Data Detection

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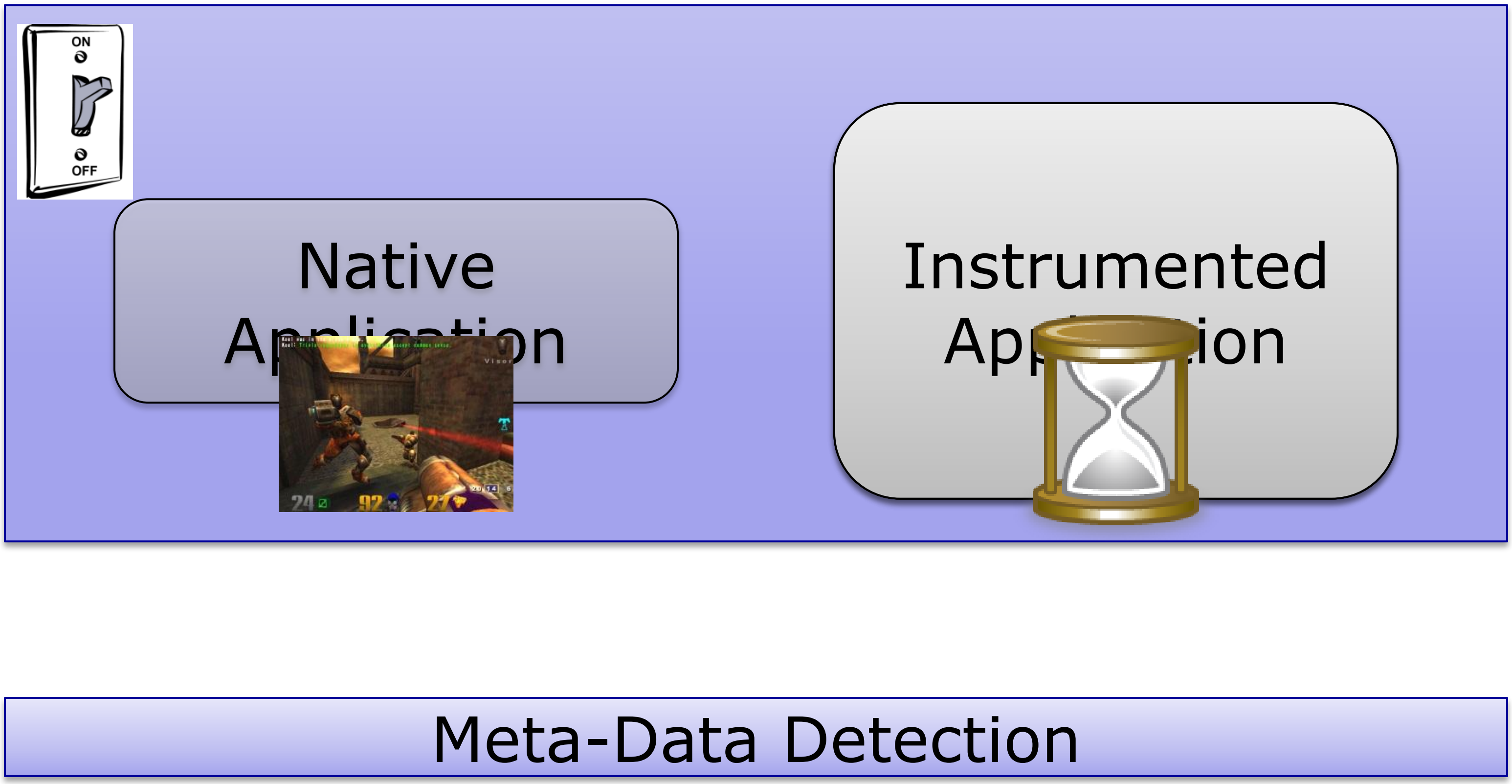

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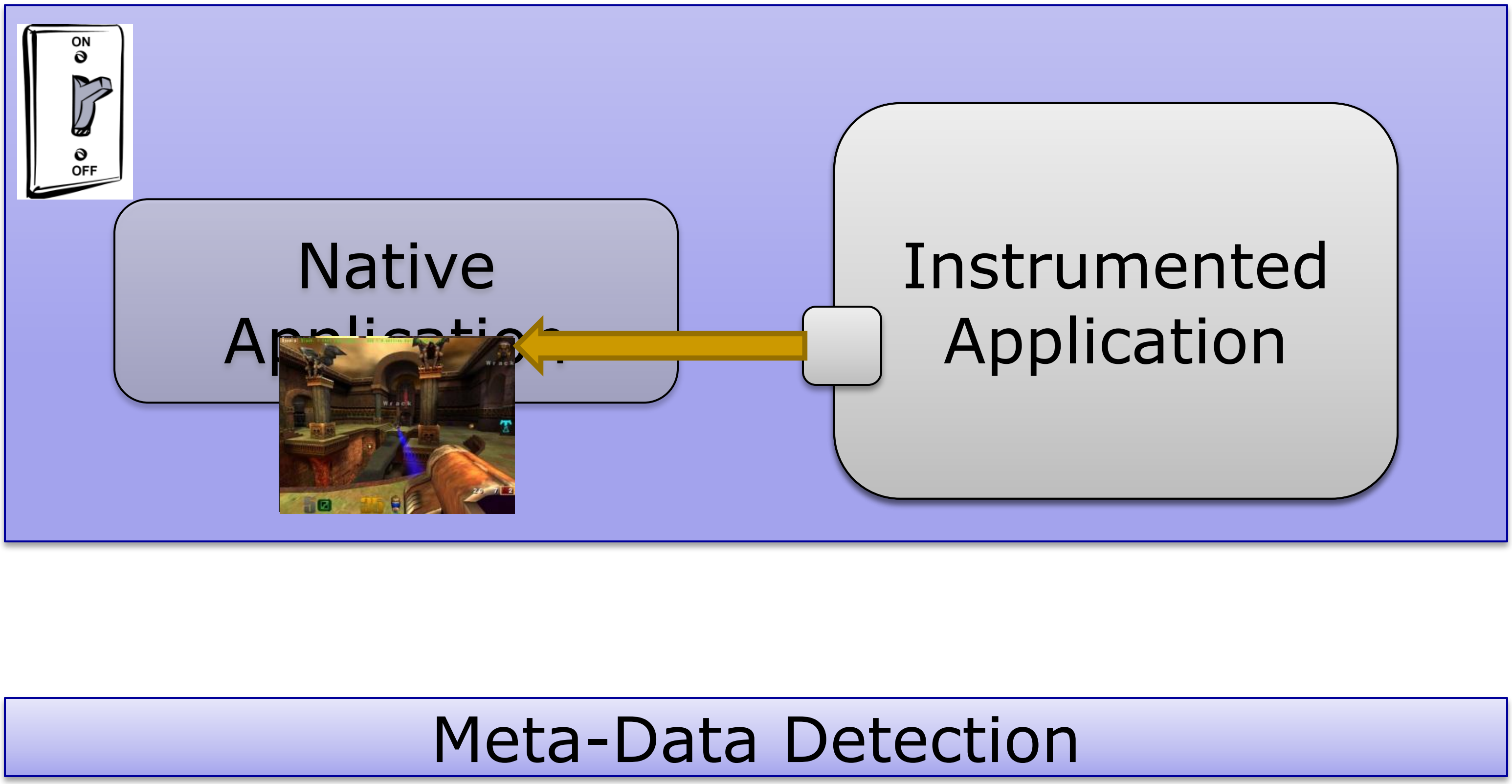

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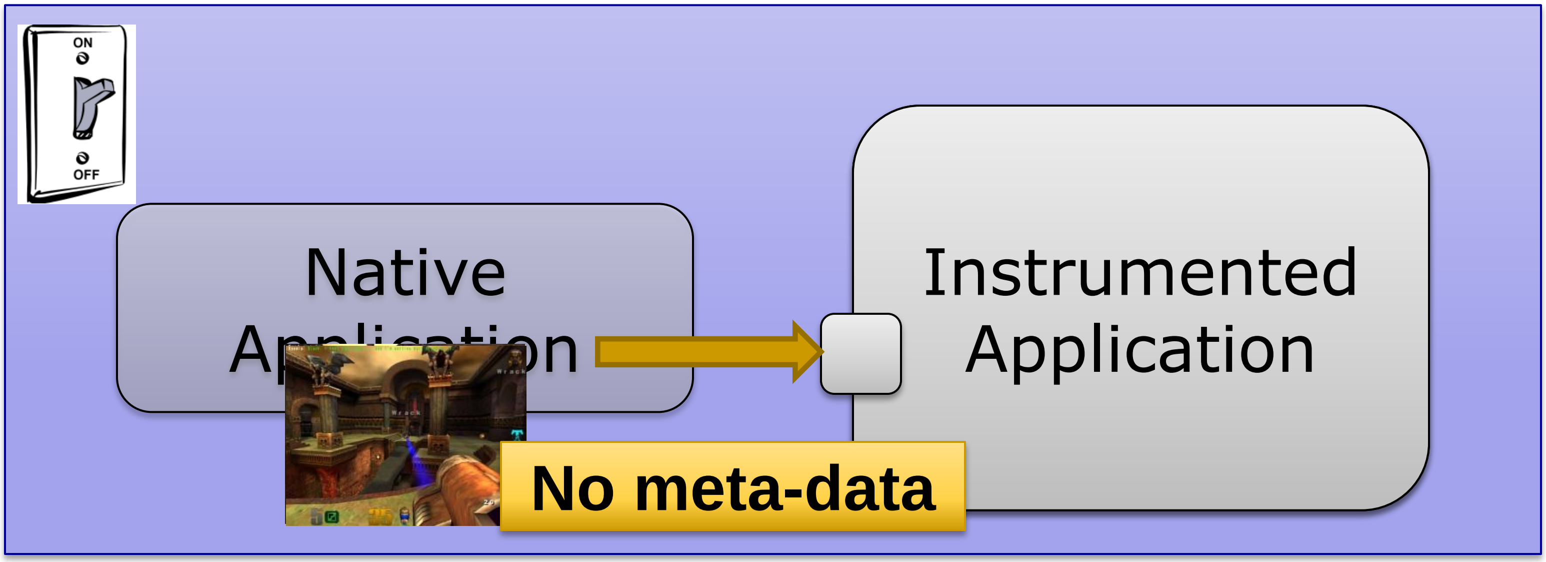

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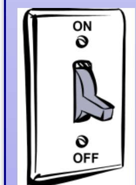

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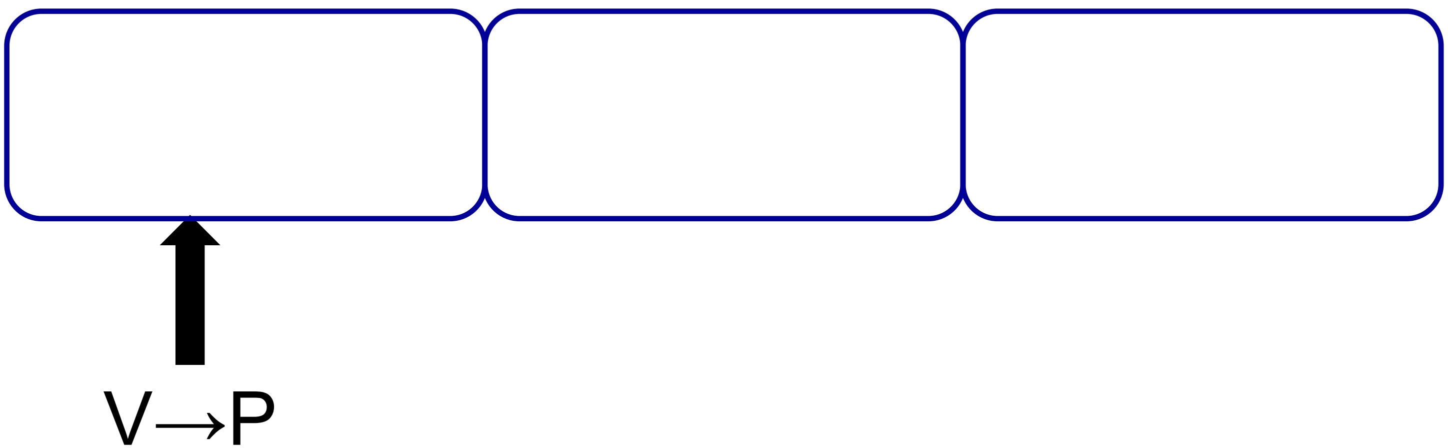

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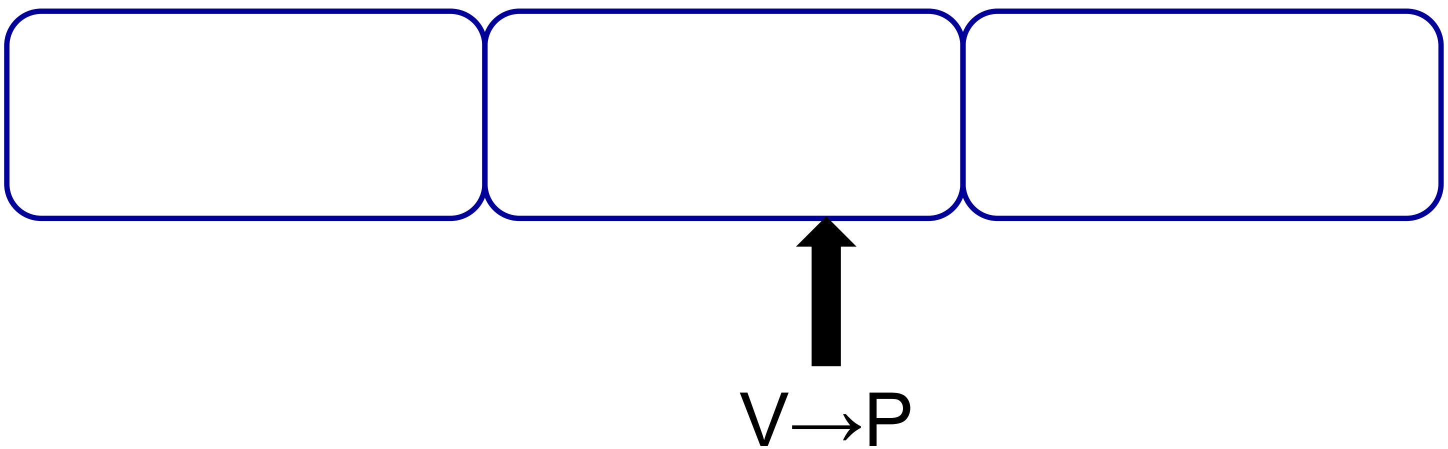

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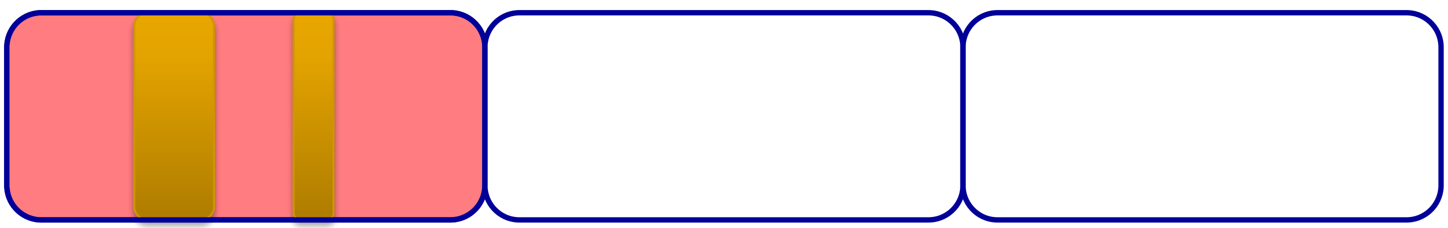

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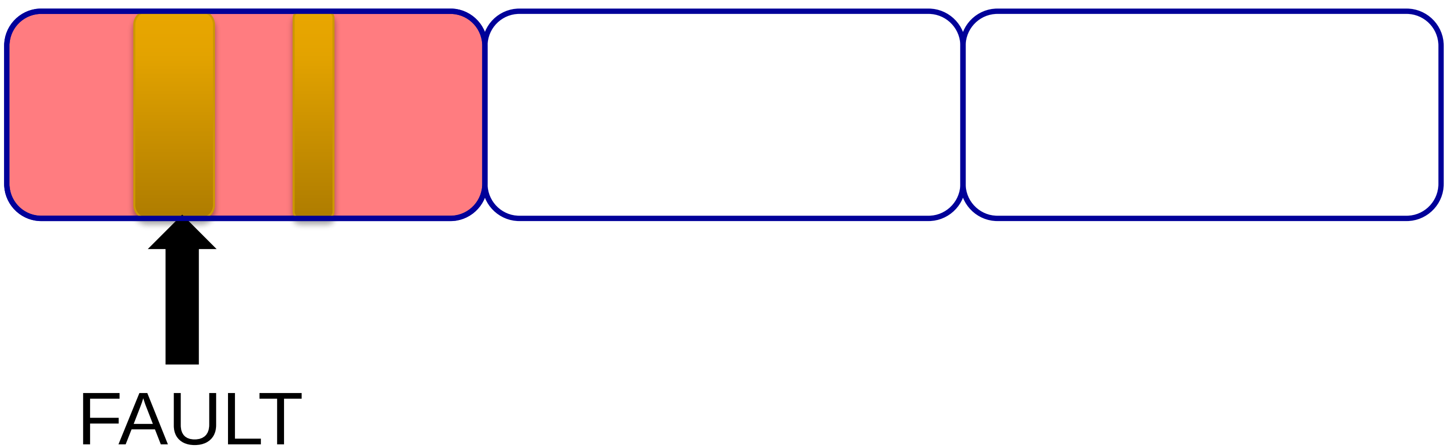

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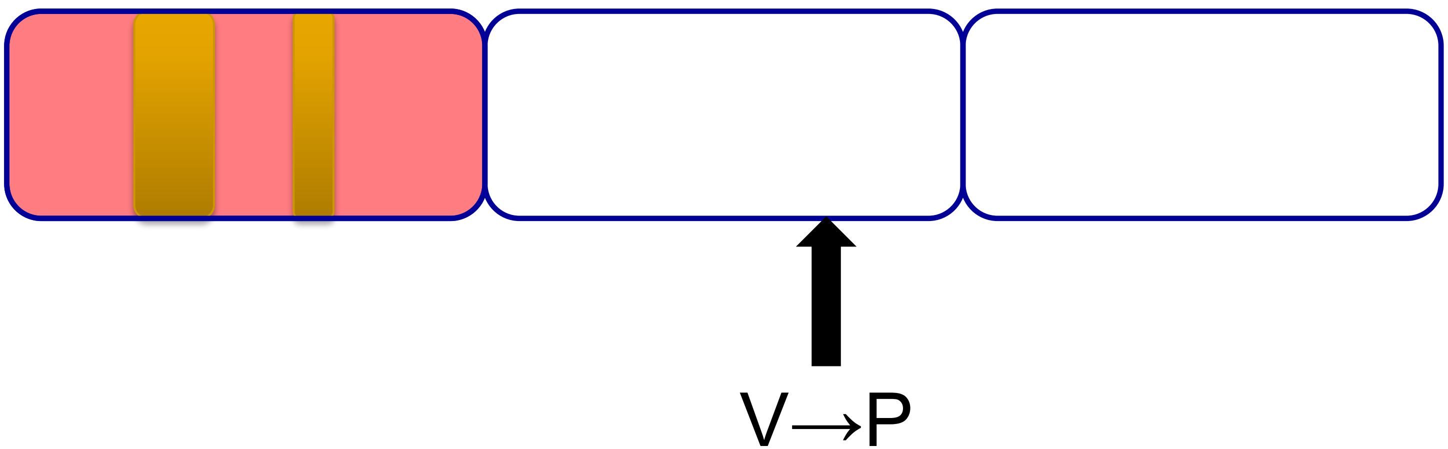
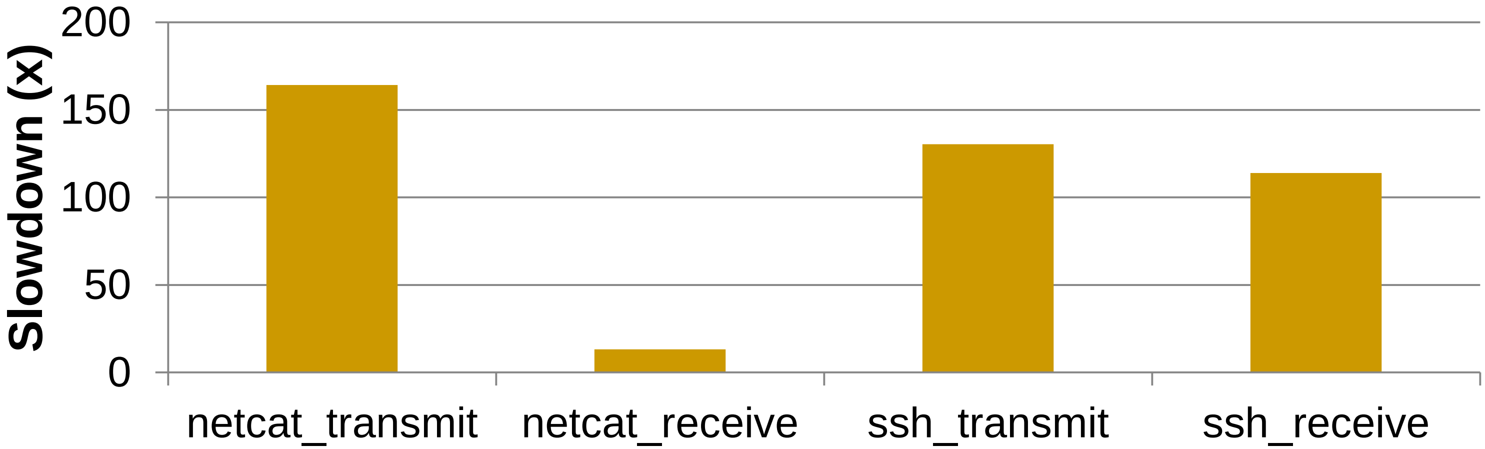


Results by Ho et al.

- 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

Thread 1
mylen=small

```
if(ptr==NULL)
len1=thread_local->mylen;
ptr=malloc(len1);
memcpy(ptr, data1, len1)
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Thread 2
mylen=large

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TIME

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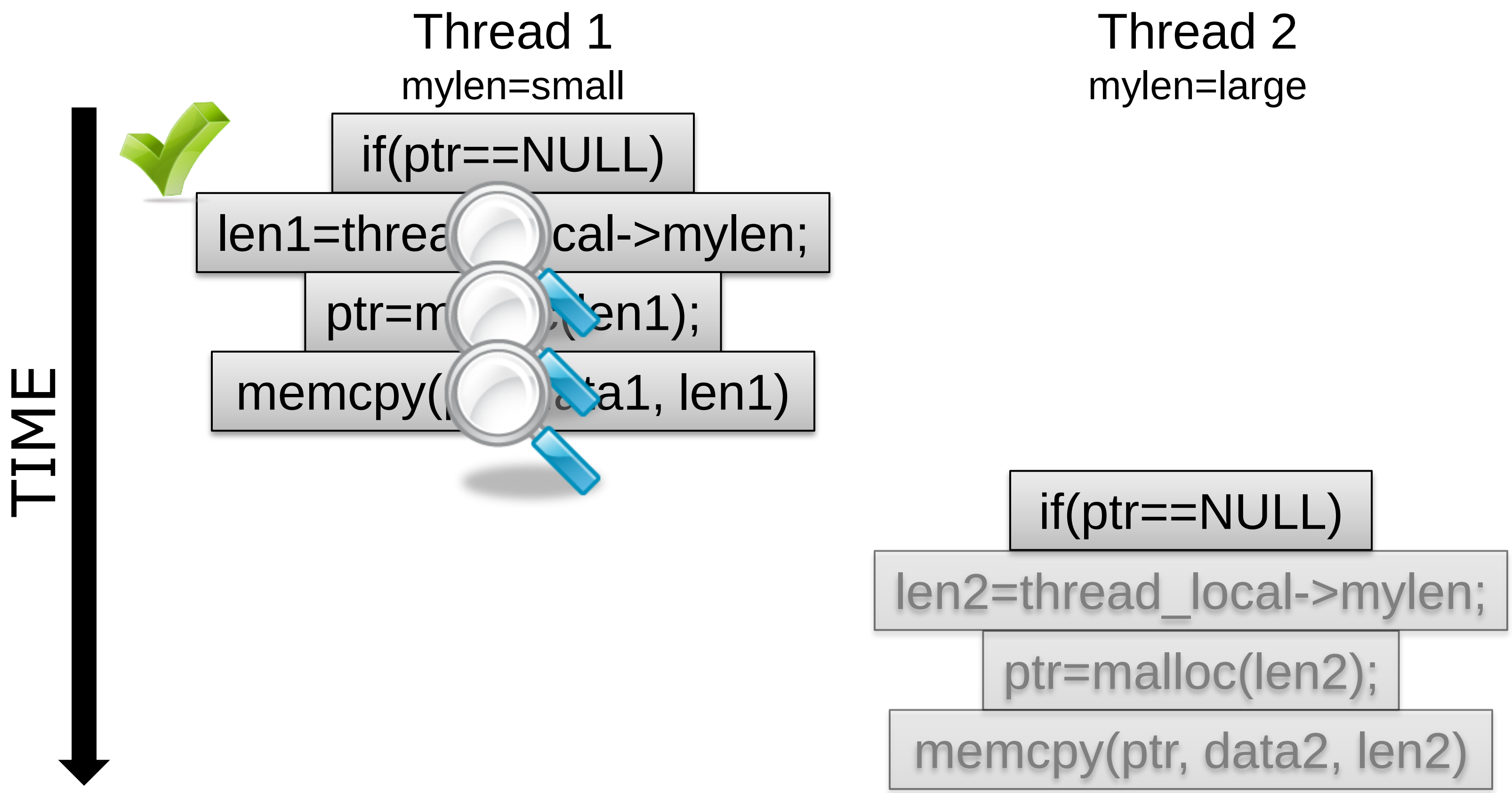

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ptr write-shared?

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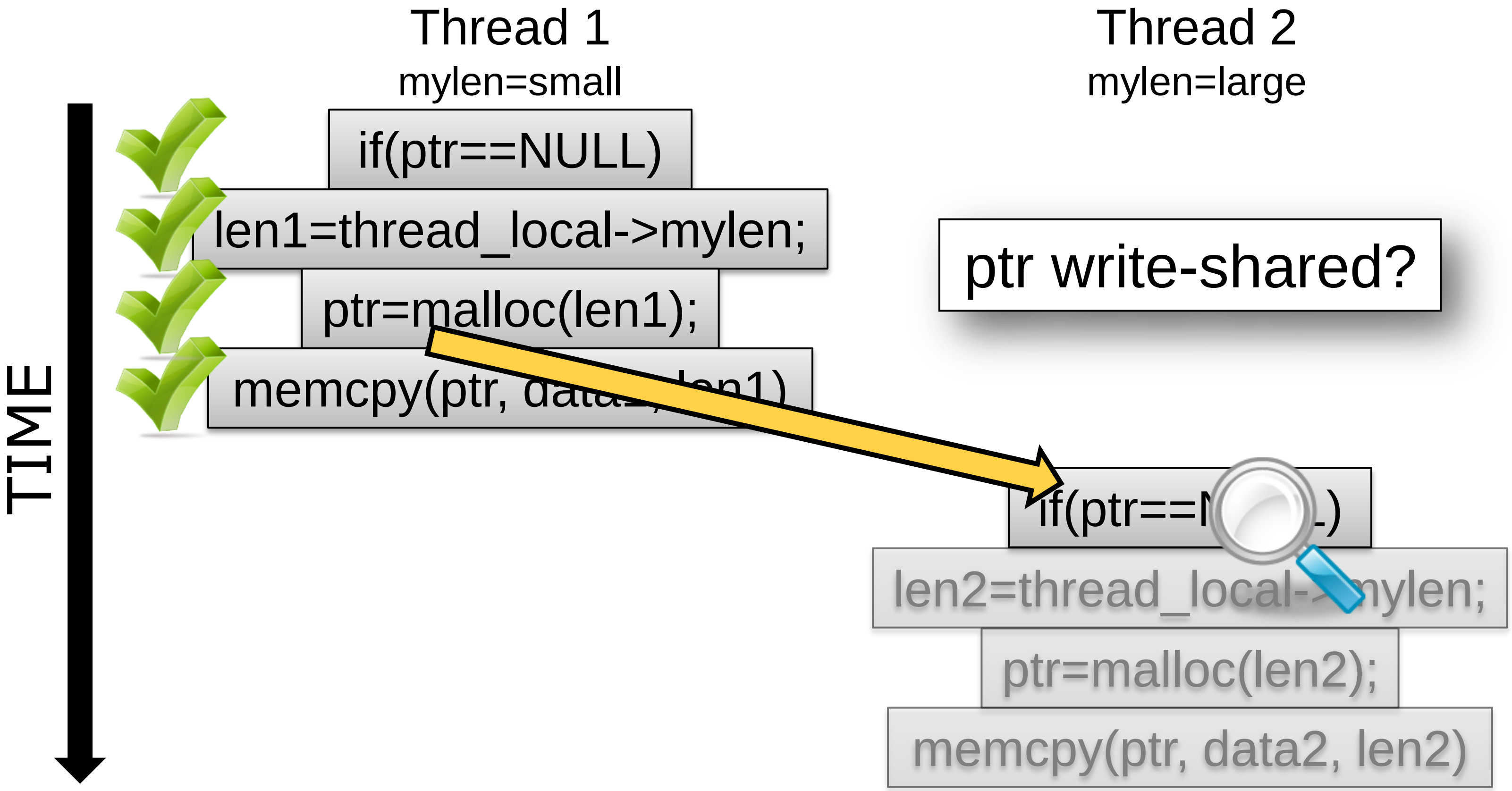

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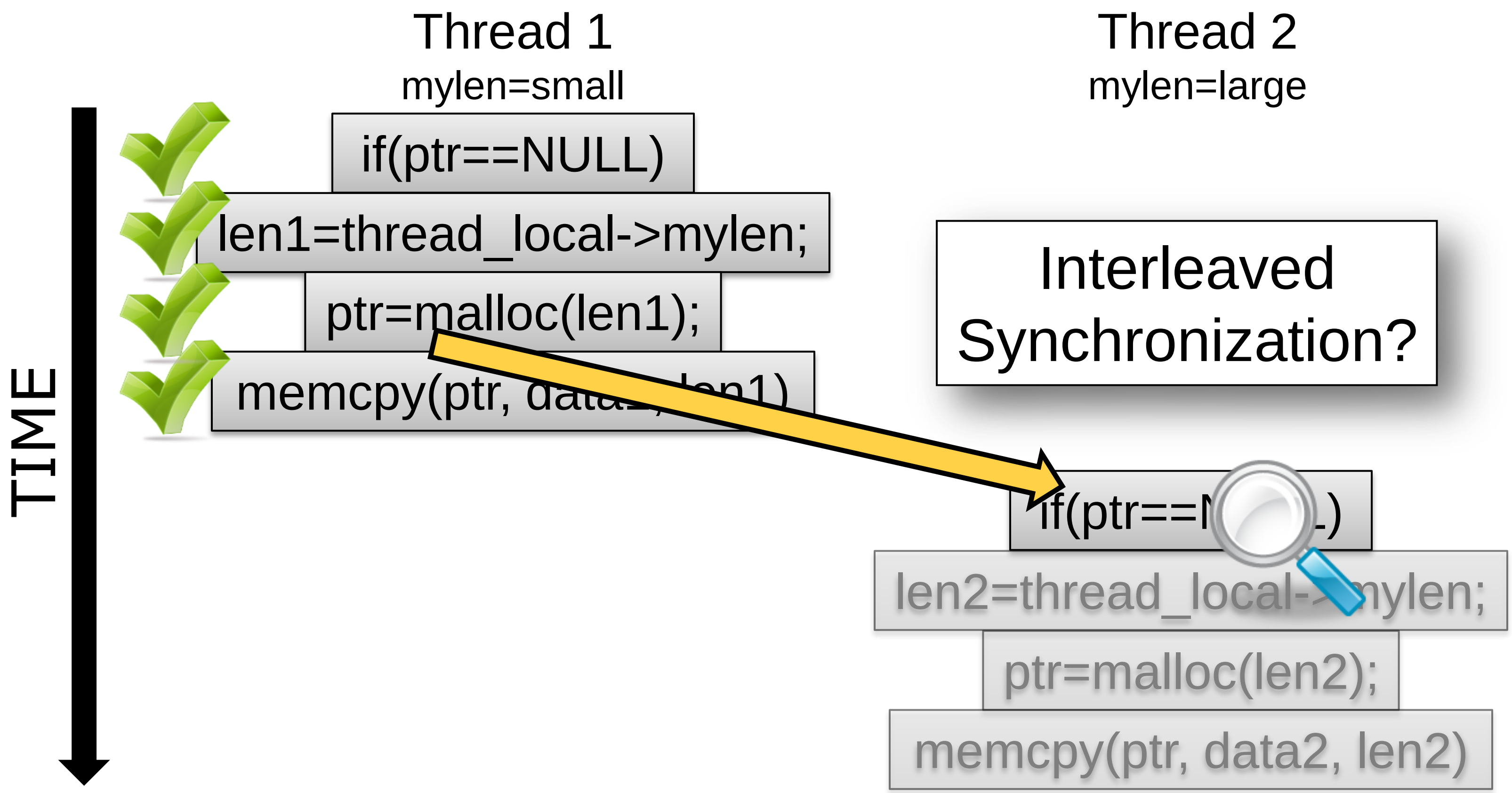

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Interleaved Synchronization?

```
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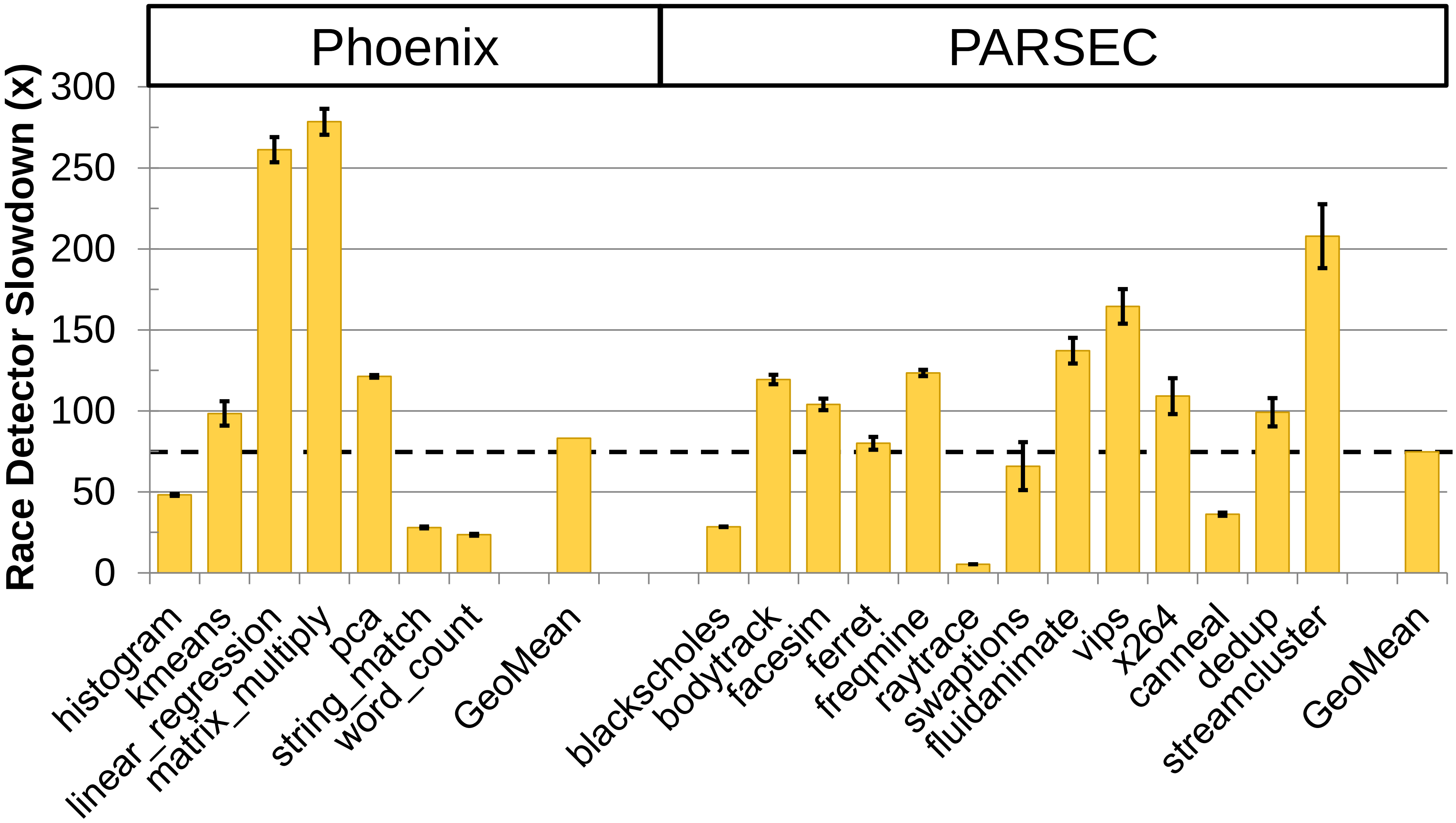
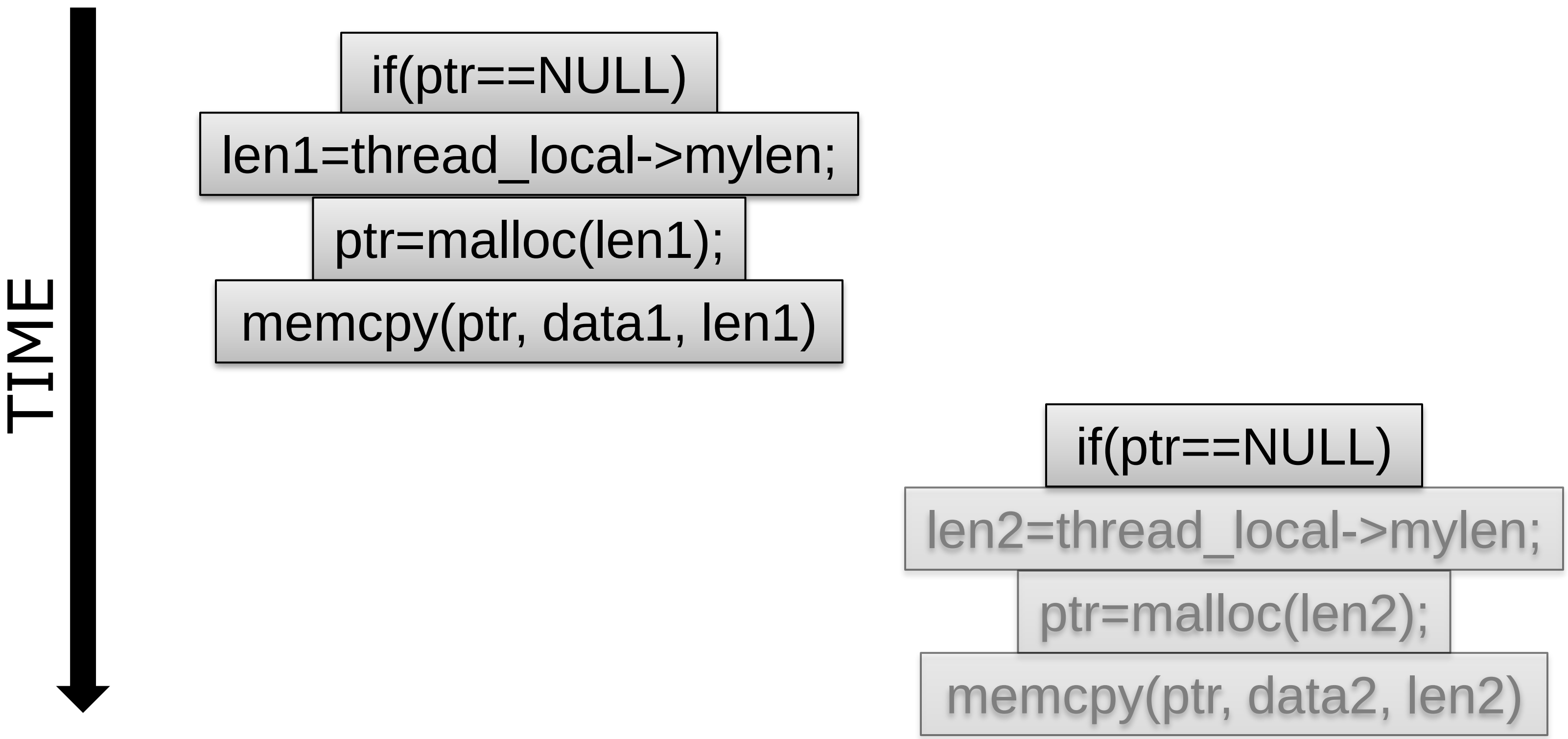
SW Race Detection is Slow



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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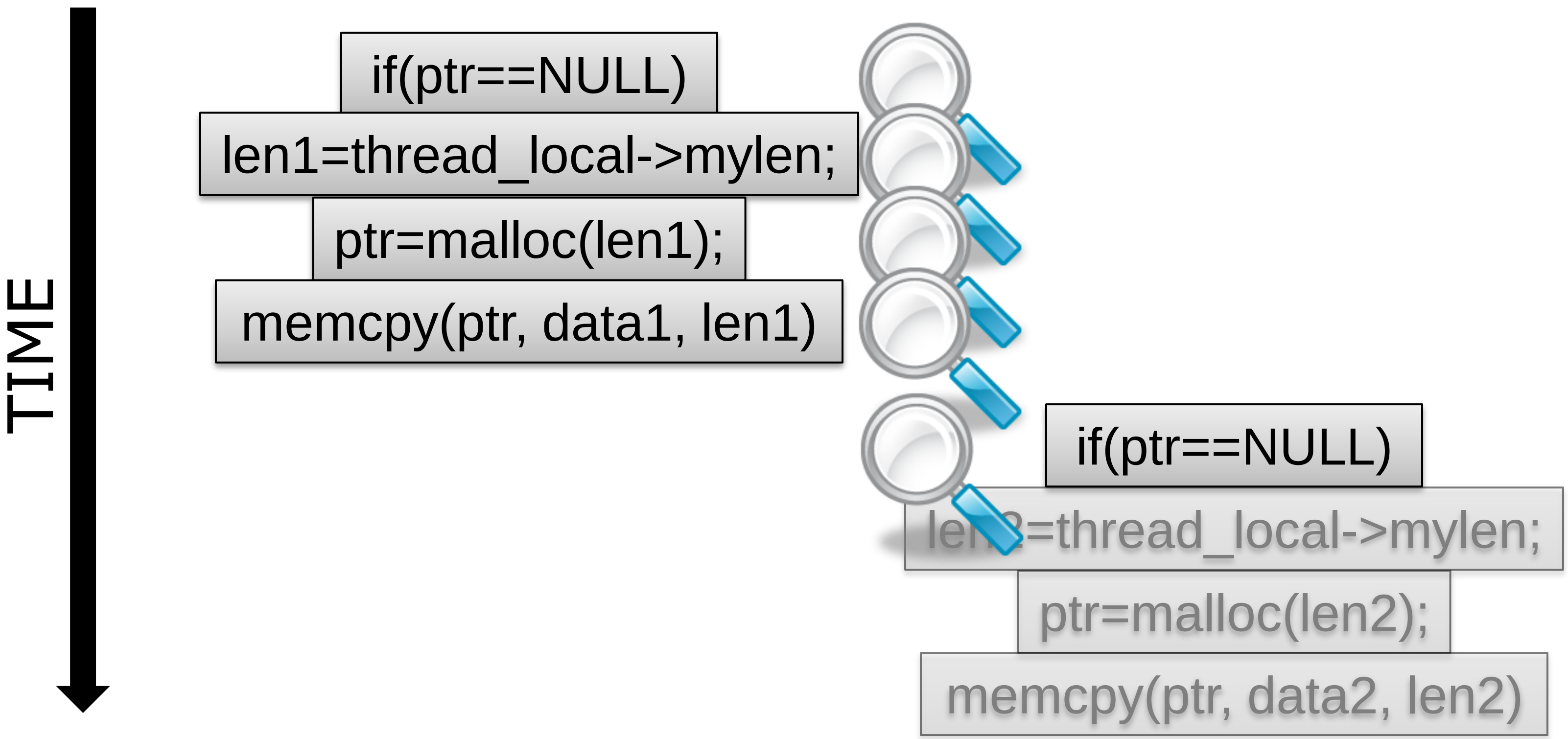

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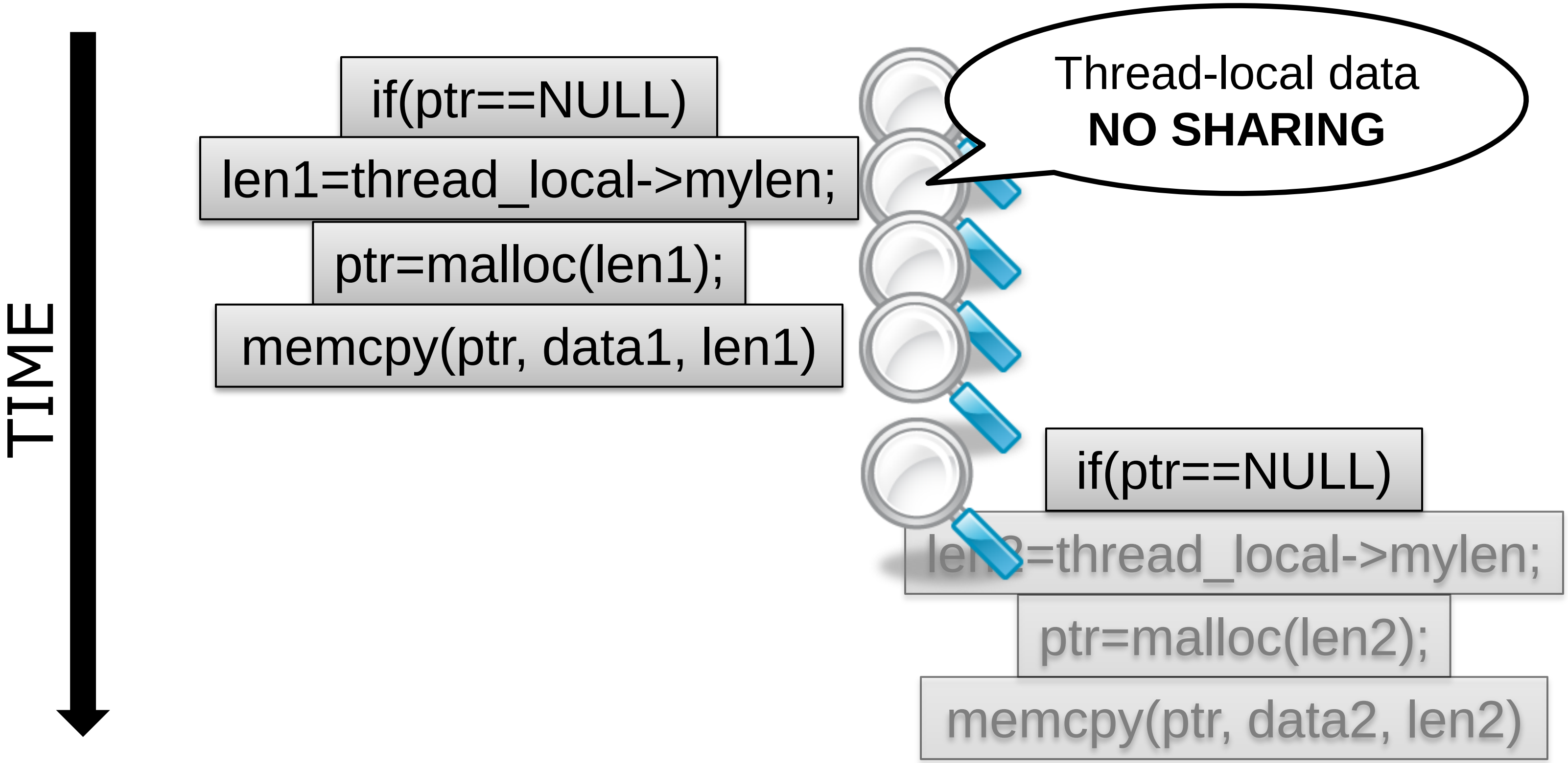

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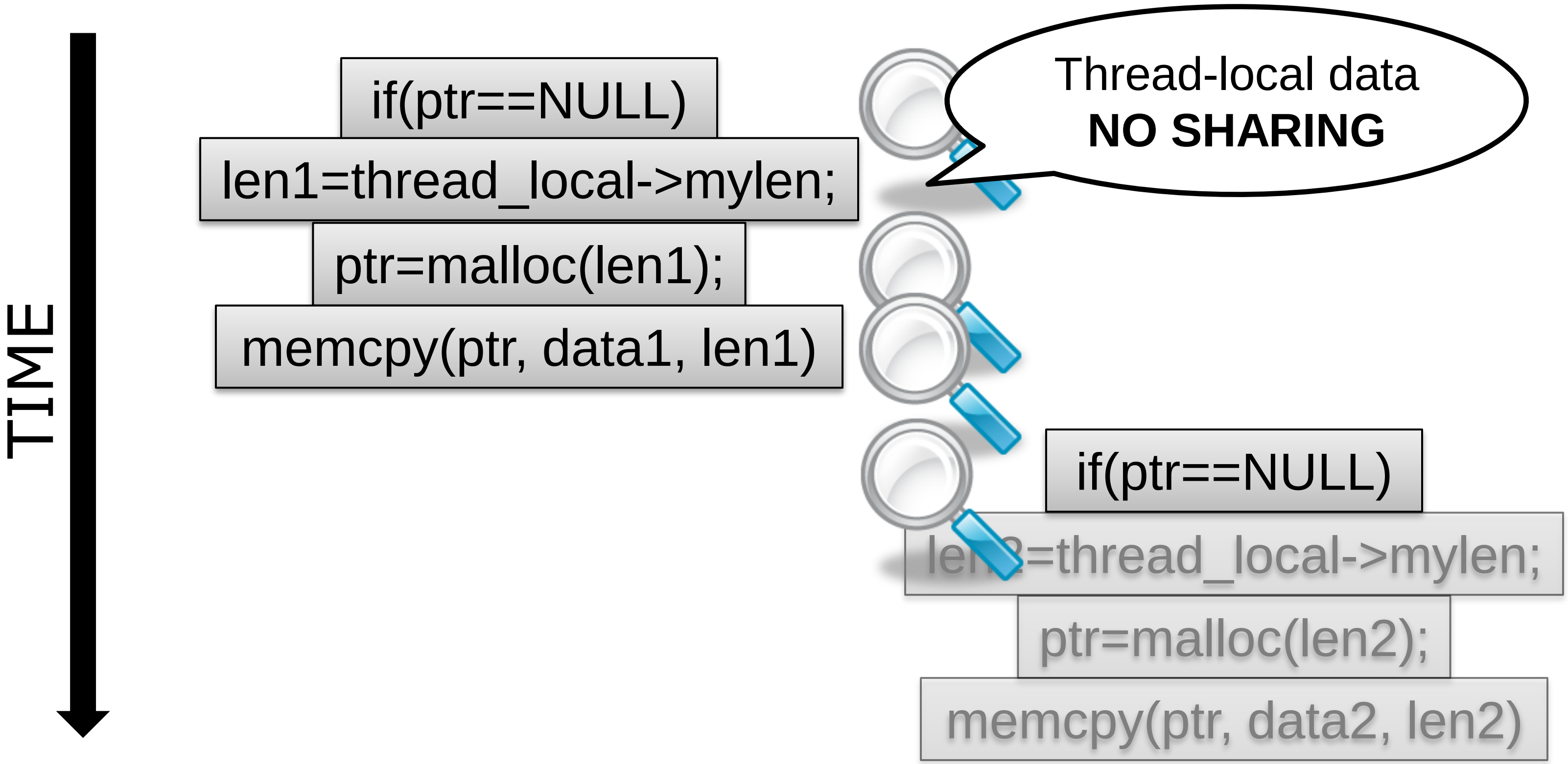

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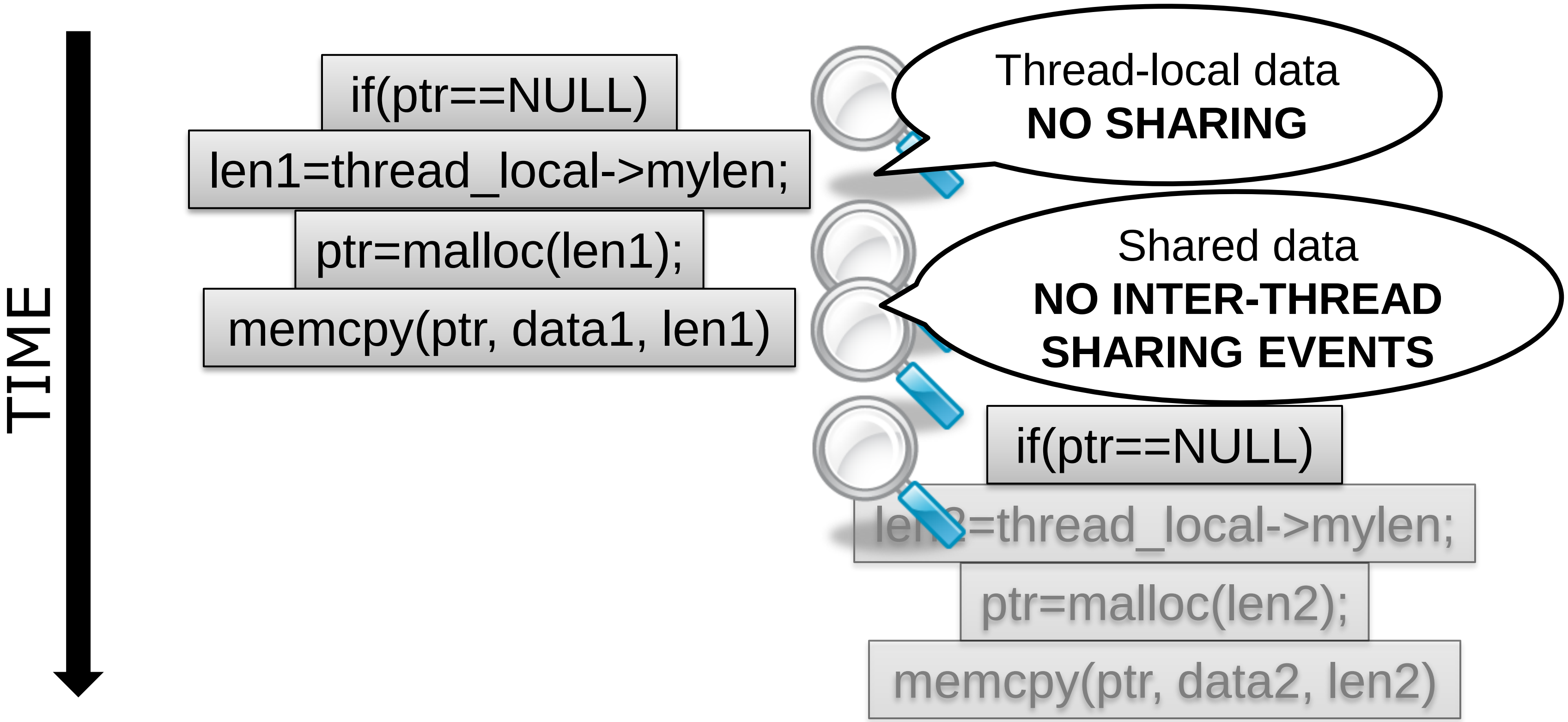

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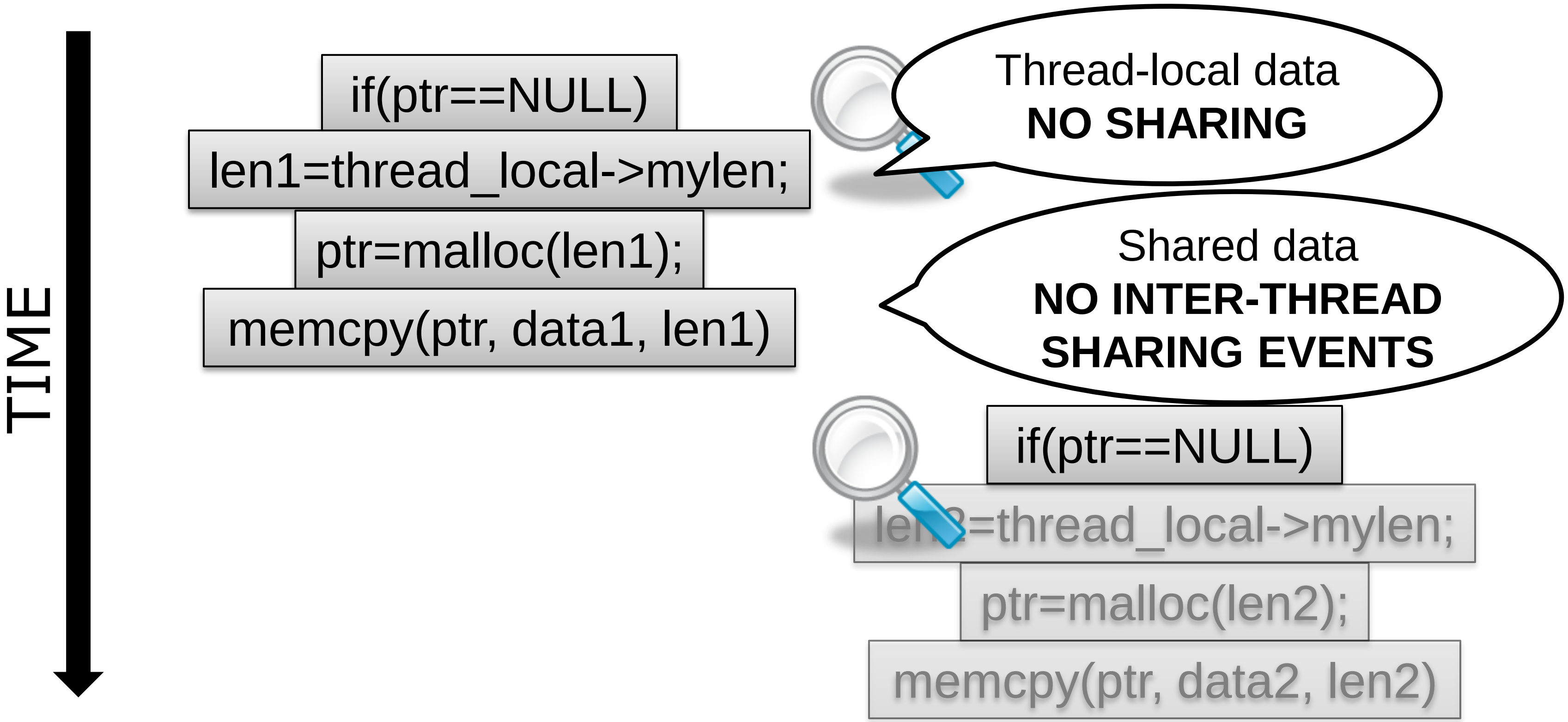

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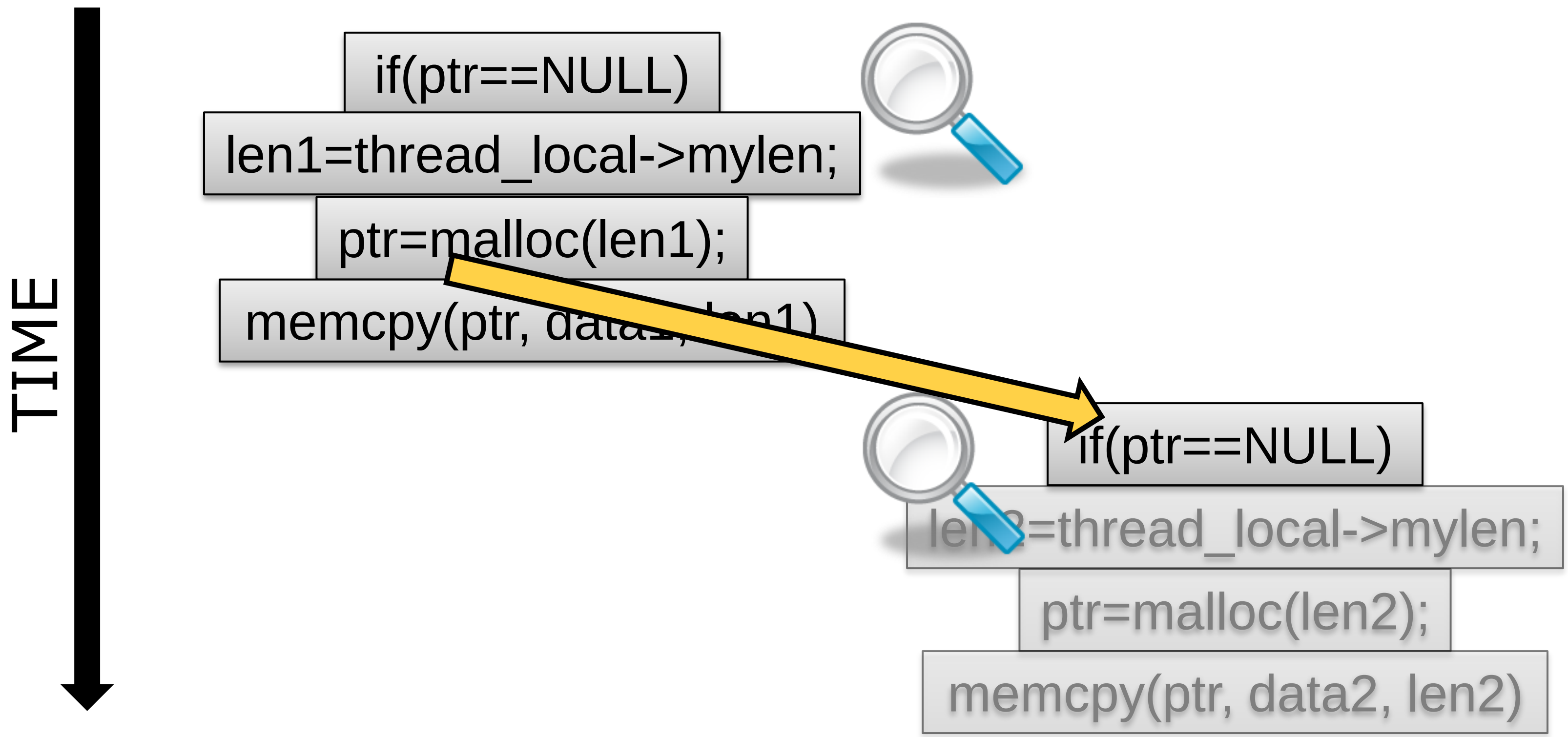
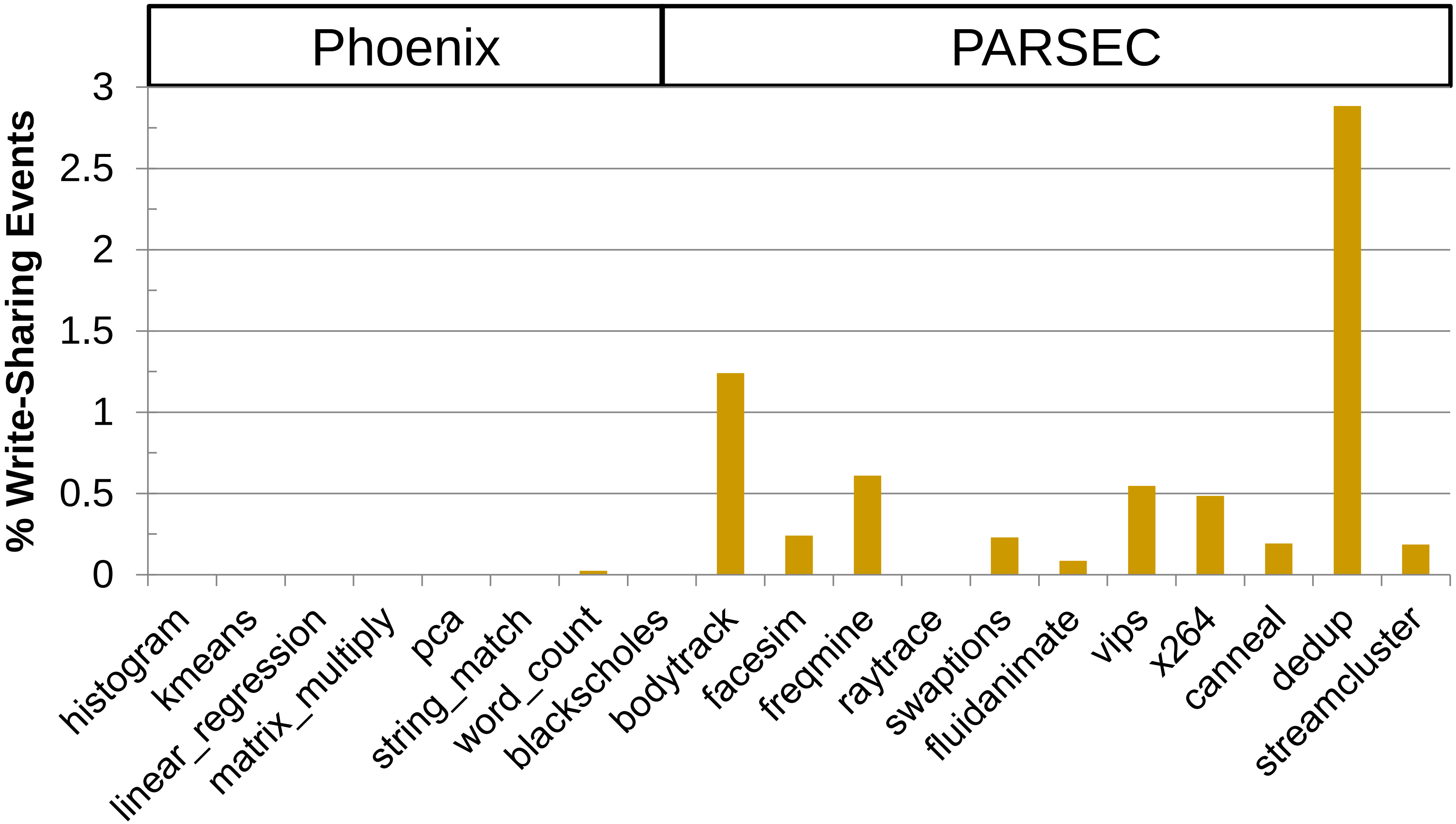
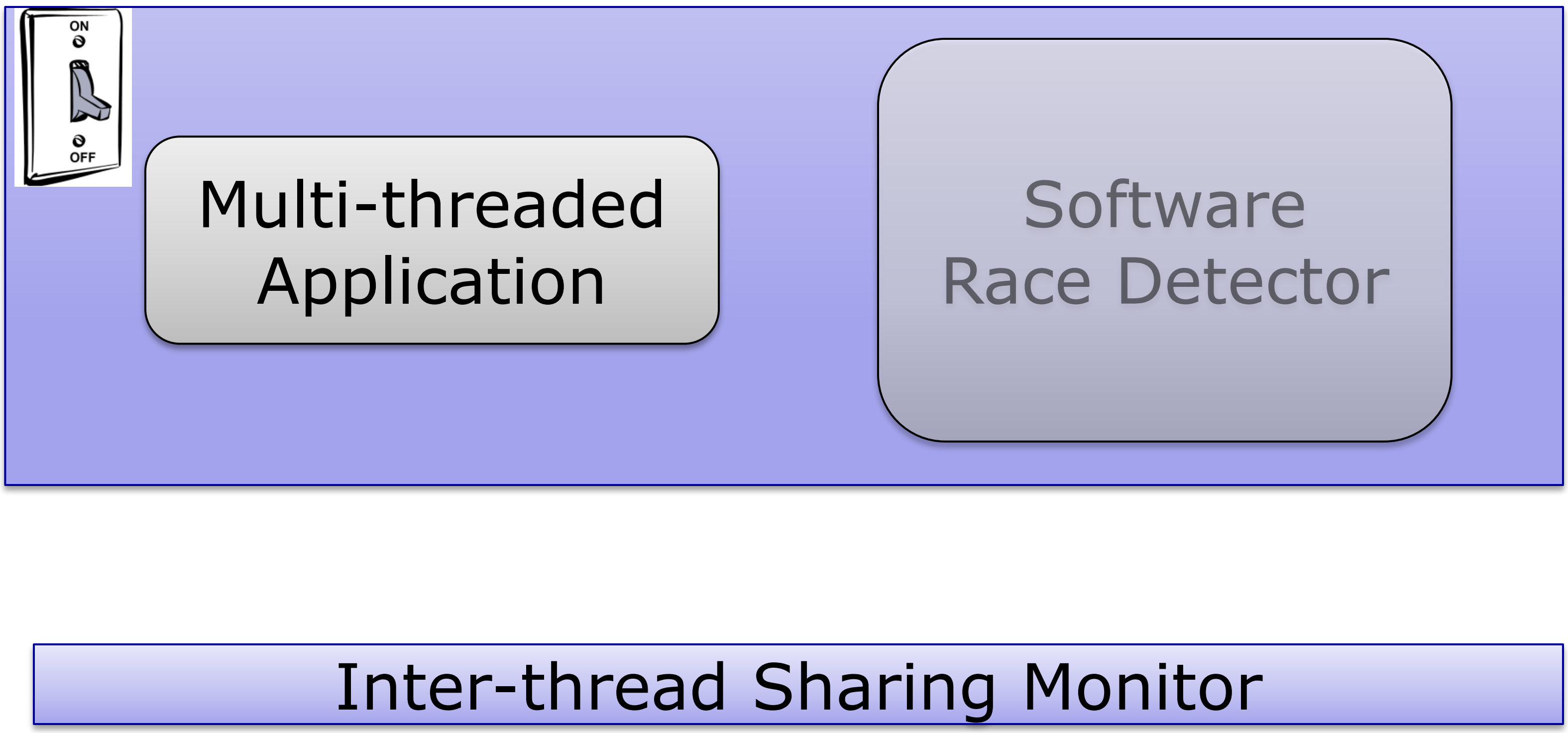


Very Little Inter-Thread Sharing



Use Demand-Driven Analysis!



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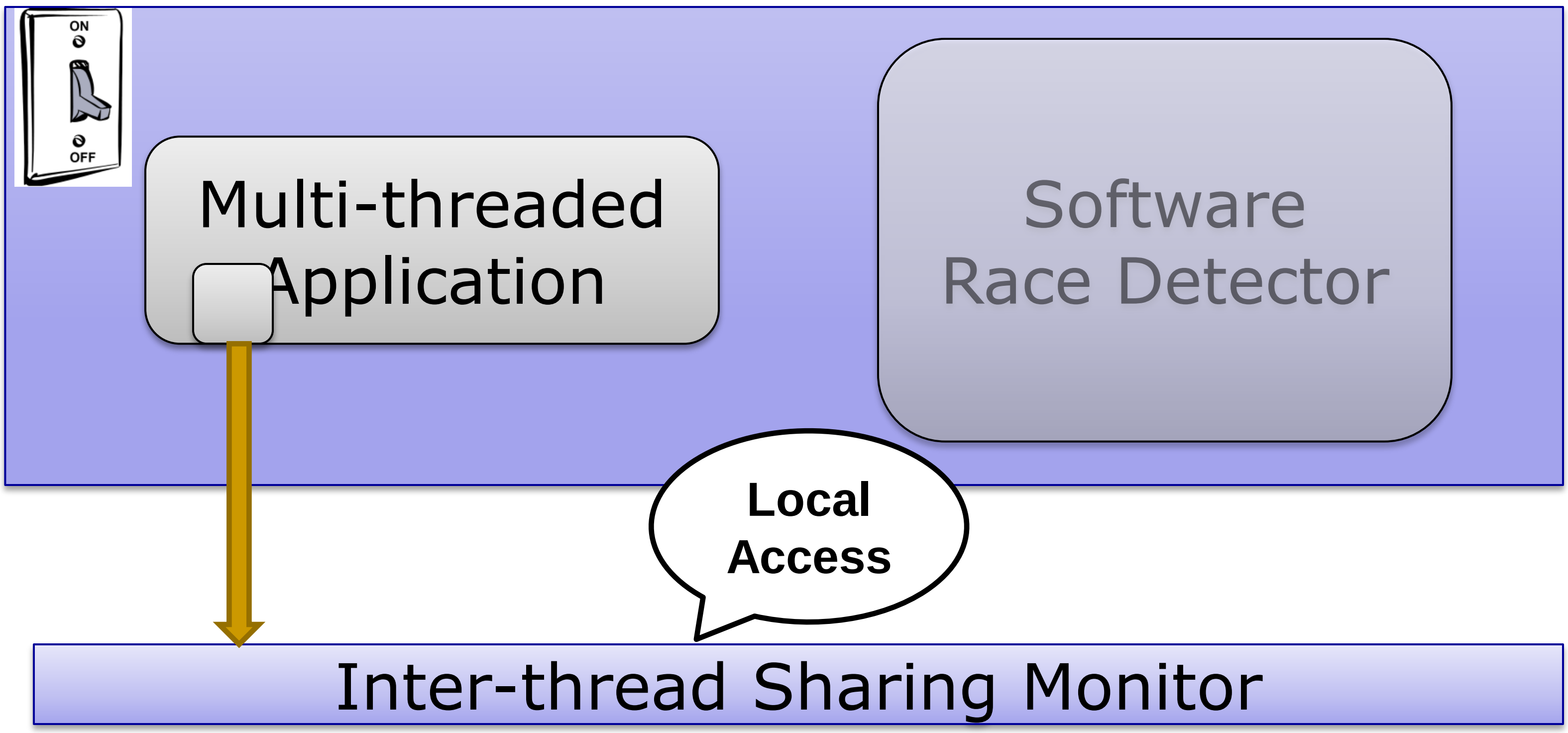

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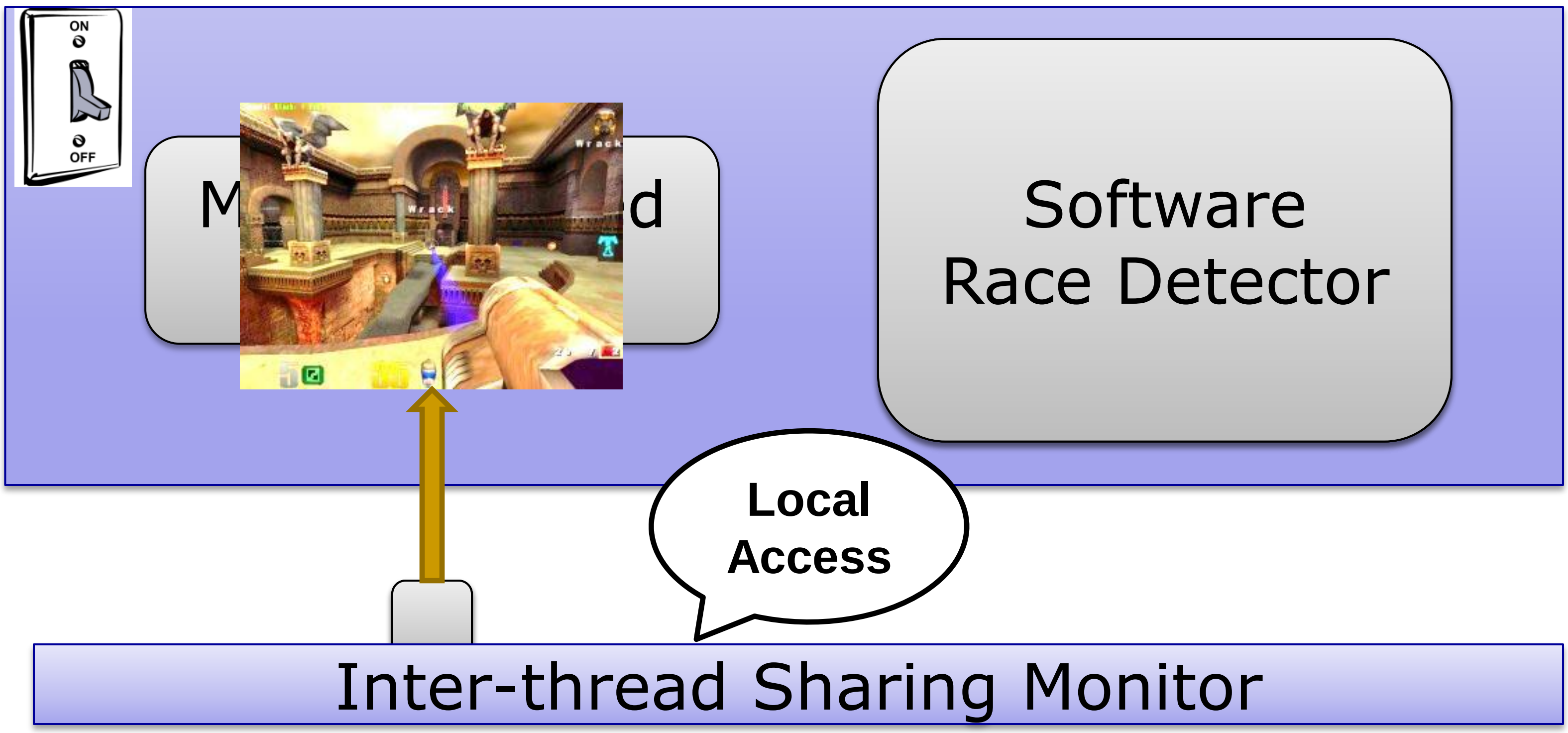

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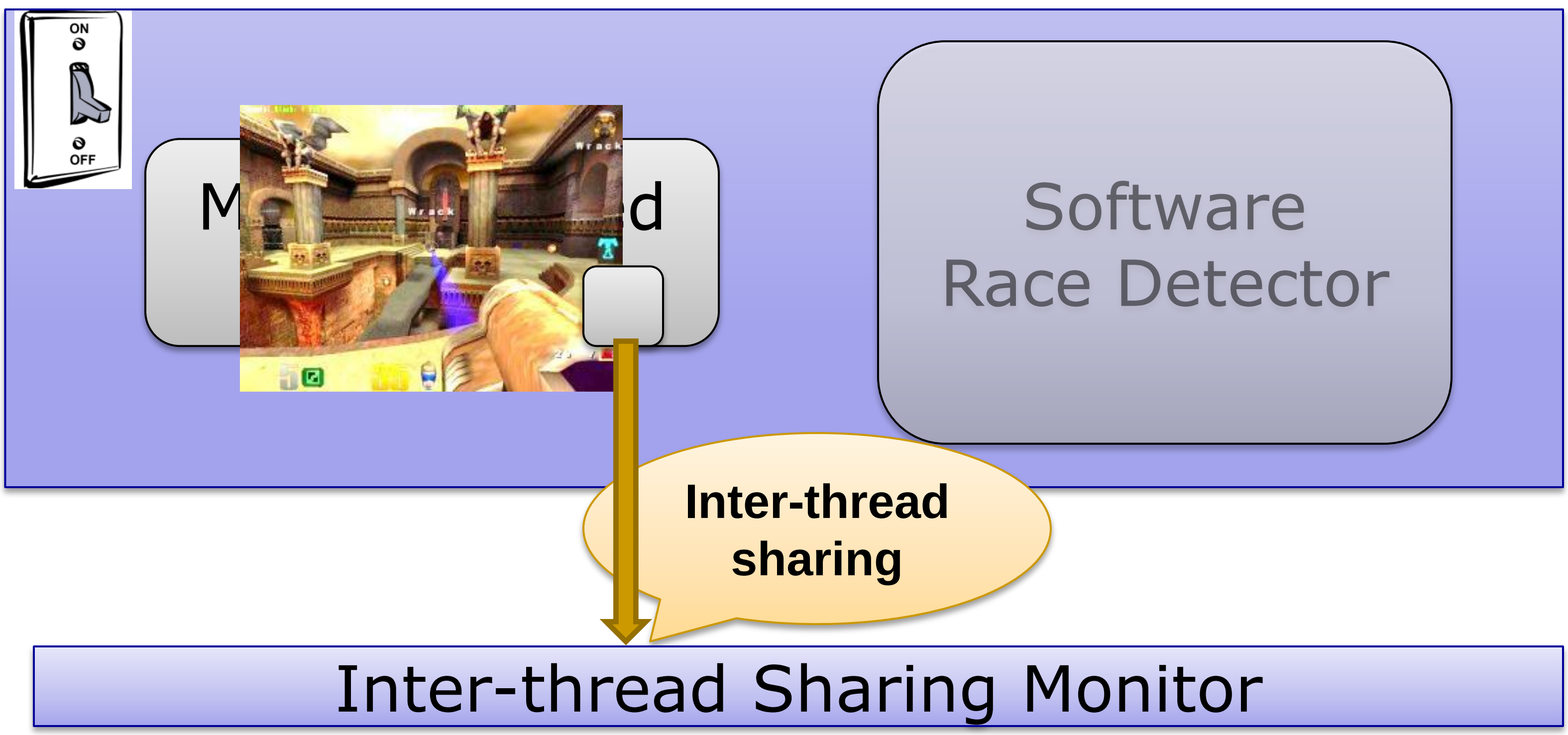

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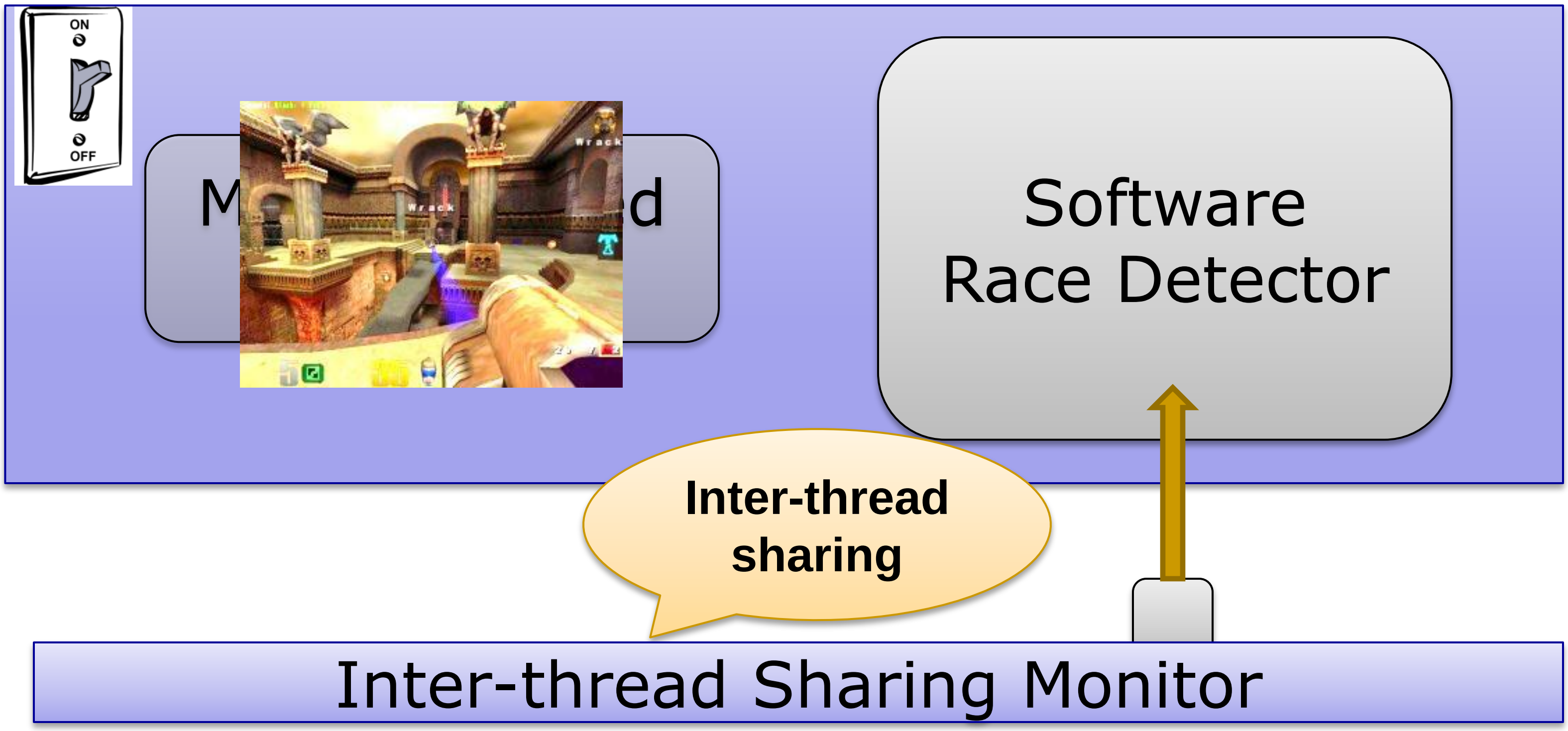

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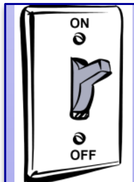
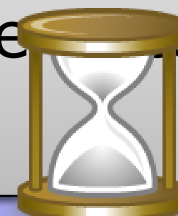


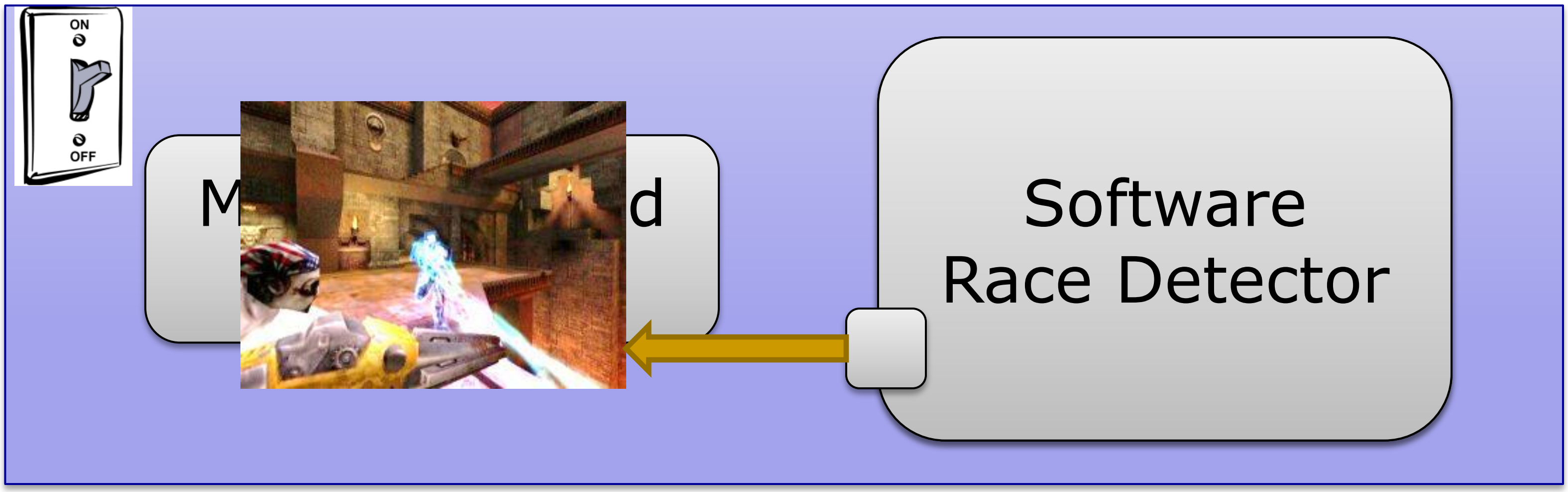
M d

Software
Race ector



Inter-thread Sharing Monitor

Use Demand-Driven Analysis!



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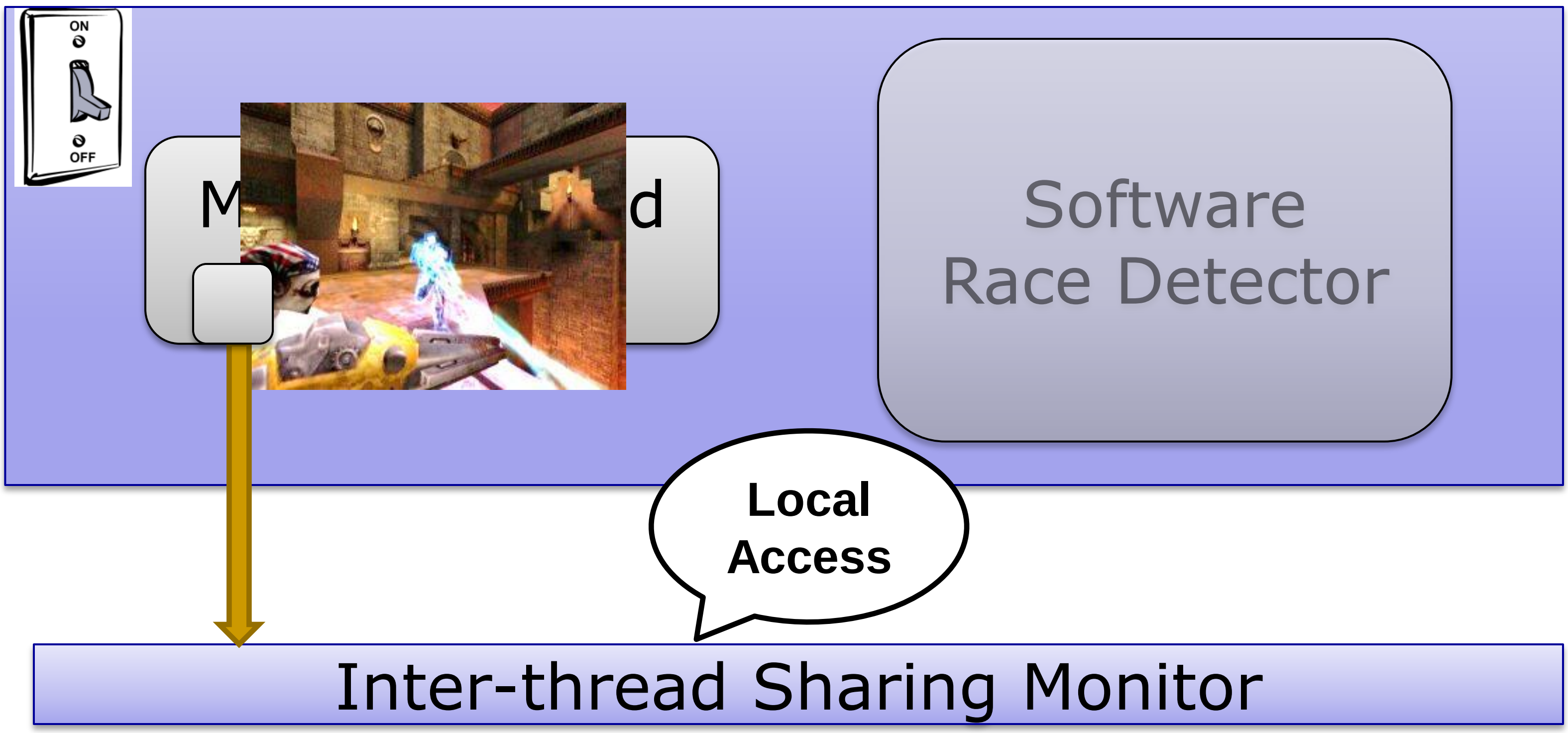
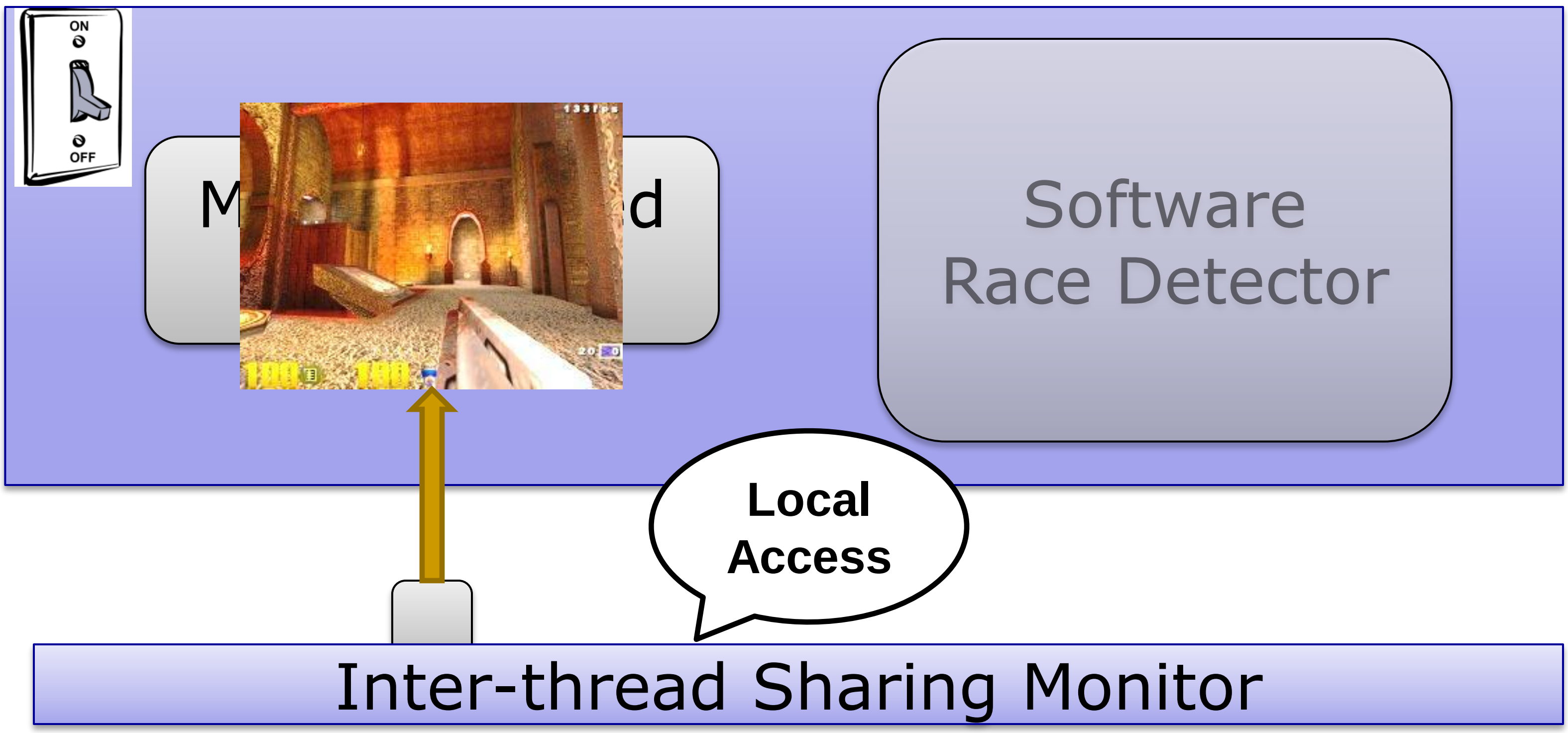


Use Demand-Driven Analysis!



Finding Inter-thread Sharing

- Virtual Memory Watchpoints?

Finding Inter-thread Sharing

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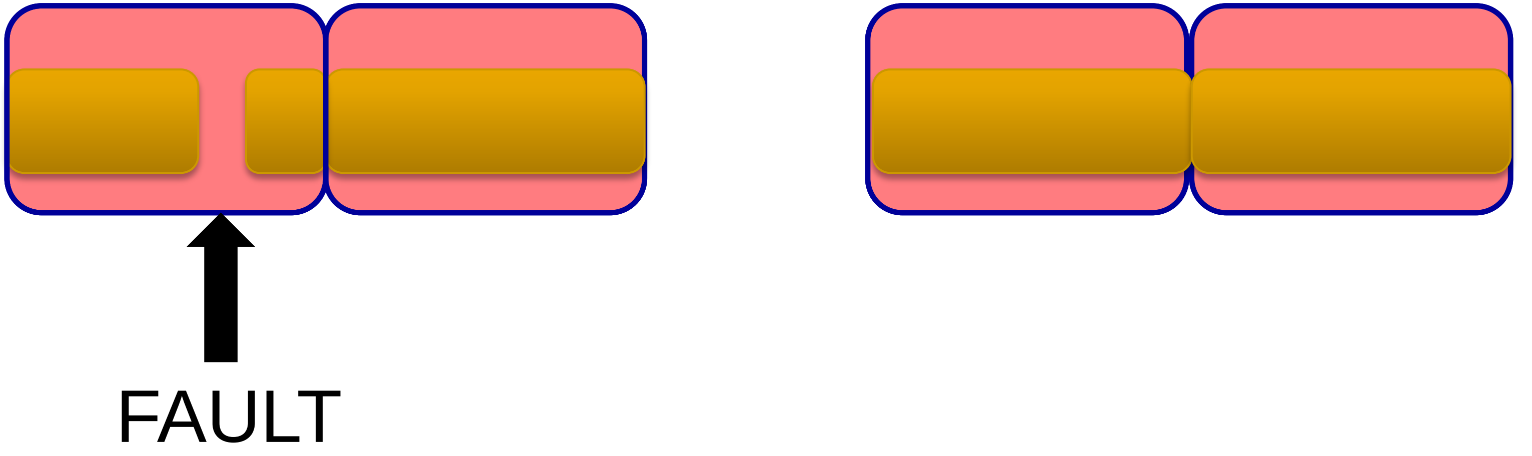

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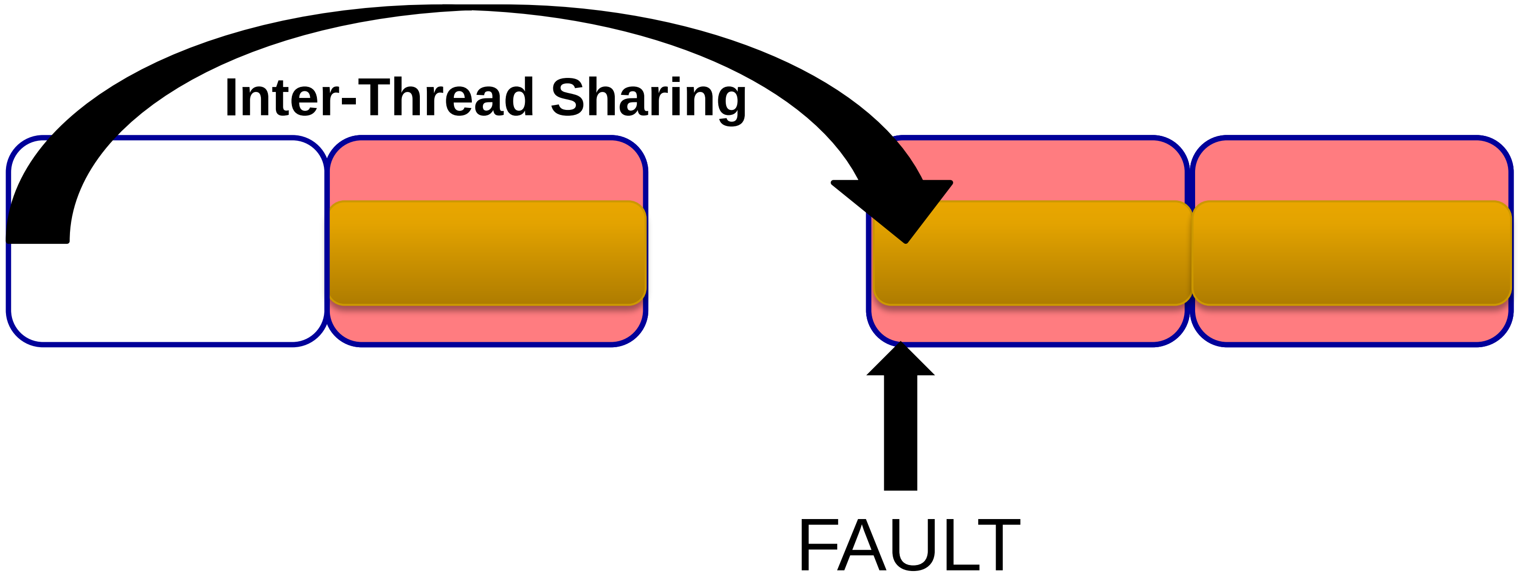

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  – ~100% of accesses cause page faults

Finding Inter-thread Sharing

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- Granularity Gap

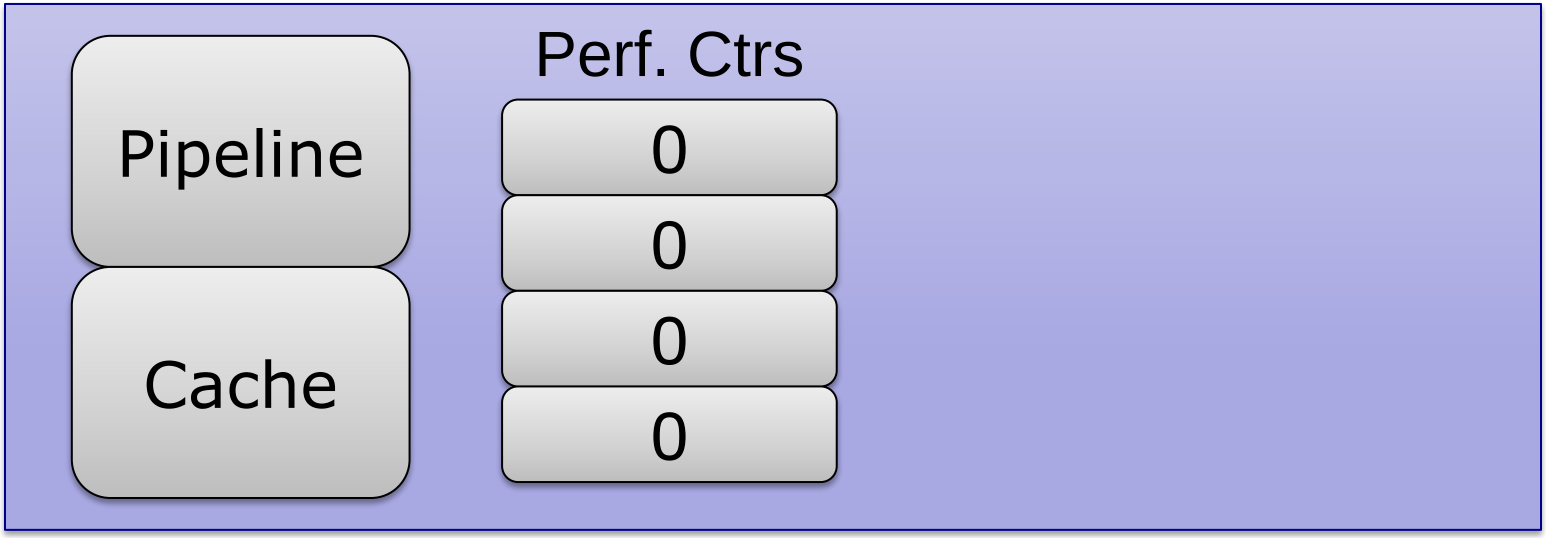
Finding Inter-thread Sharing

- 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

- Hardware Performance Counters



Hardware Sharing Detector

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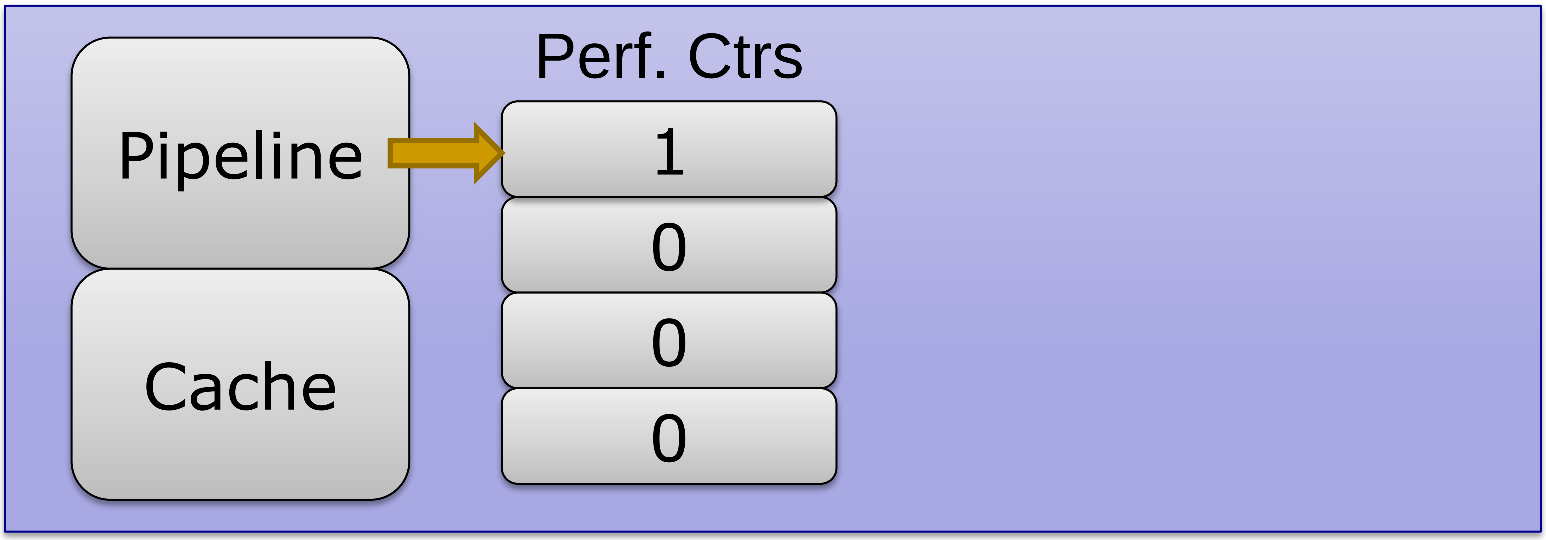

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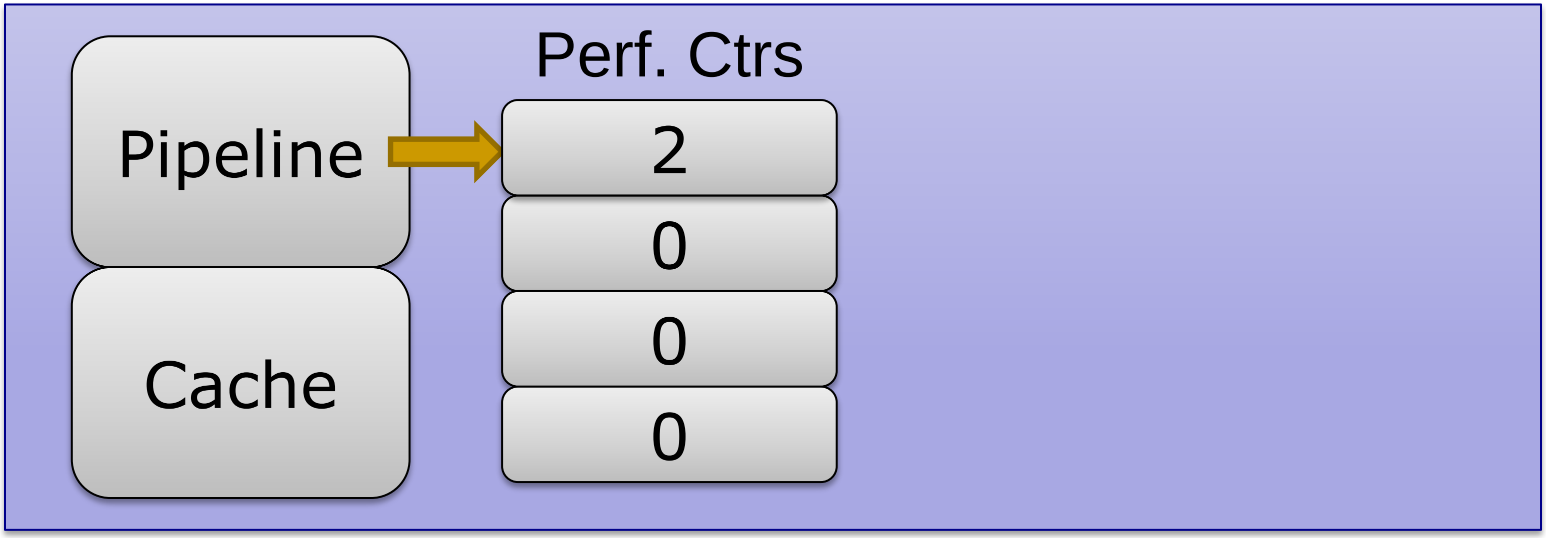

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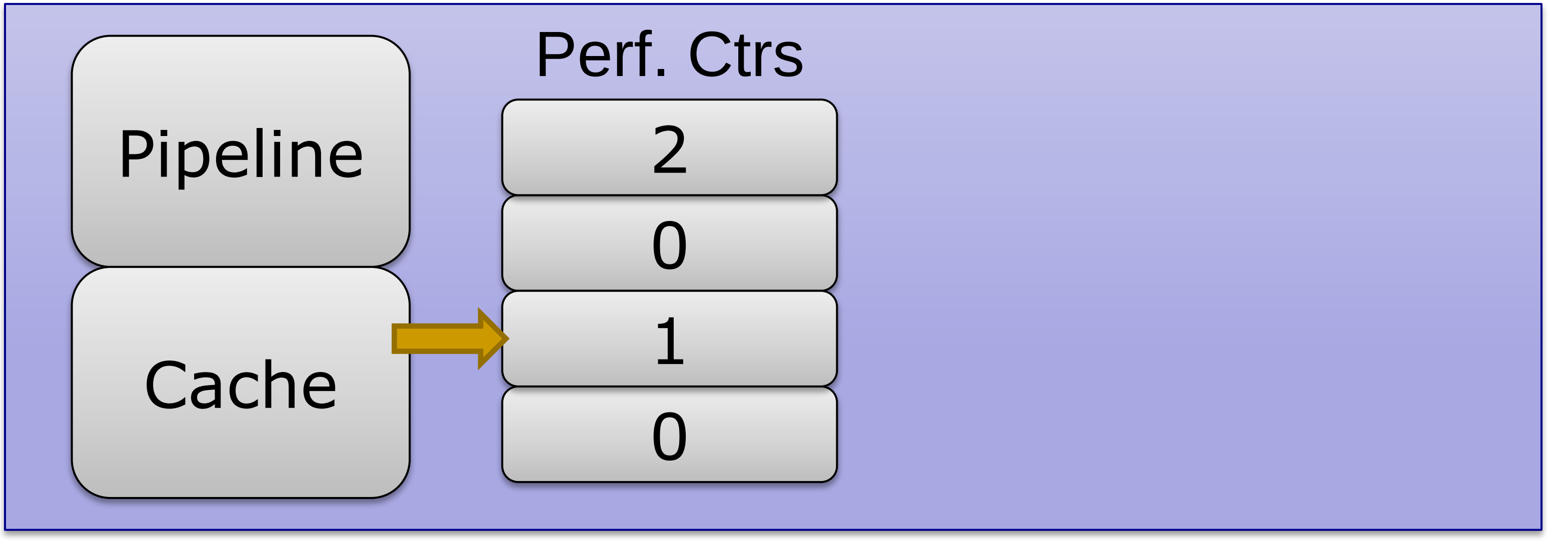

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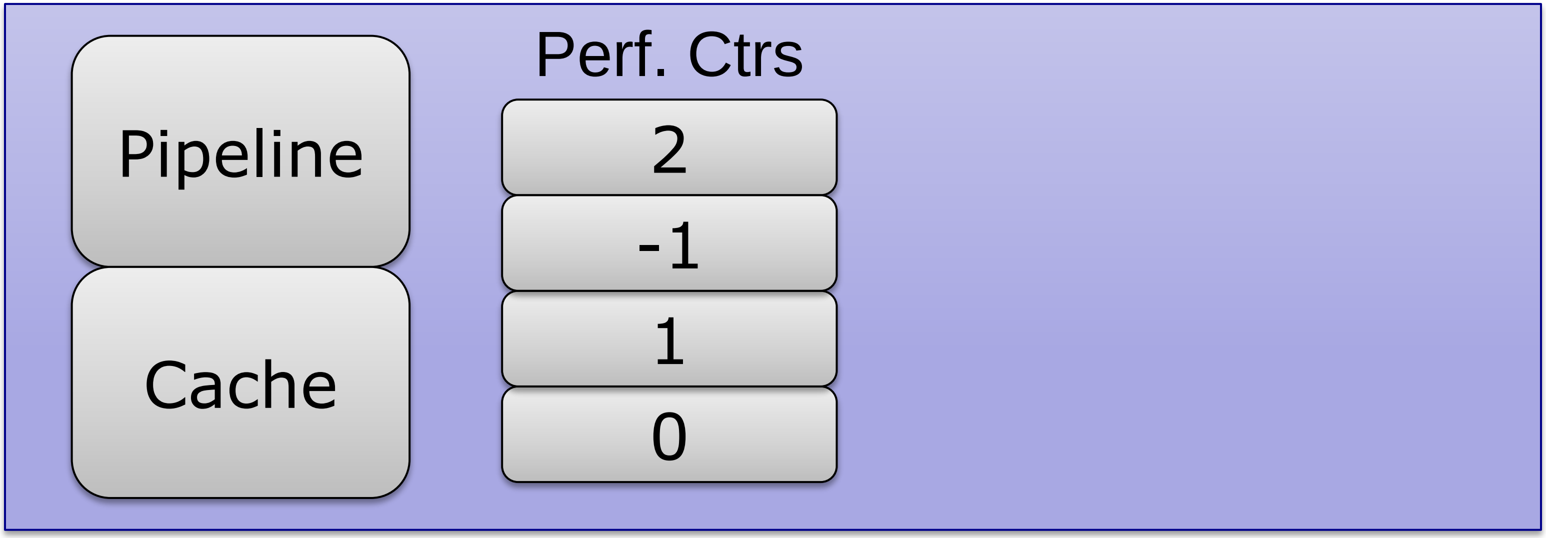

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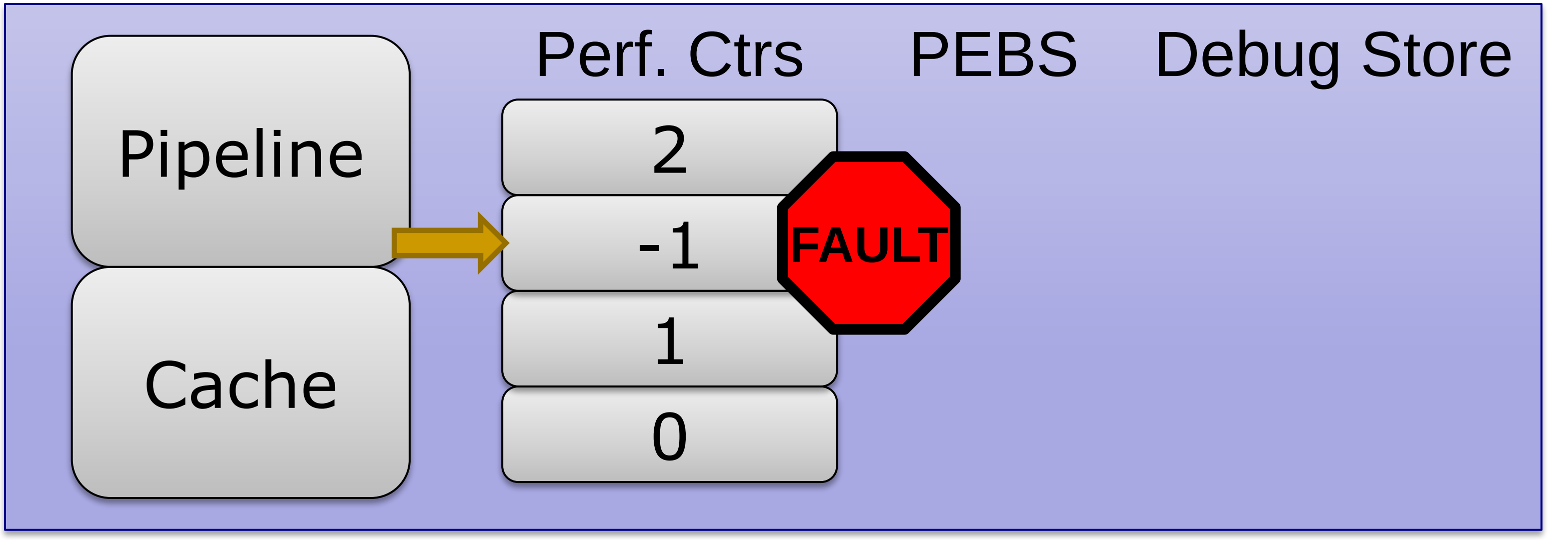

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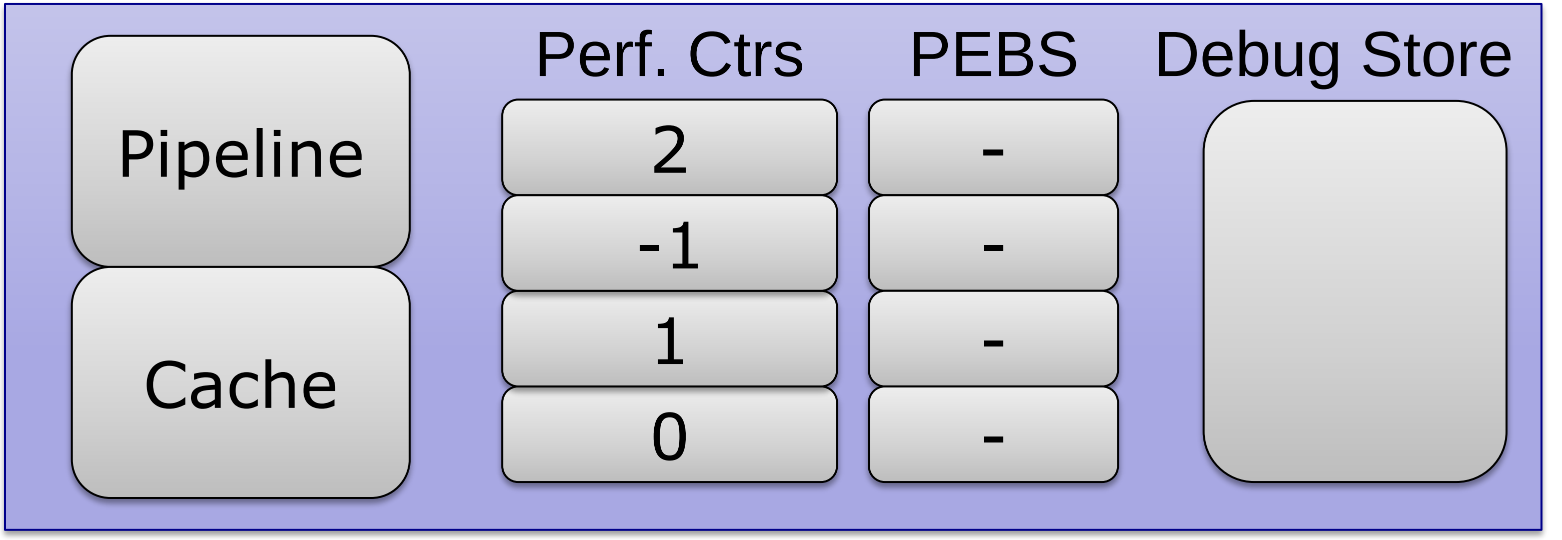

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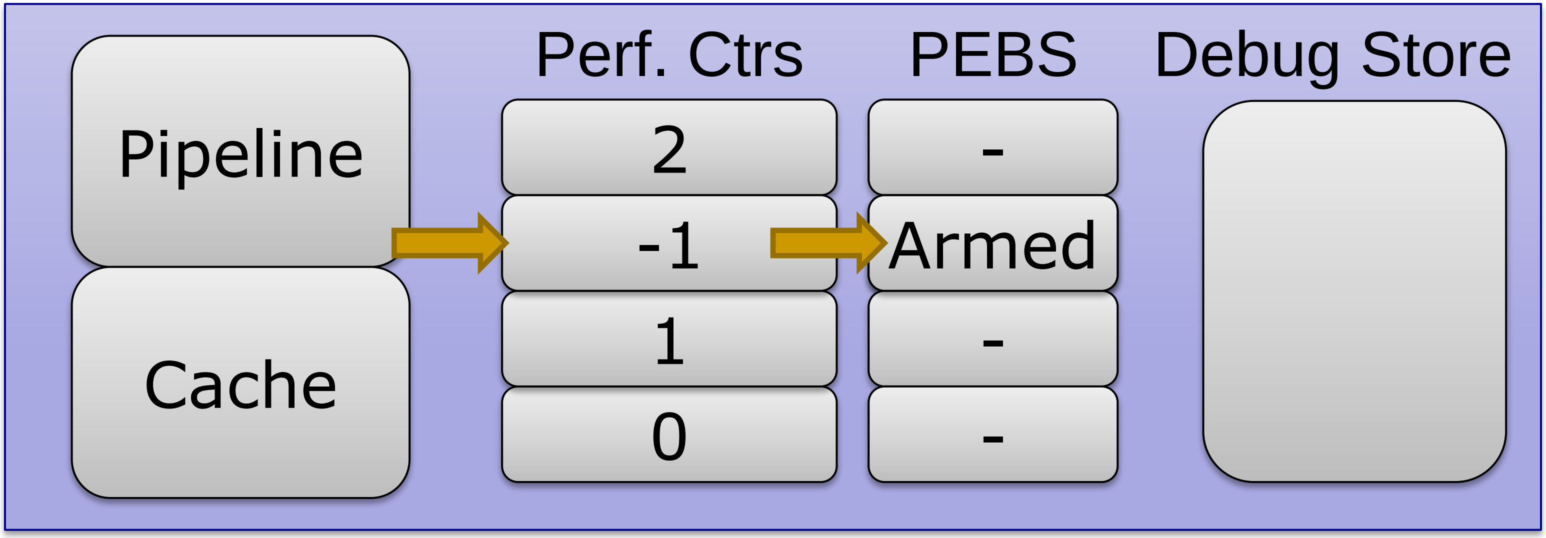

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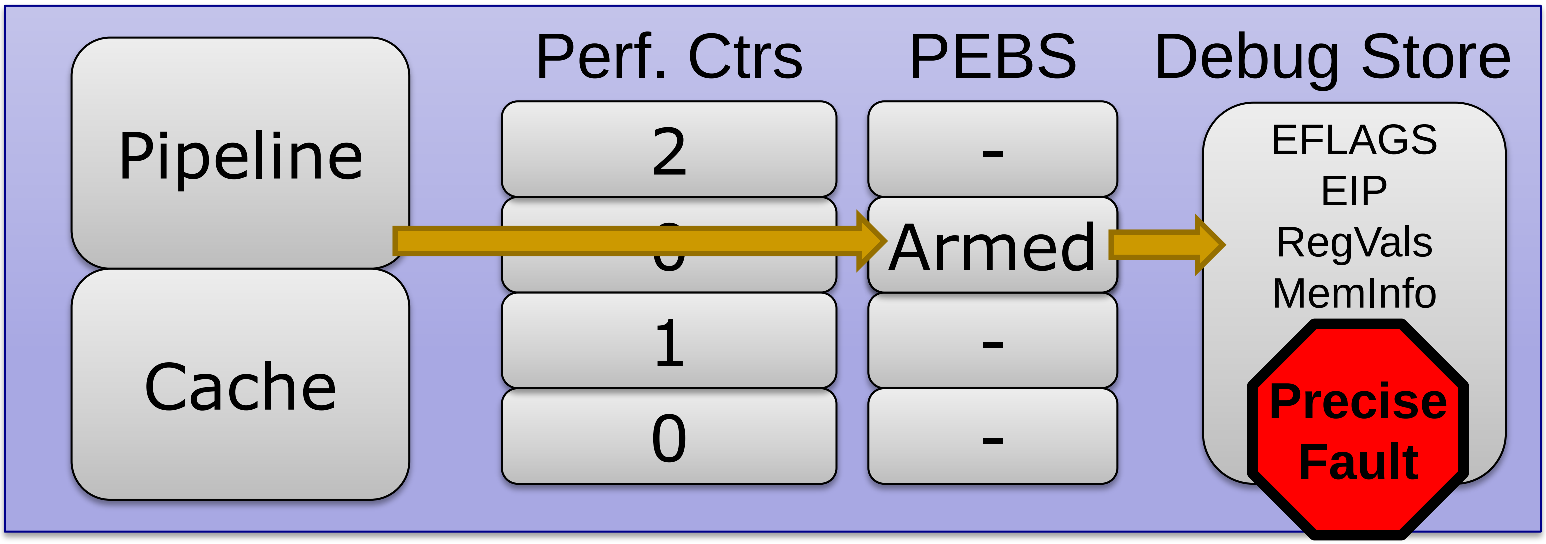

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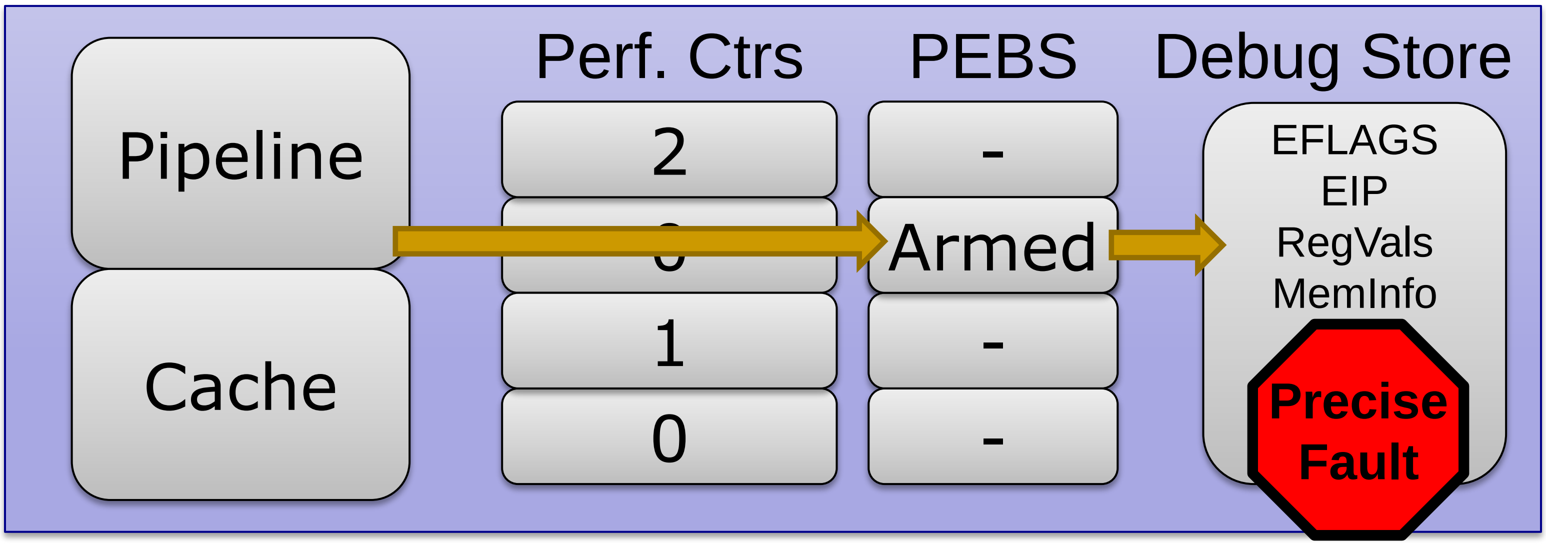
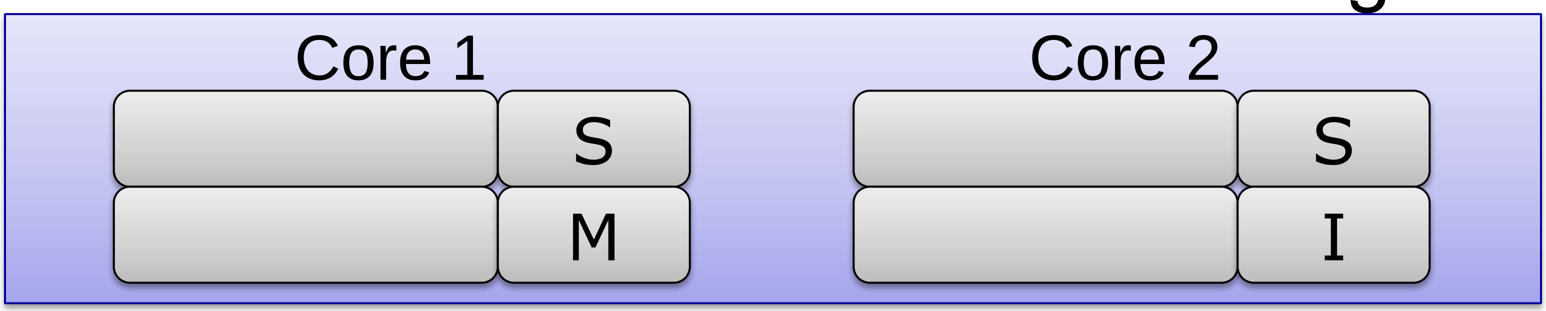


- Intel's HITM event: W→R Data Sharing



Hardware Sharing Detector

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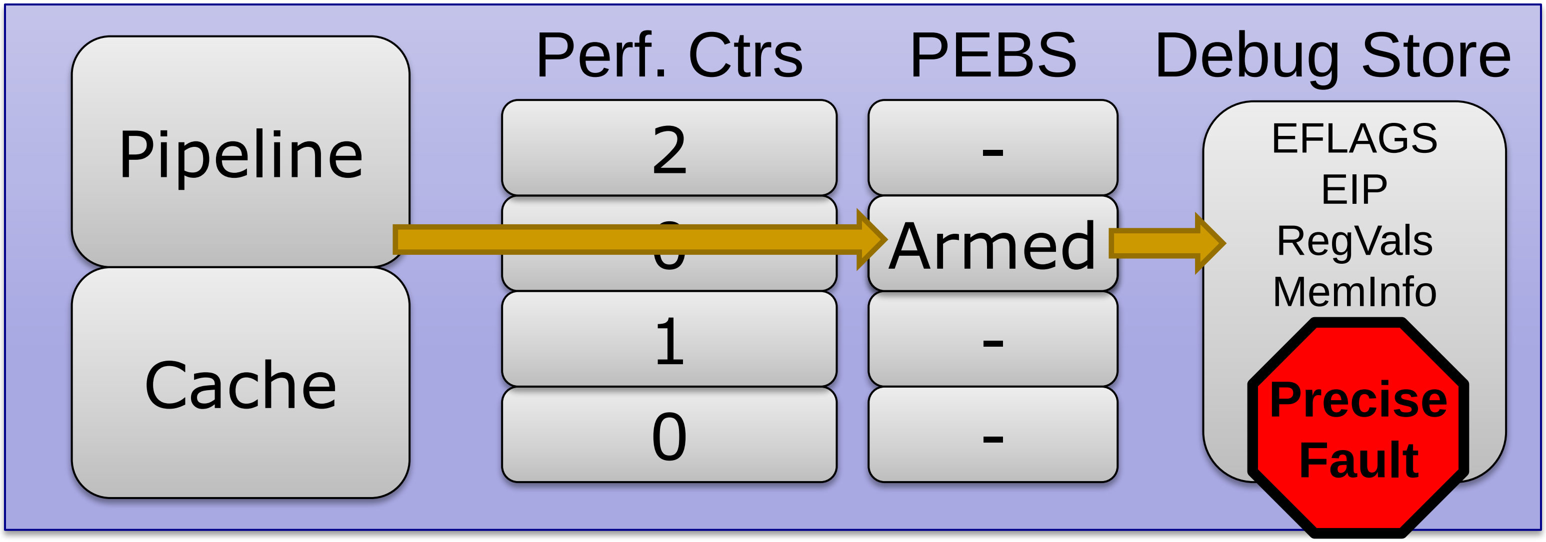

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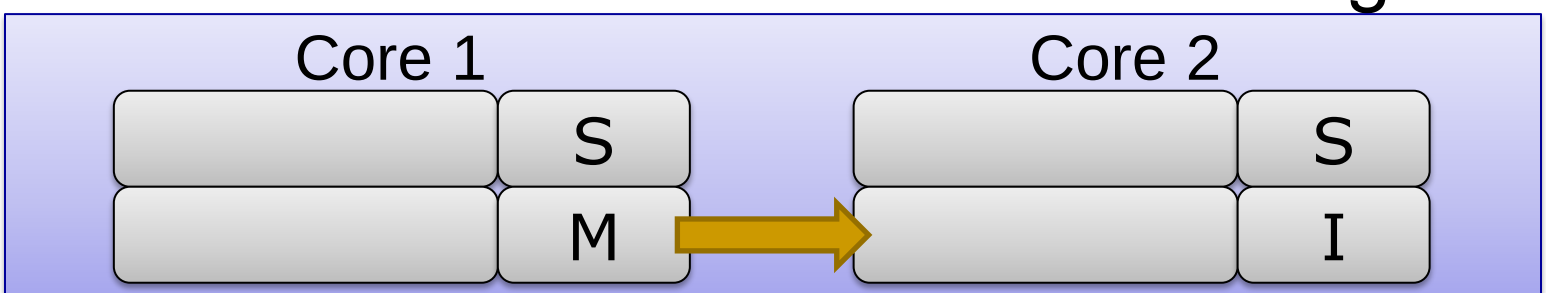

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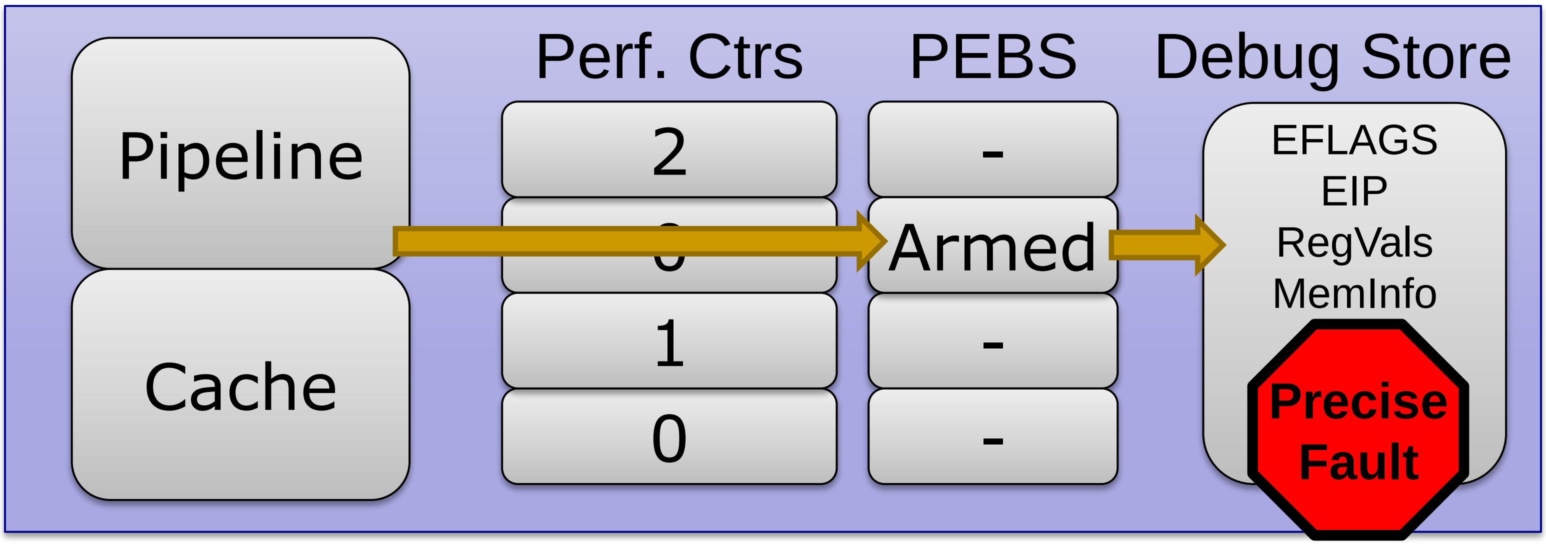

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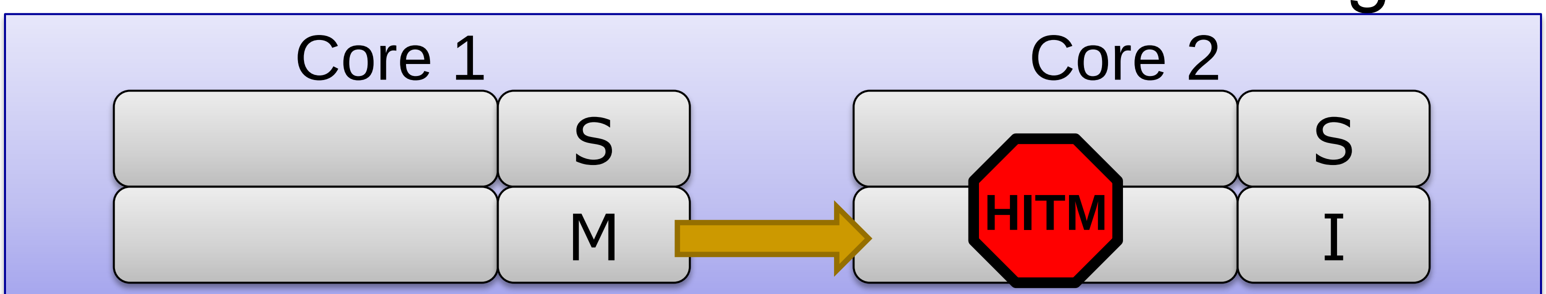


Potential Accuracy & Perf. Problems

- Limitations of Performance Counters
  - HITM only finds W→R Data Sharing
  - Hardware prefetcher events aren't counted

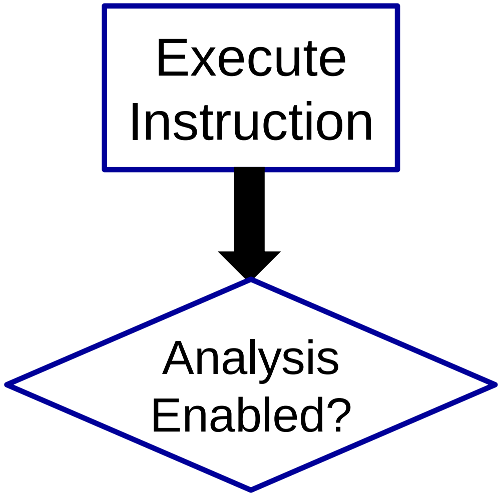
- Limitations of Cache Events
  - SMT sharing can't be counted
  - Cache eviction causes missed events
  - False sharing, etc…

- 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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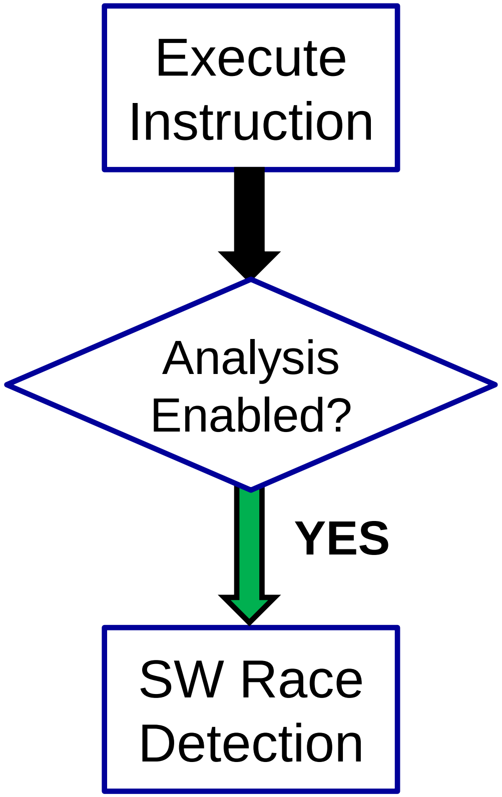

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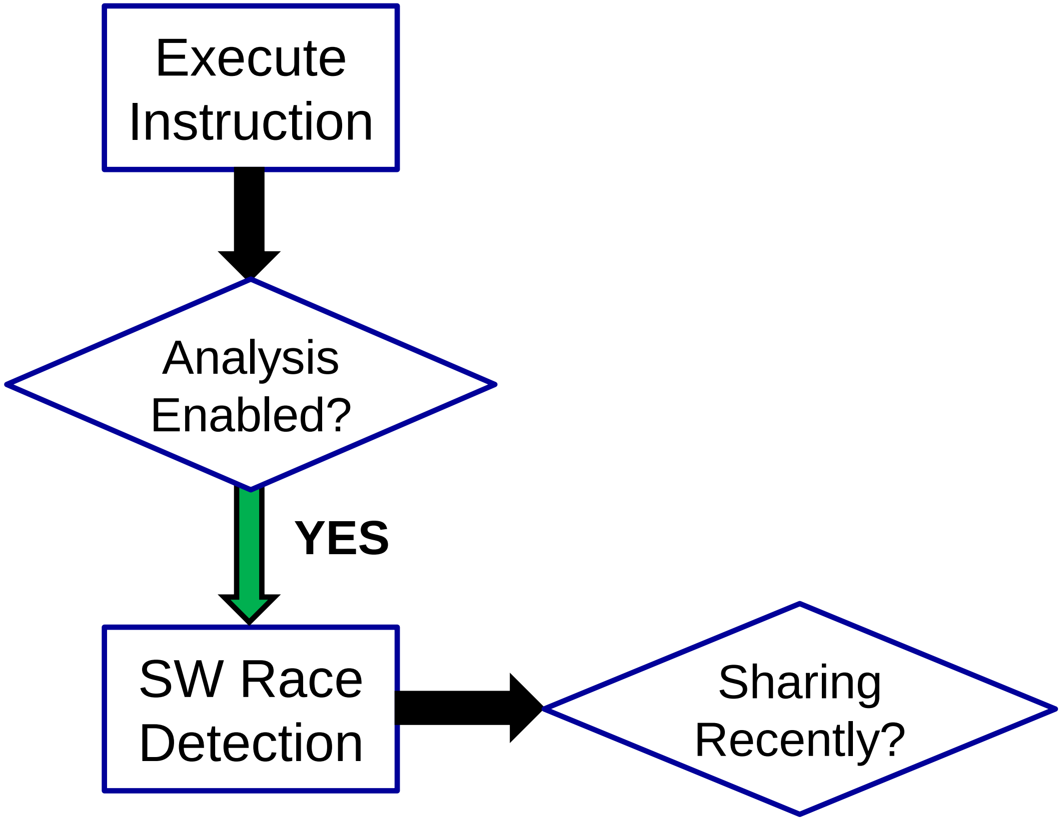

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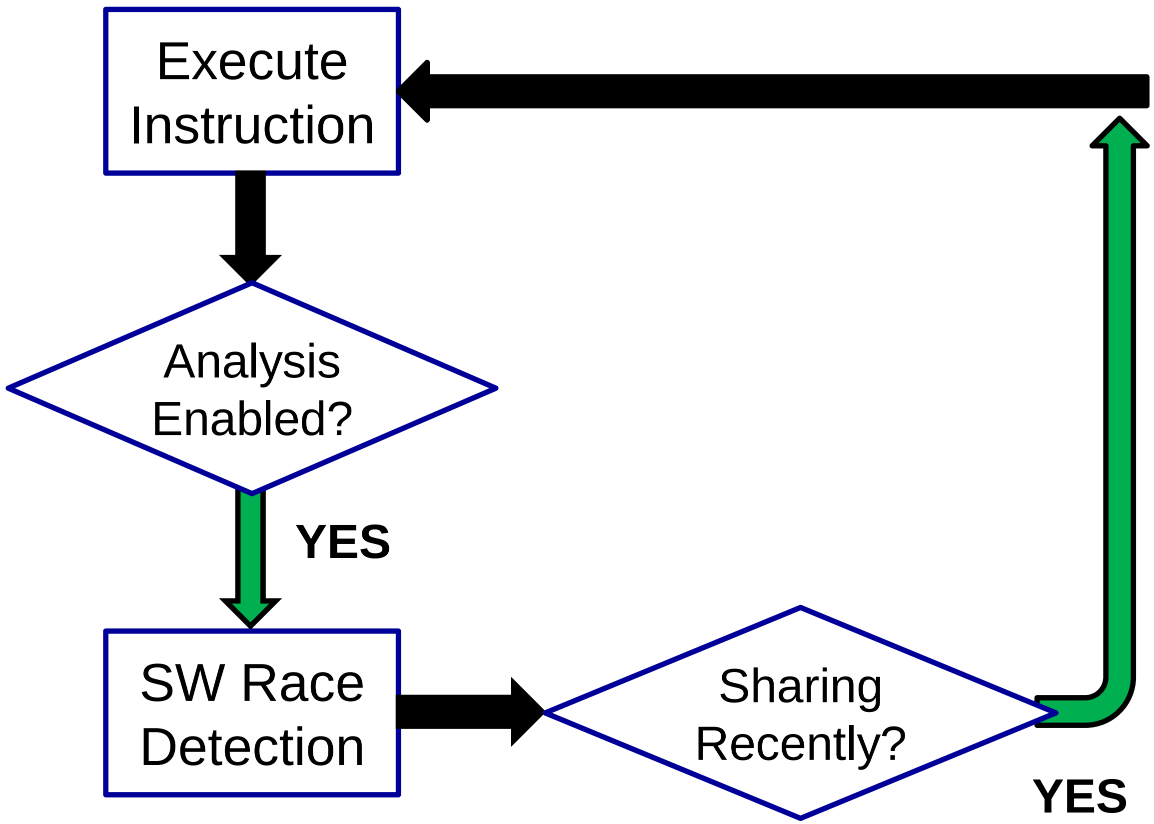

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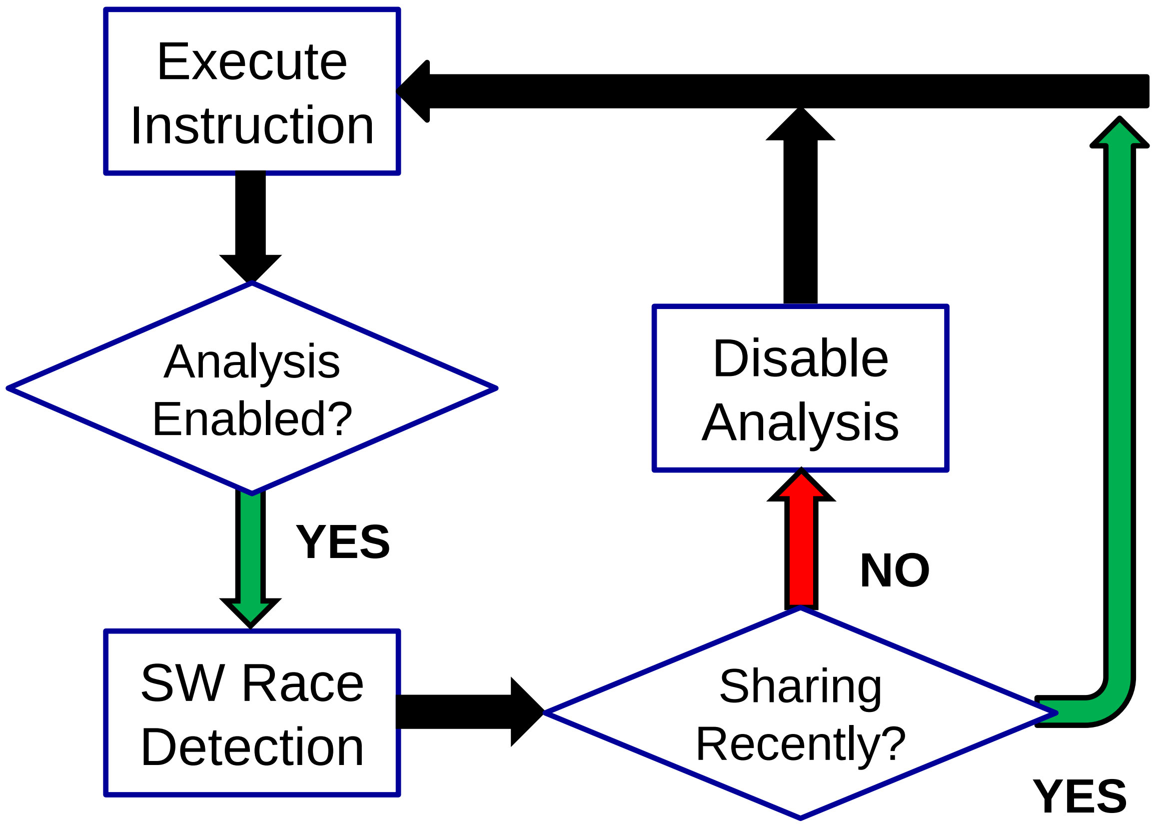

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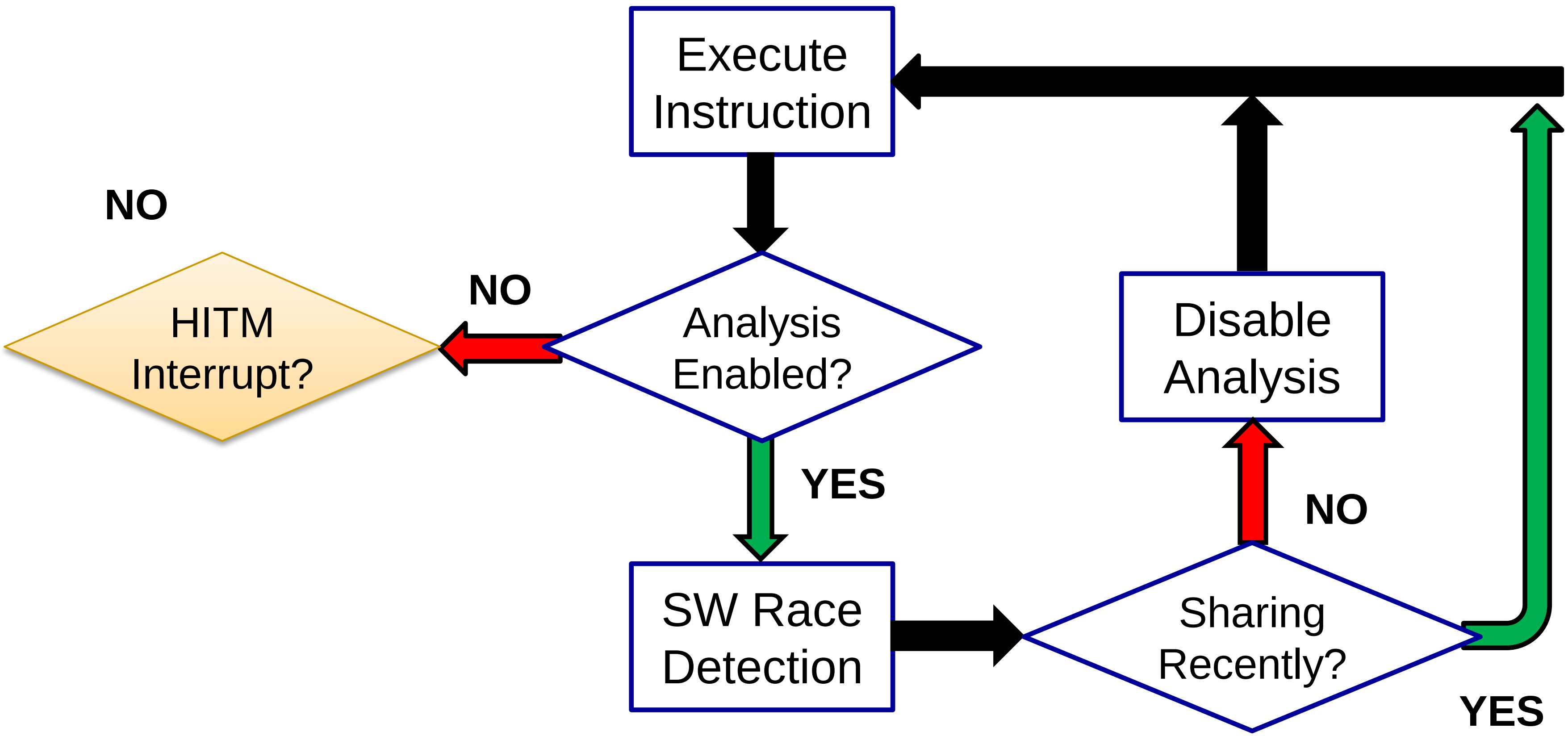

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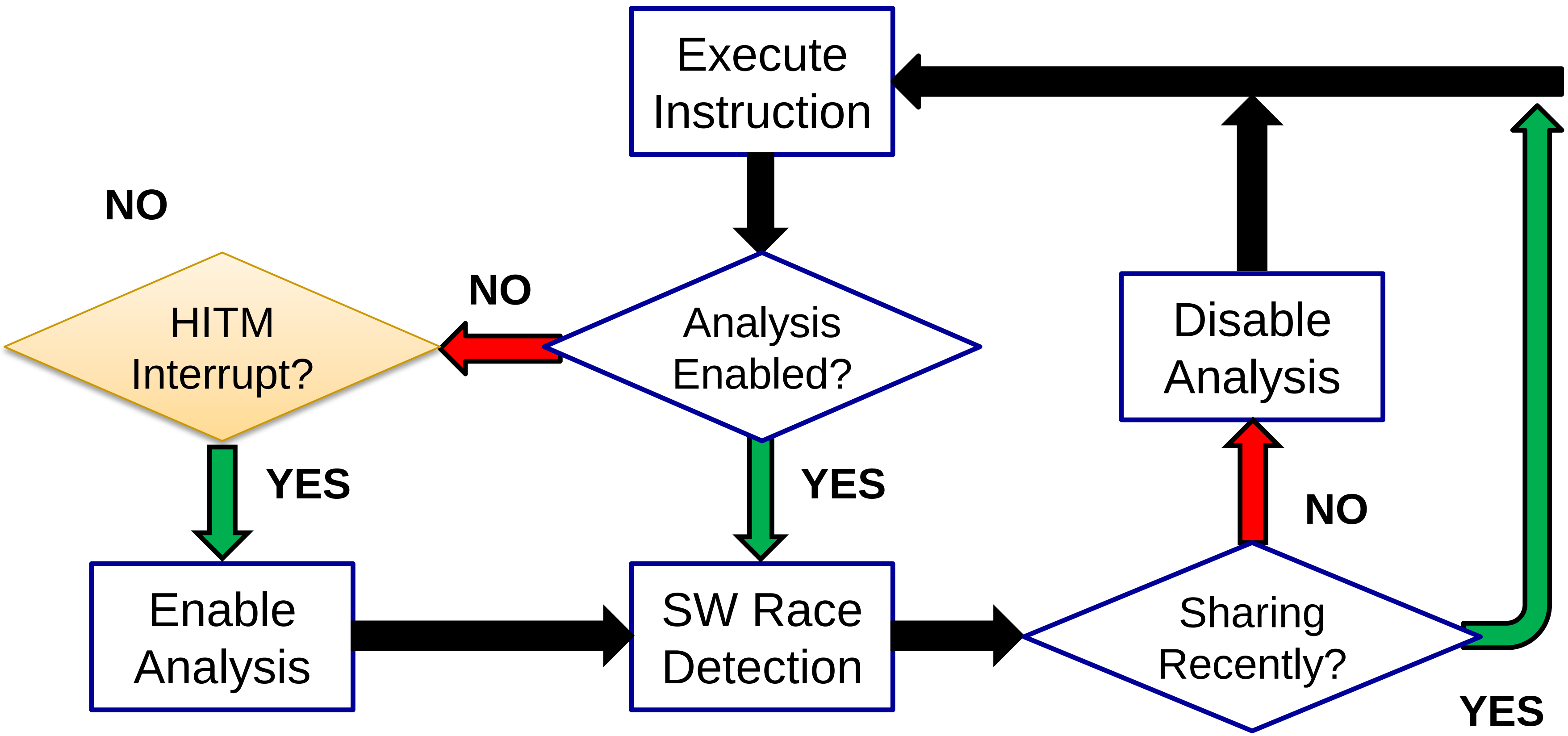

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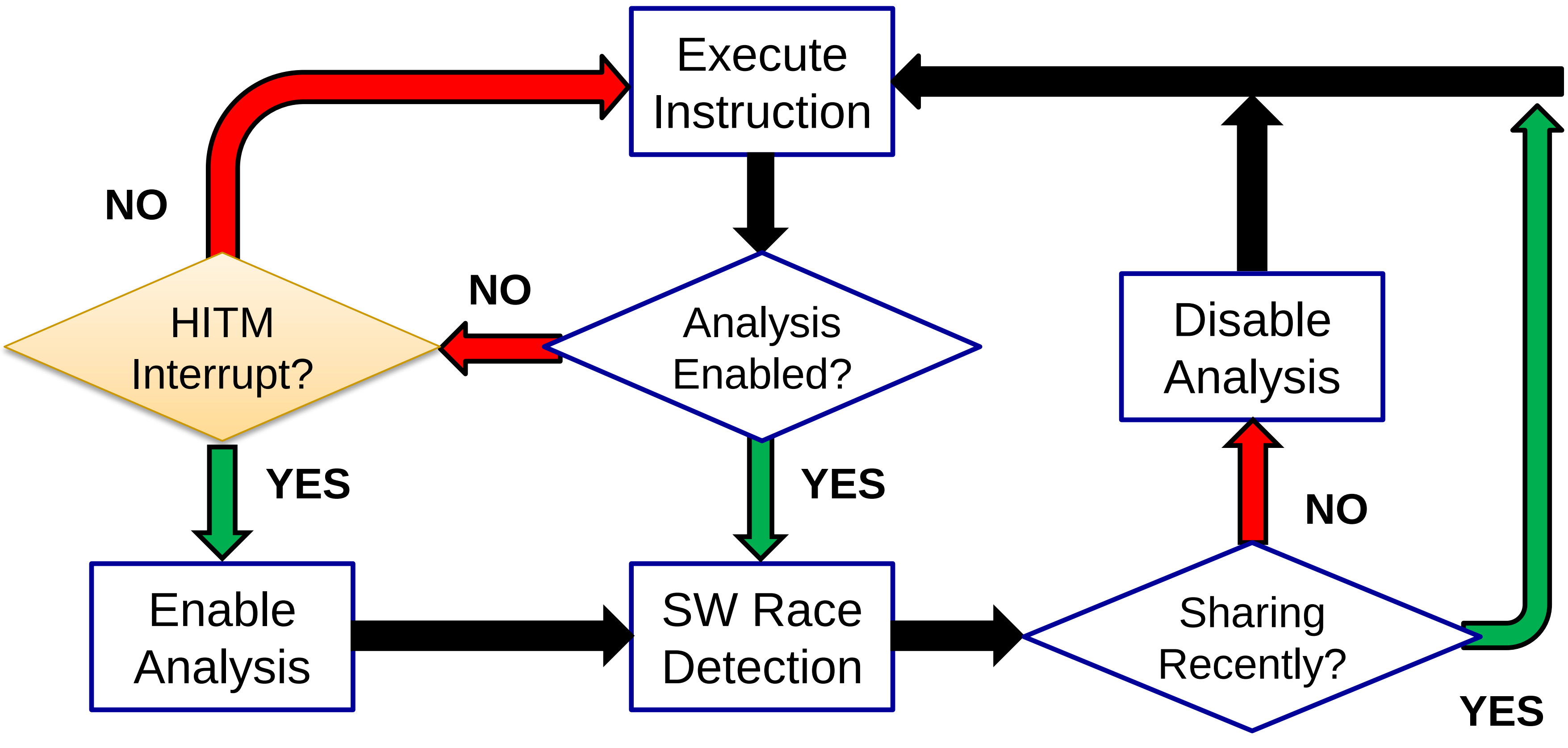
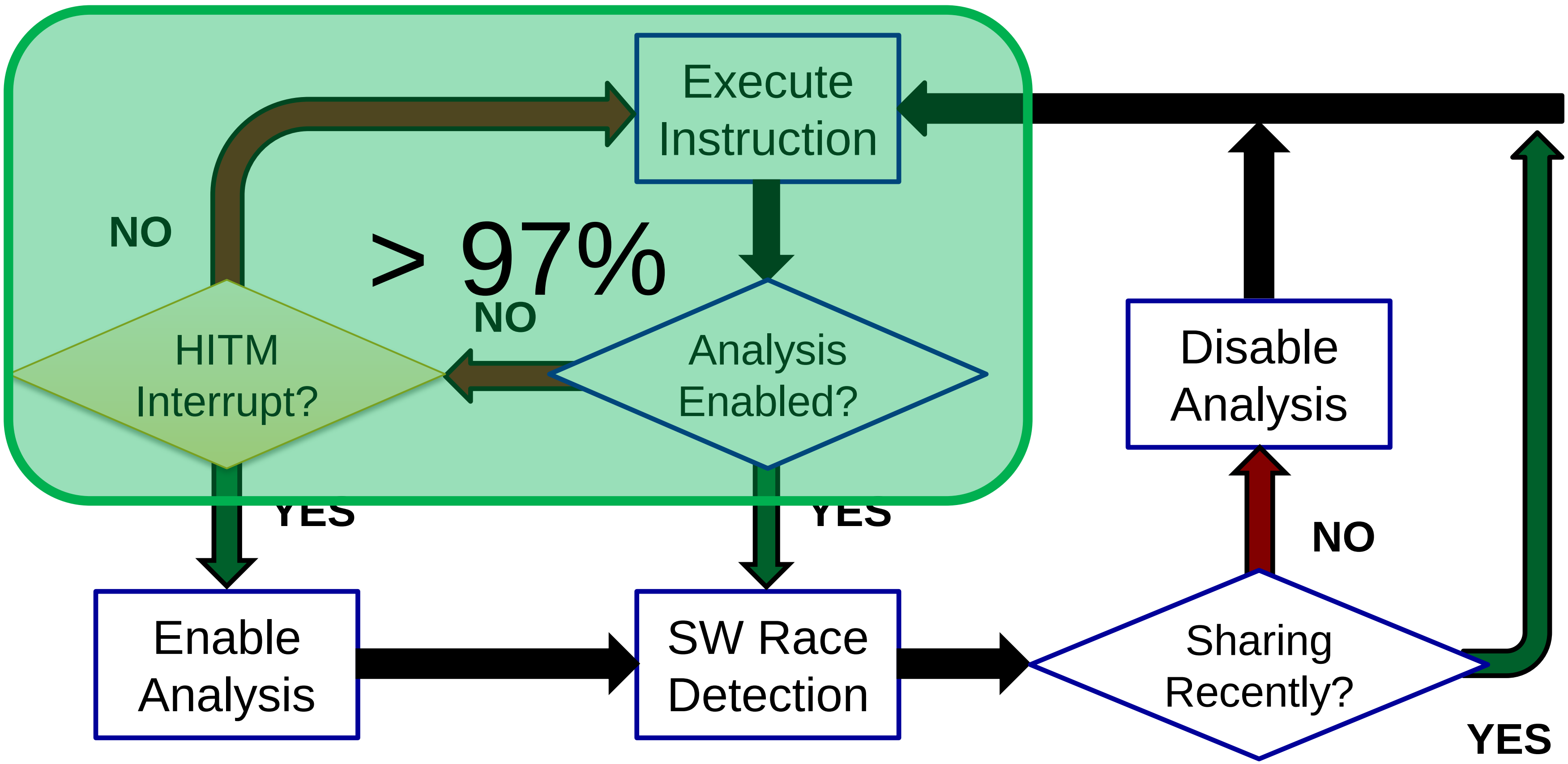
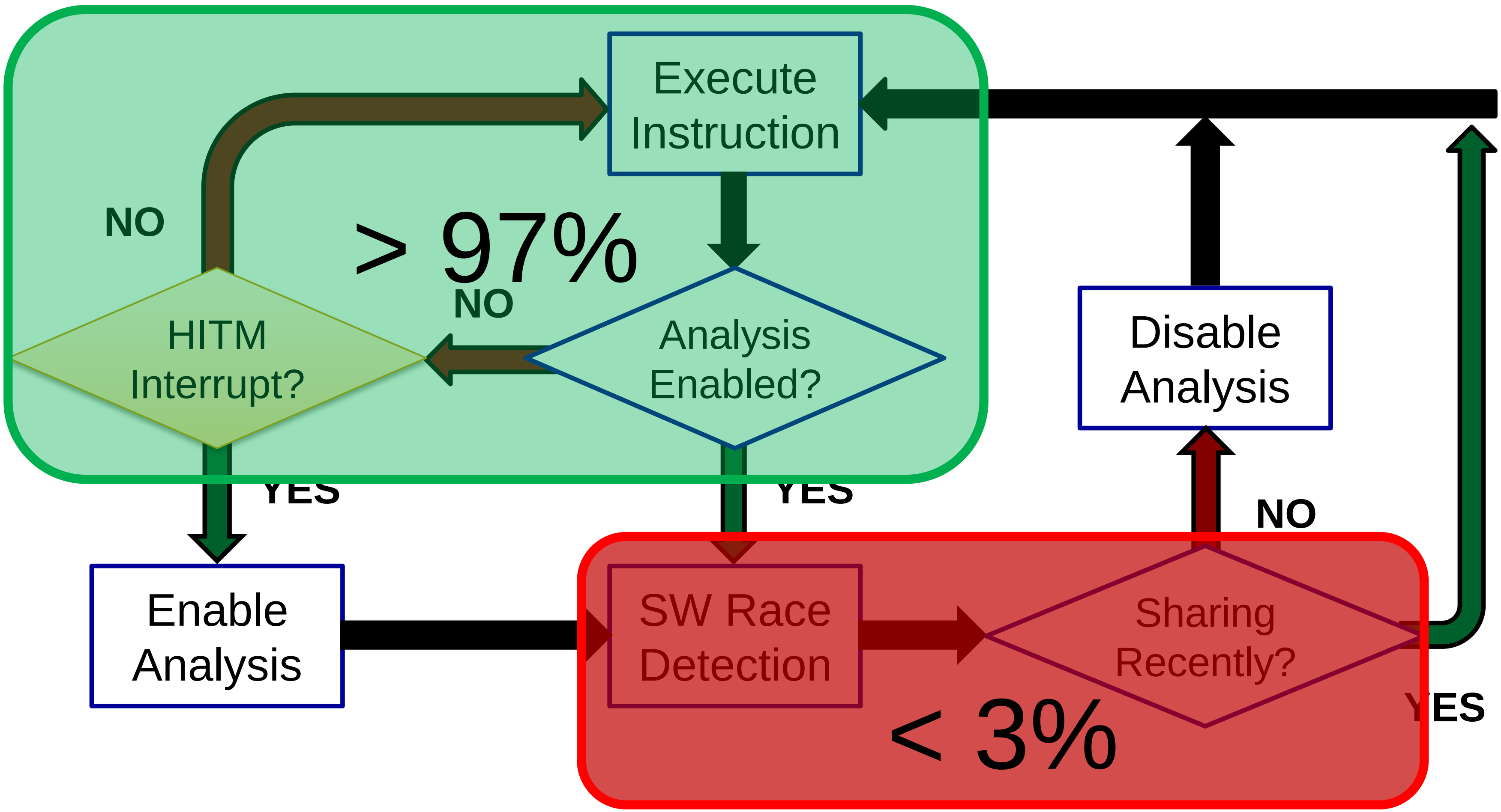


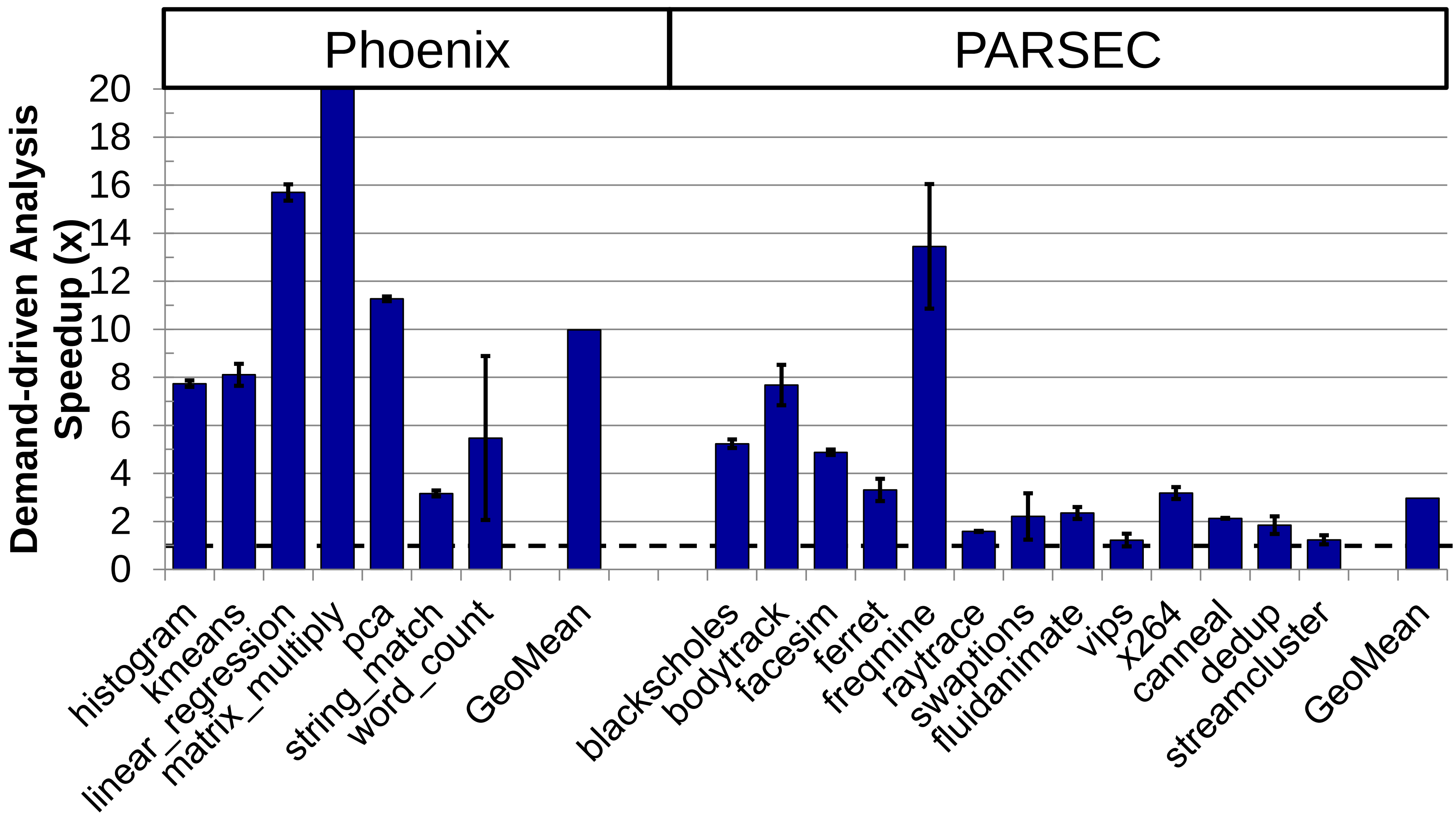
On-Demand Analysis on Real HW



On-Demand Analysis on Real HW



Performance Increases



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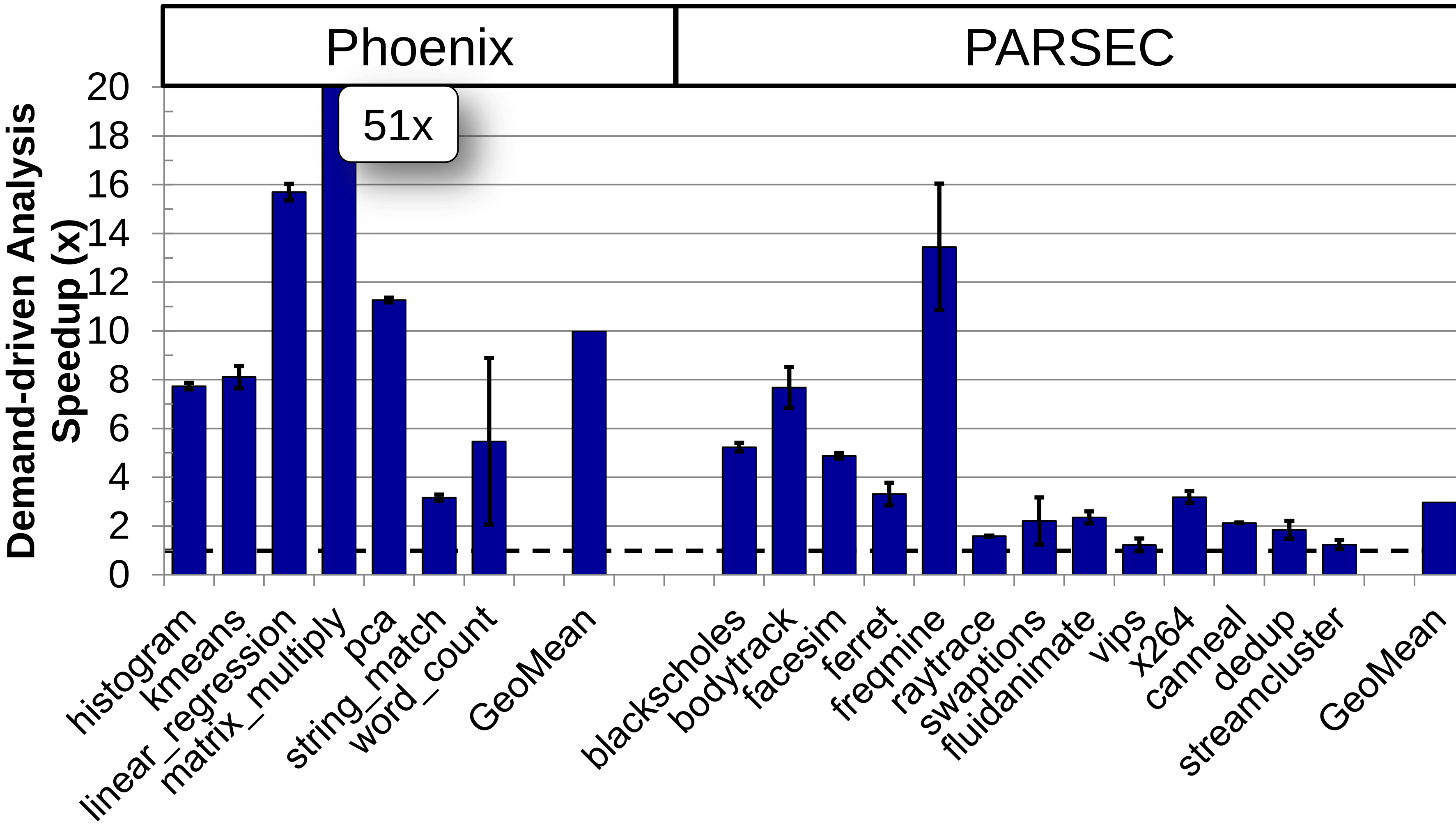
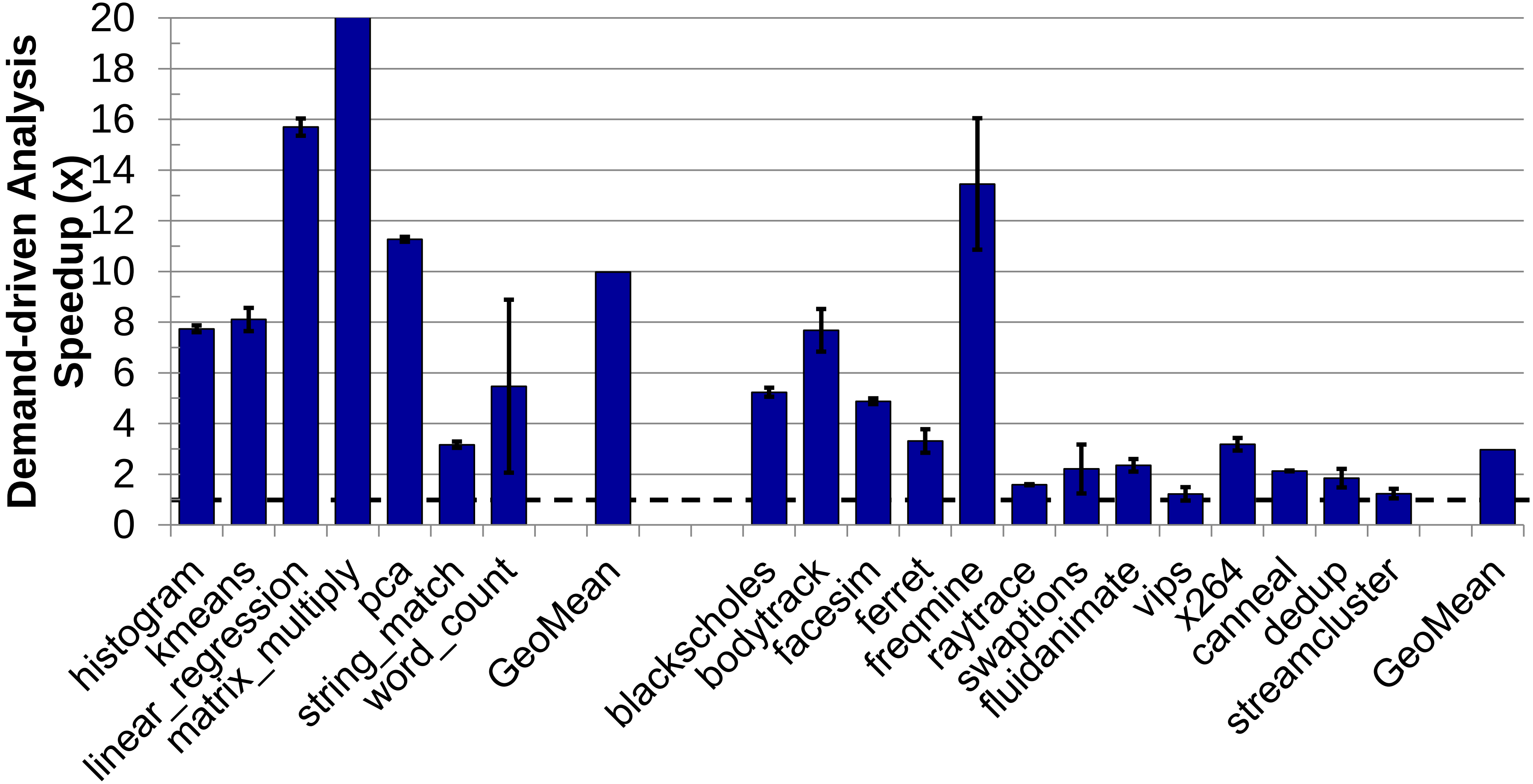


Demand-Driven Analysis Accuracy



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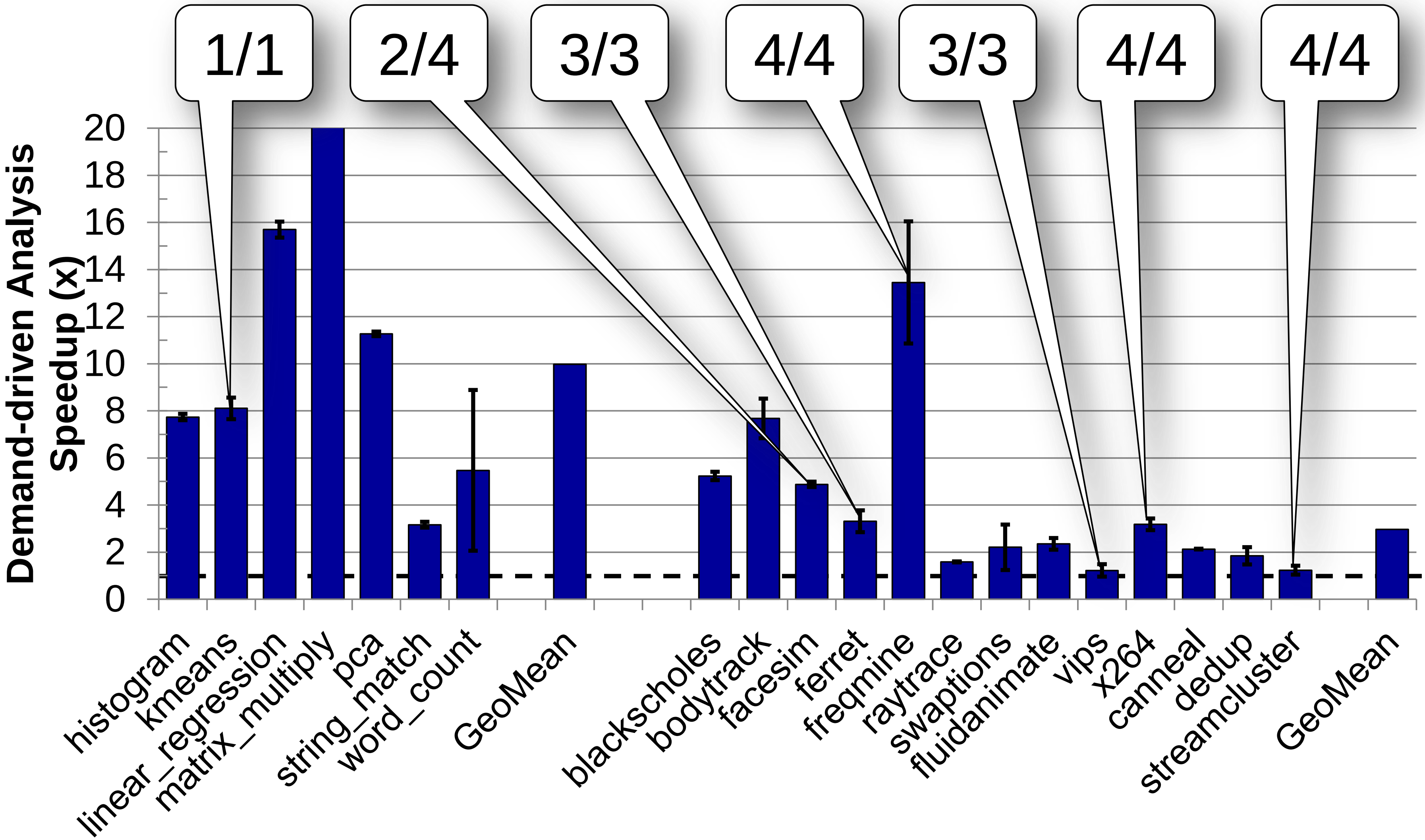

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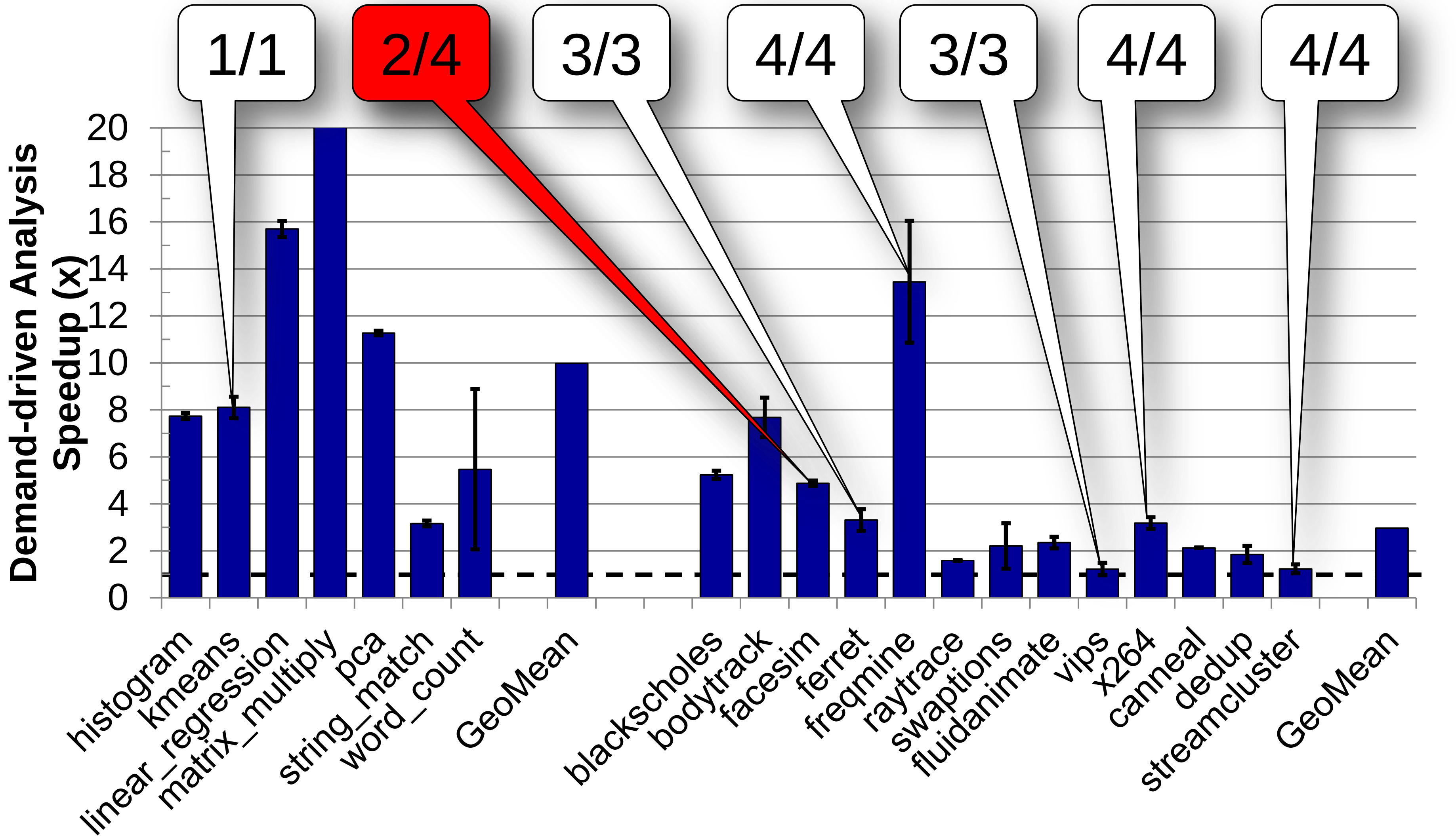

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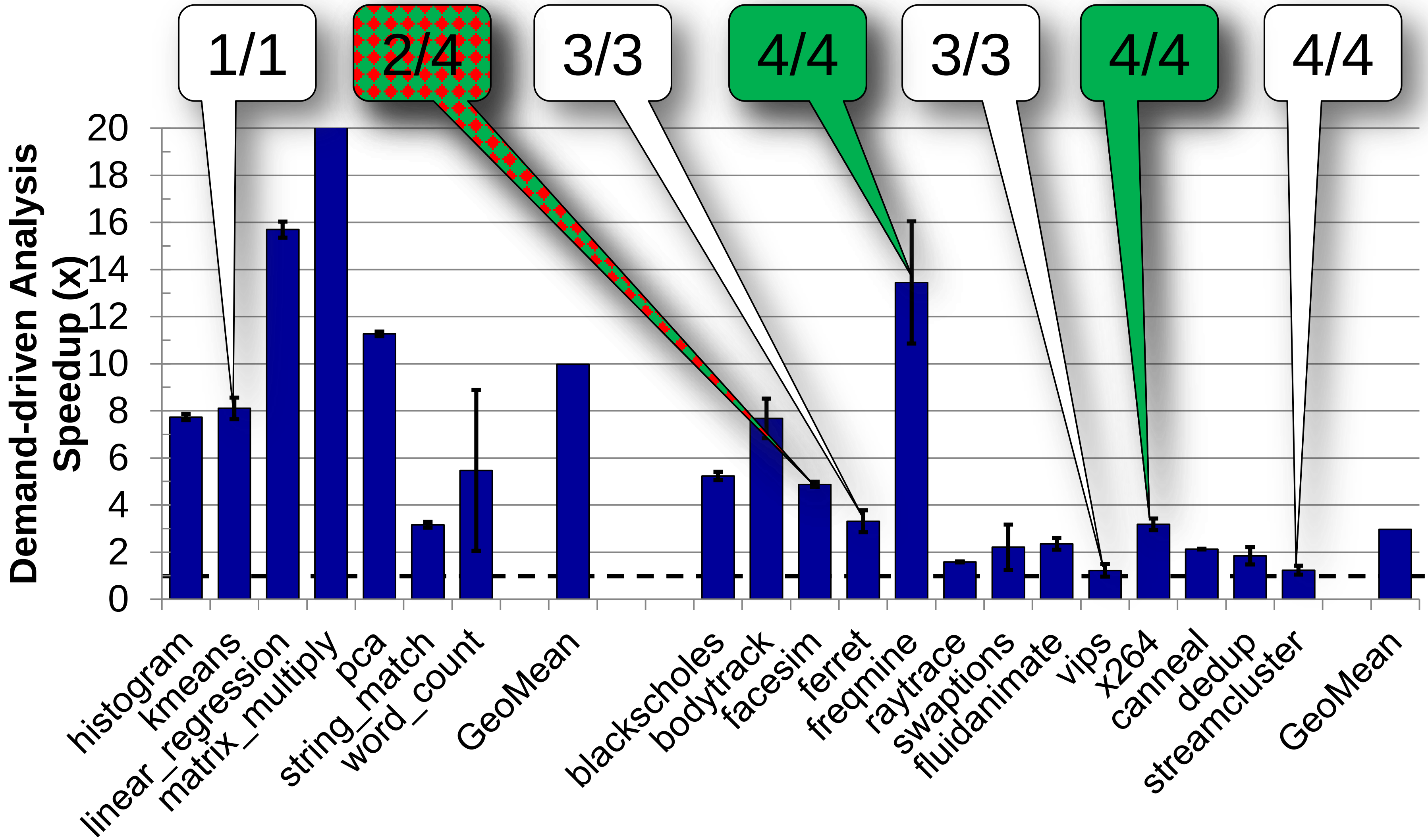

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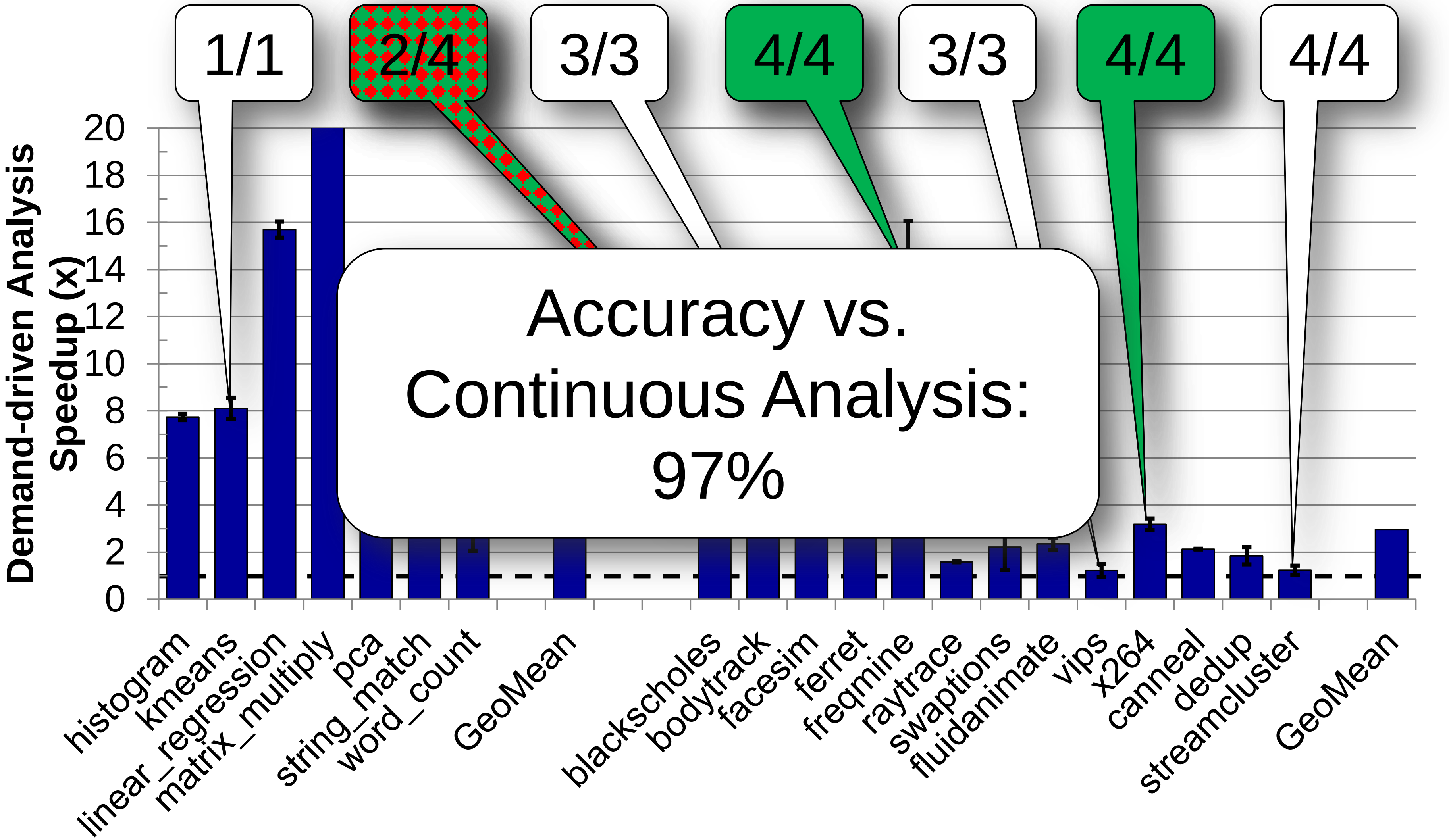
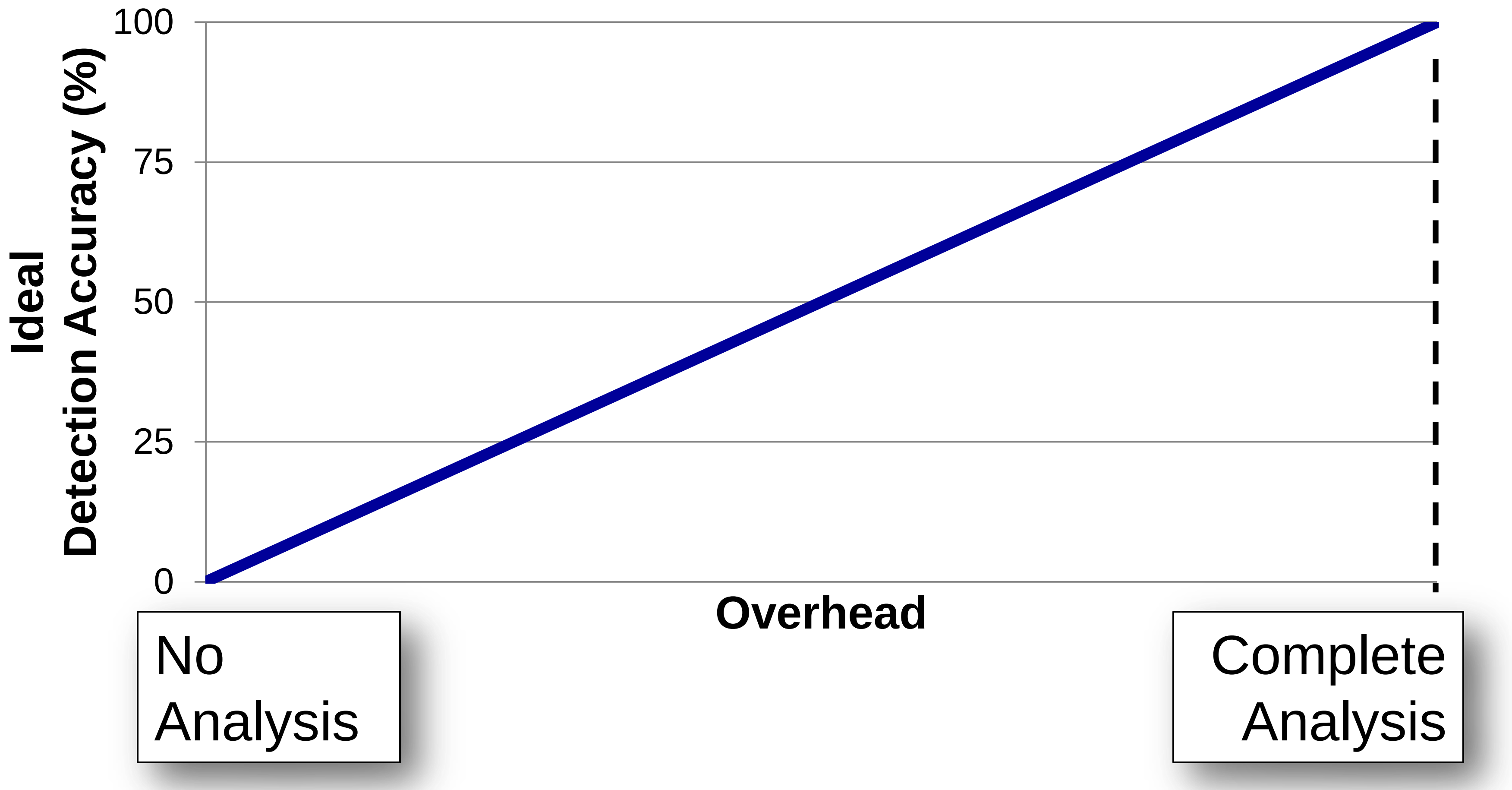


Outline

- Problem Statement
- Background Information
  - Demand-Driven Dynamic Dataflow Analysis
- Proposed Solutions
  - Demand-Driven Data Race Detection
  - Sampling to Cap Maximum Overheads

Reducing Overheads Further: Sampling

- Lower overheads by skipping some analyses



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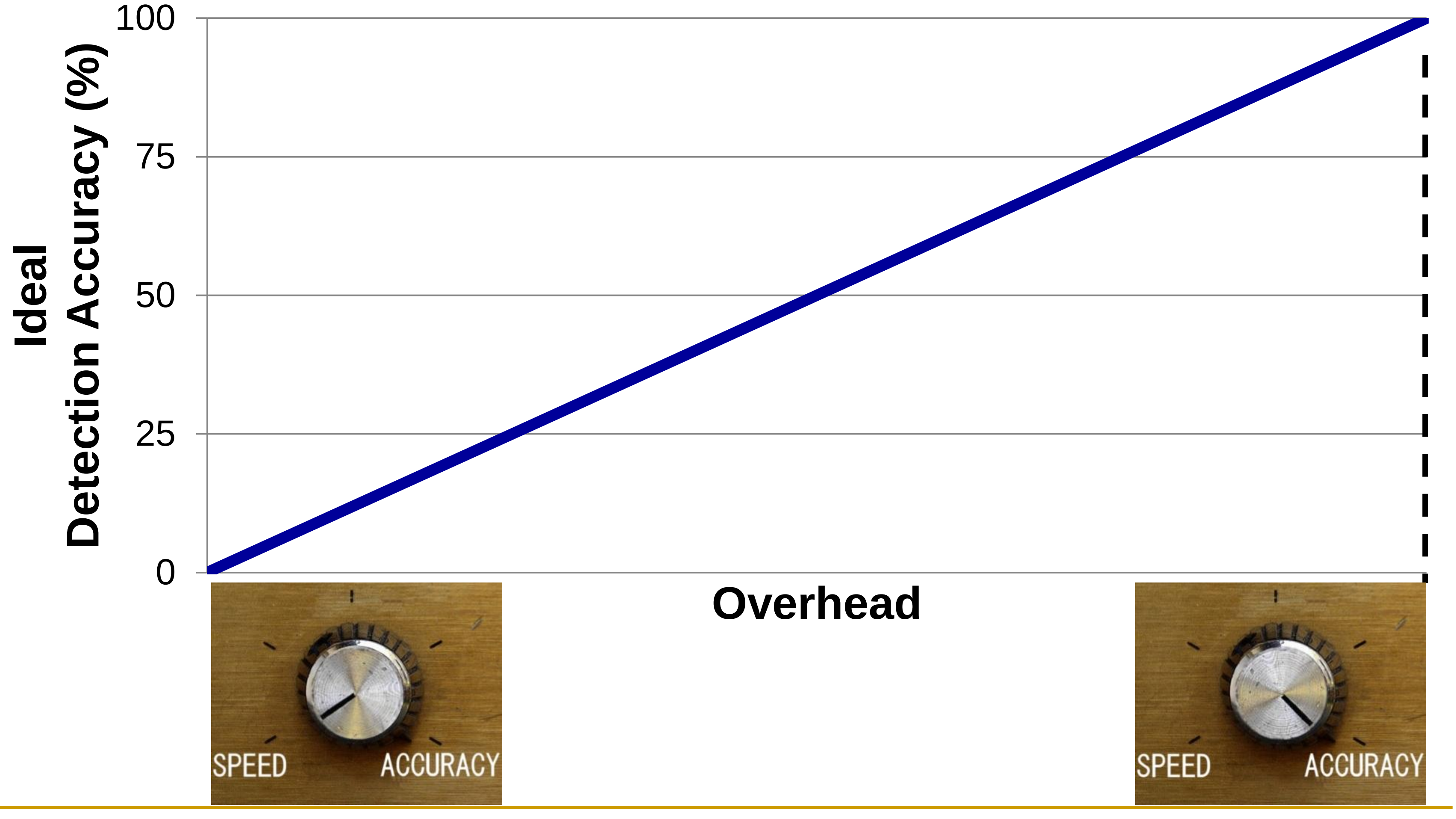

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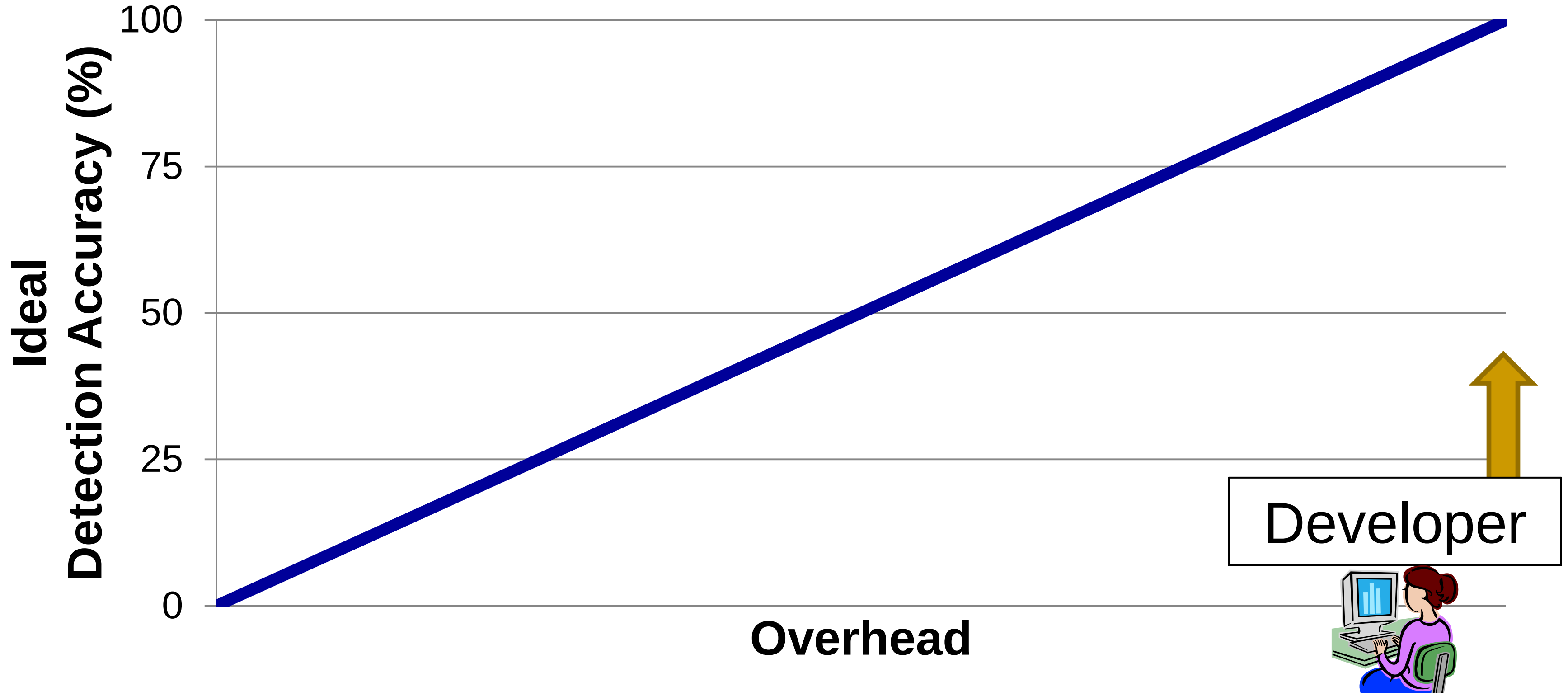

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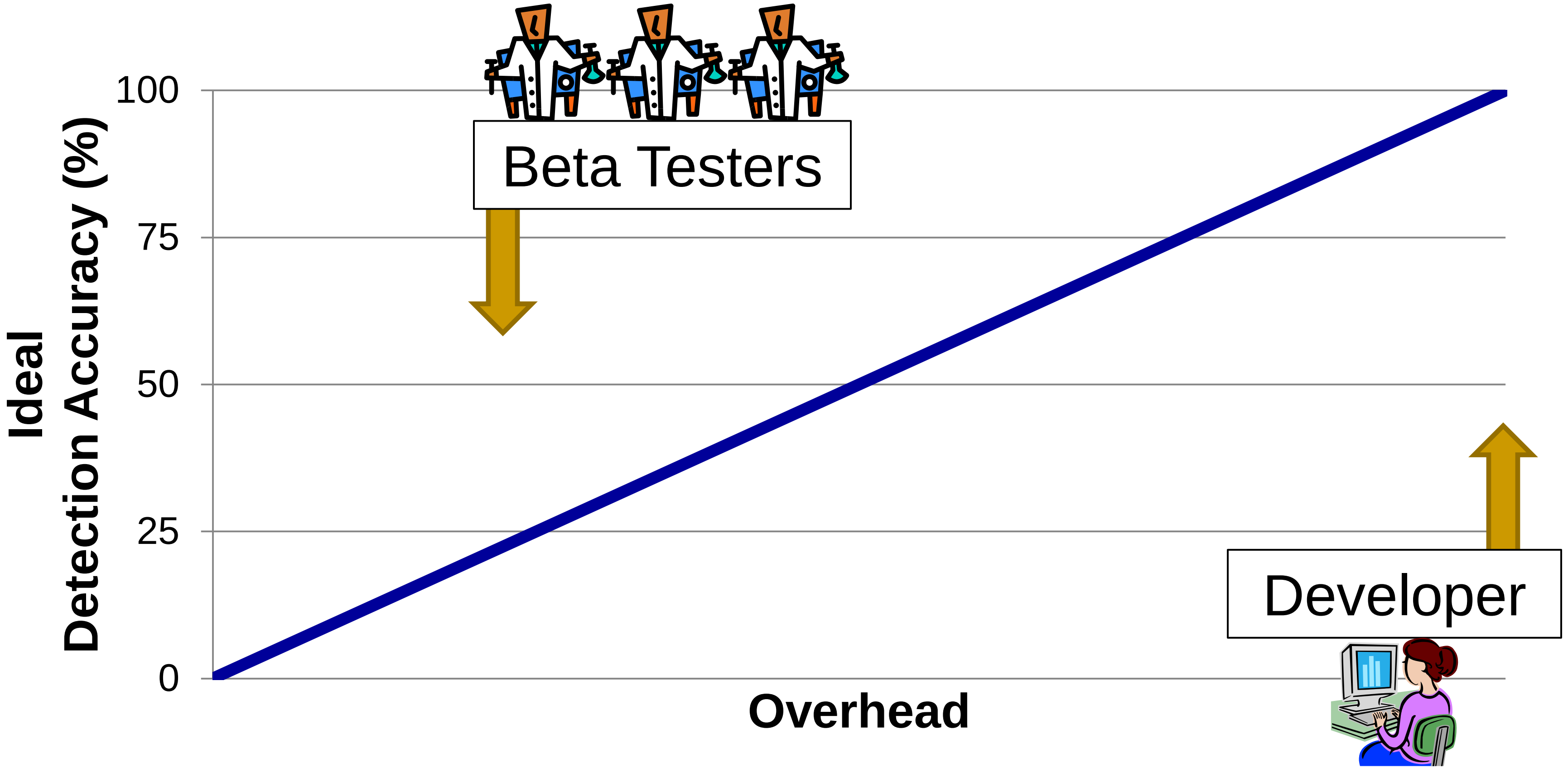
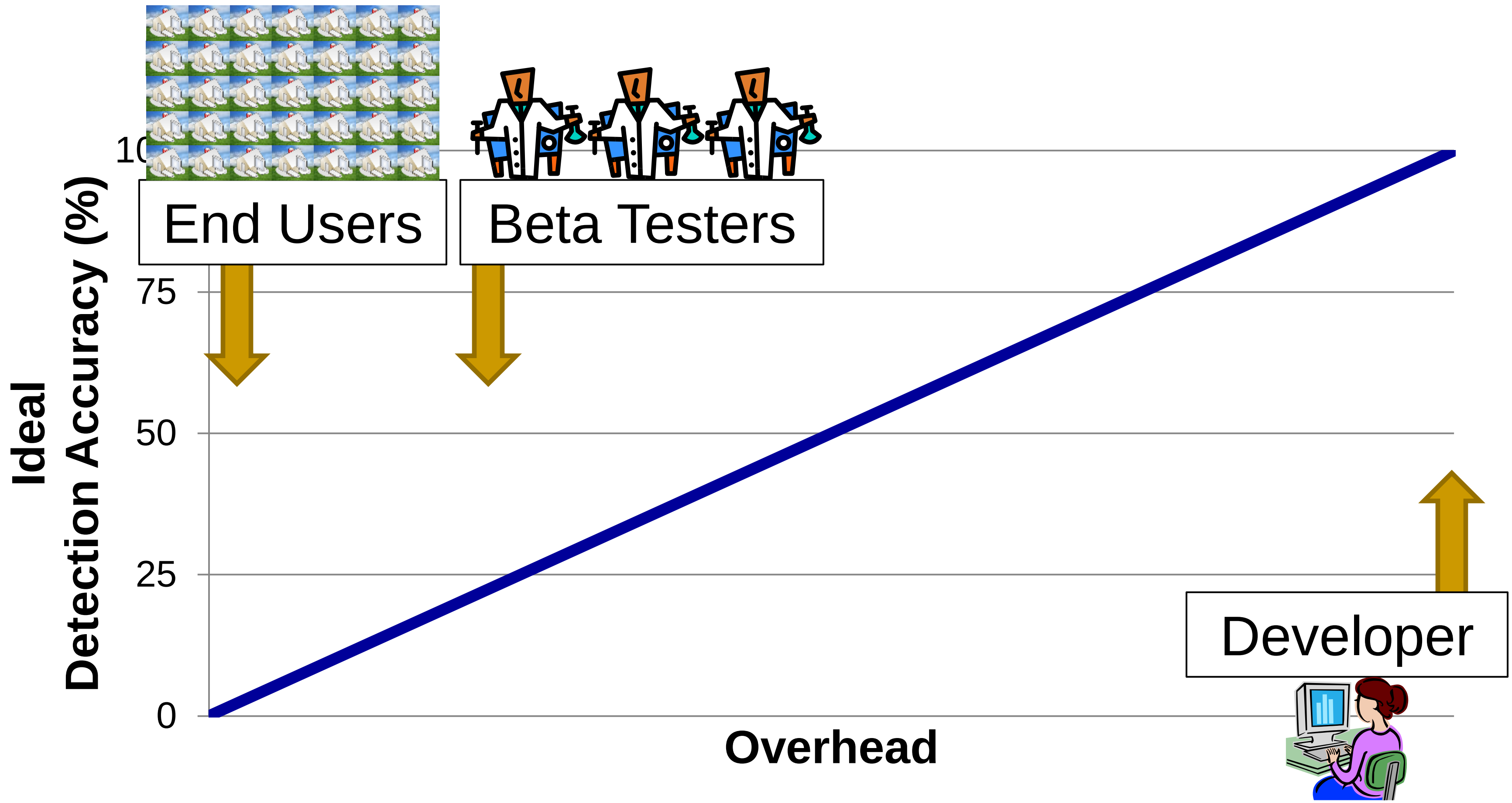


Sampling Allows Distribution



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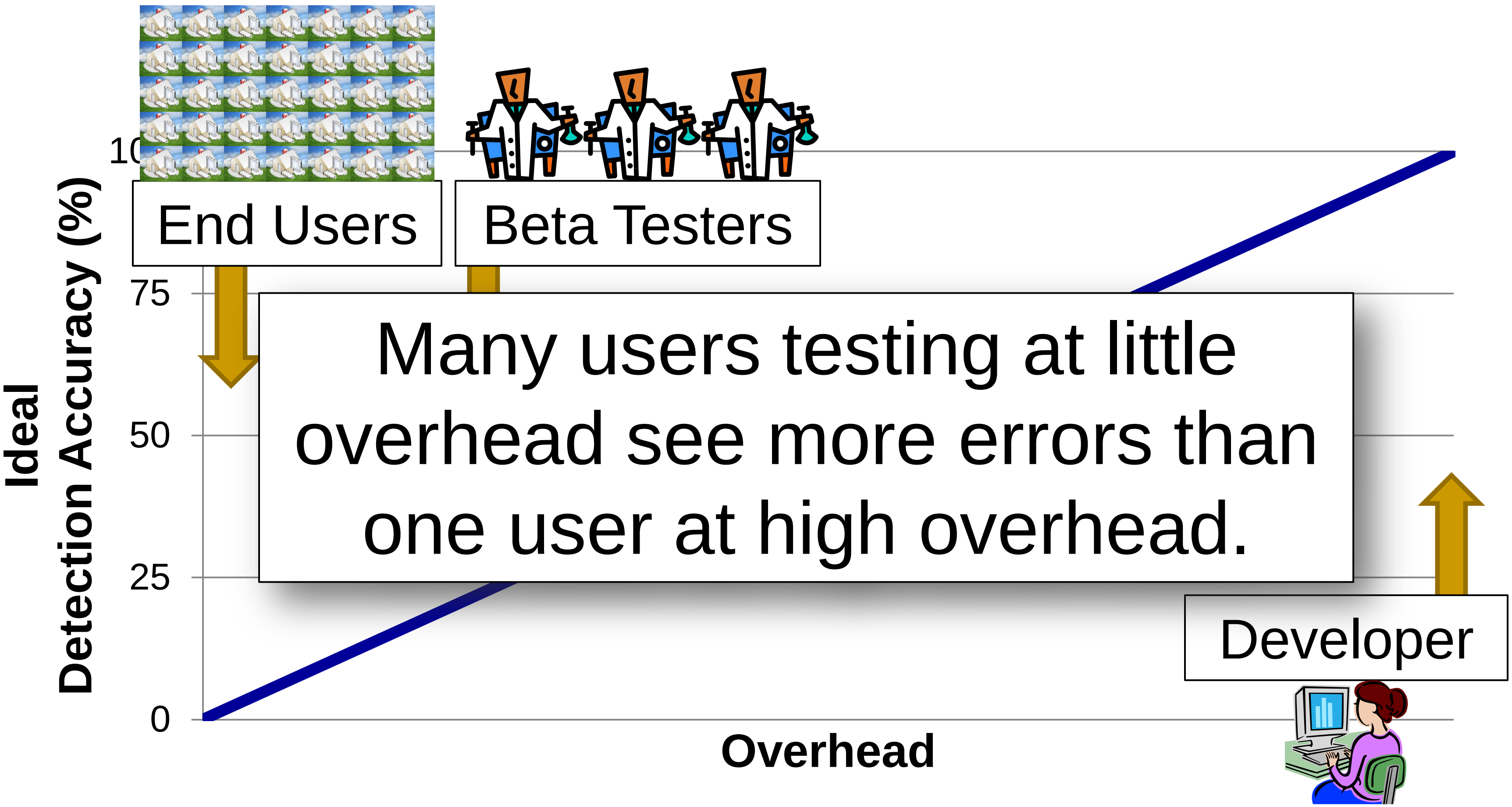
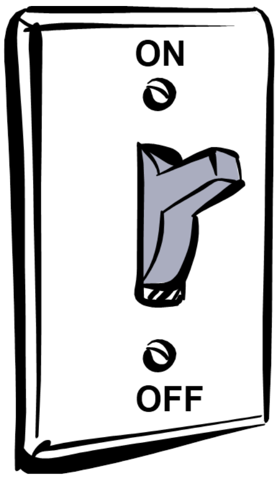


Many users testing at little overhead see more errors than one user at high overhead.

Cannot Naïvely Sample Code

Input



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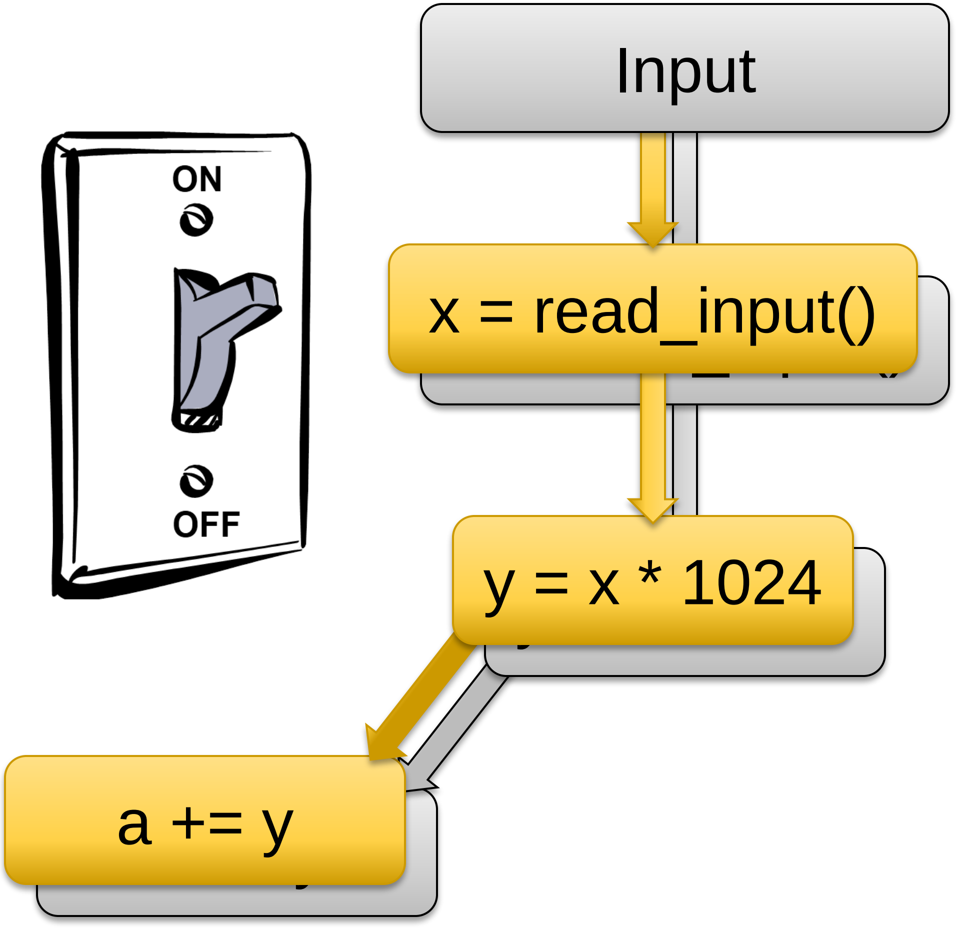

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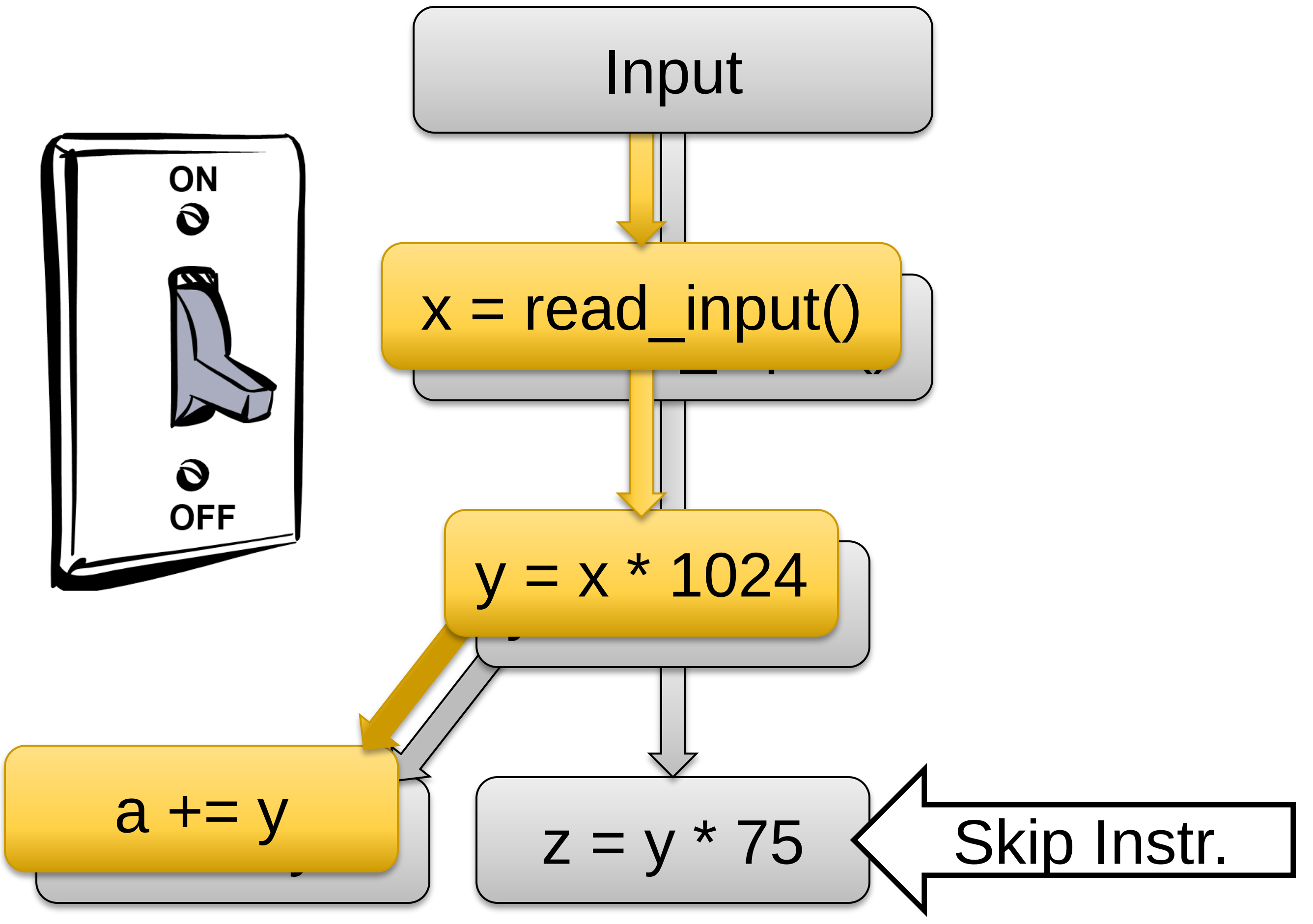

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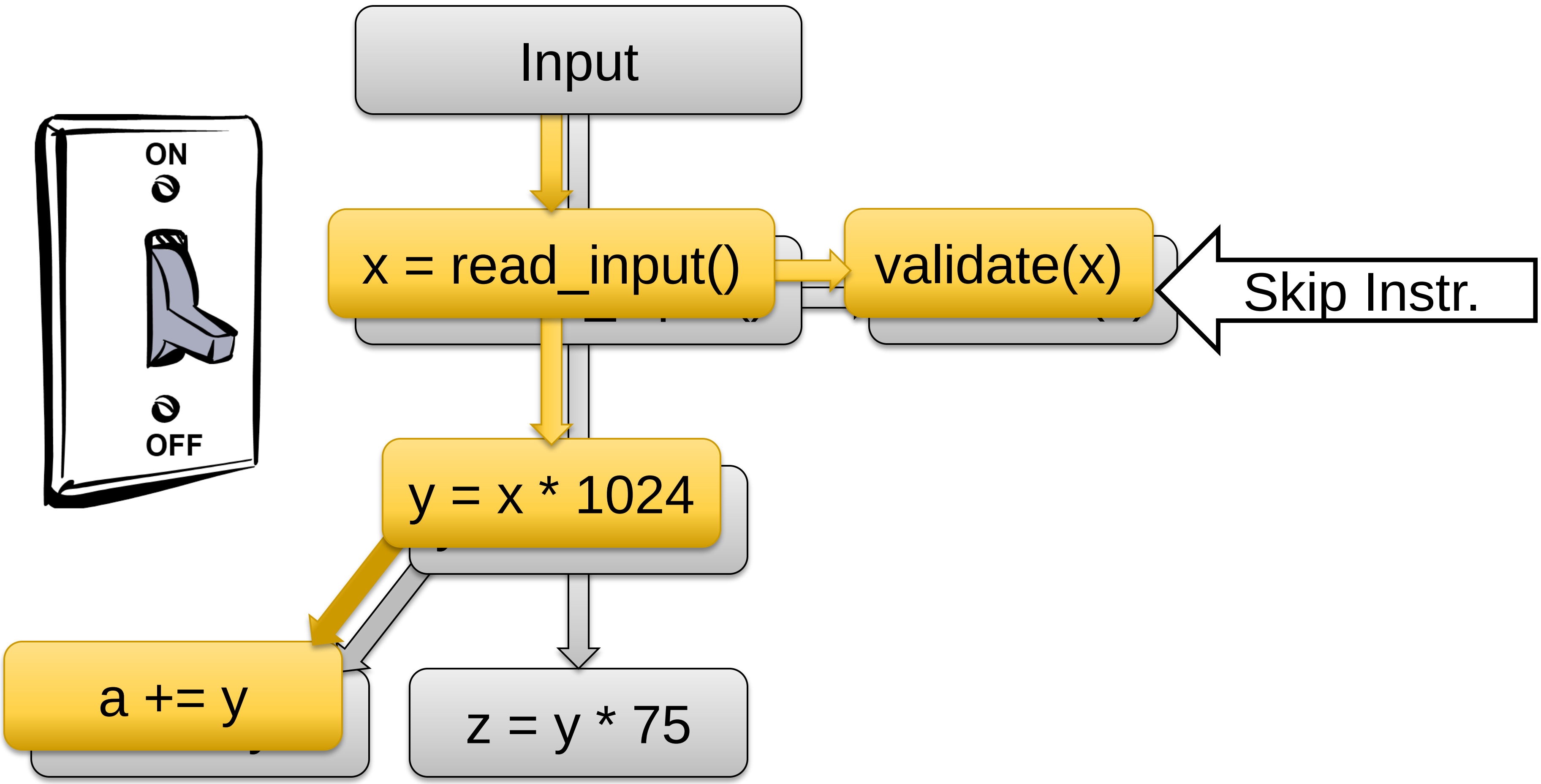

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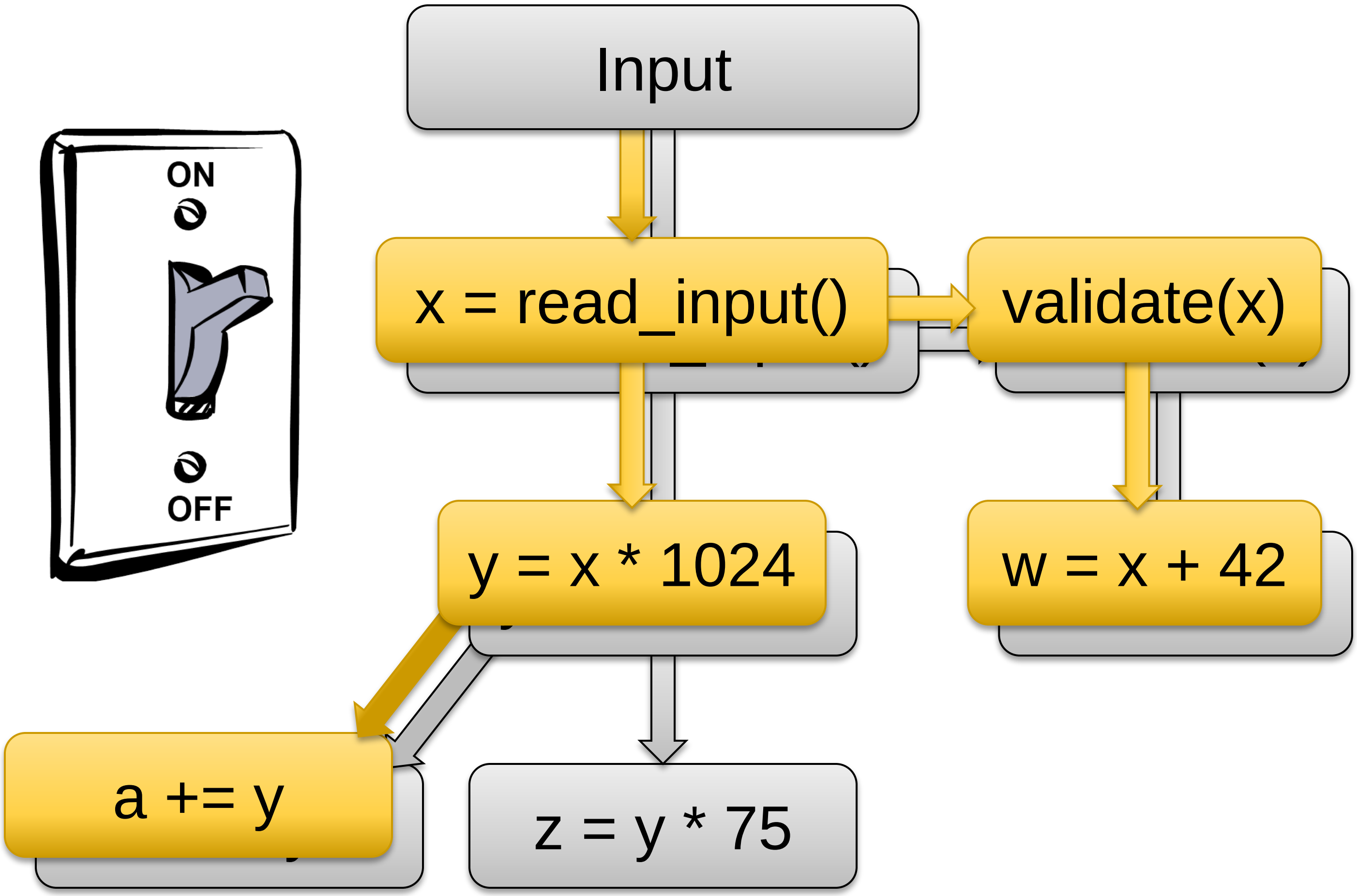

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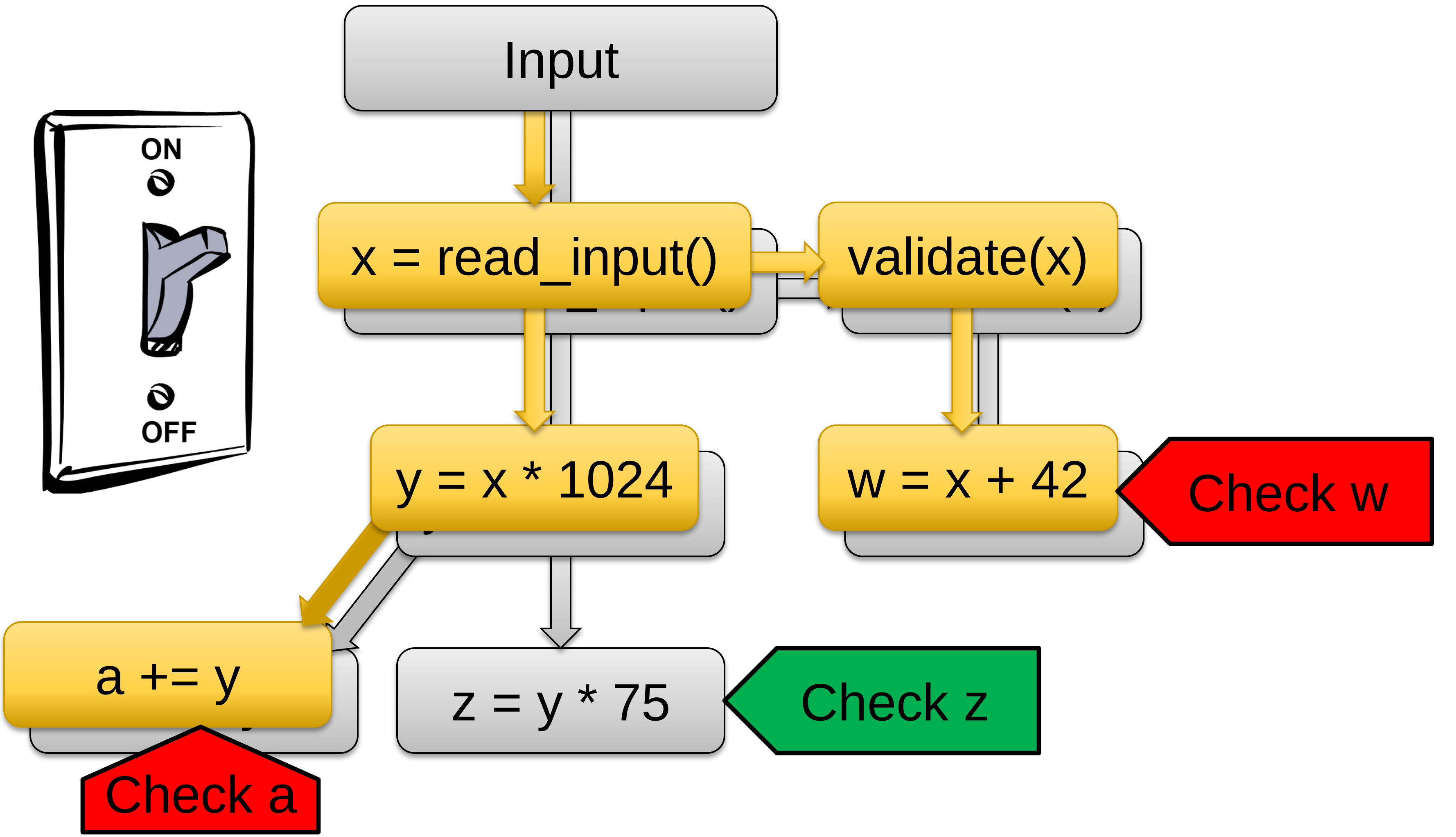

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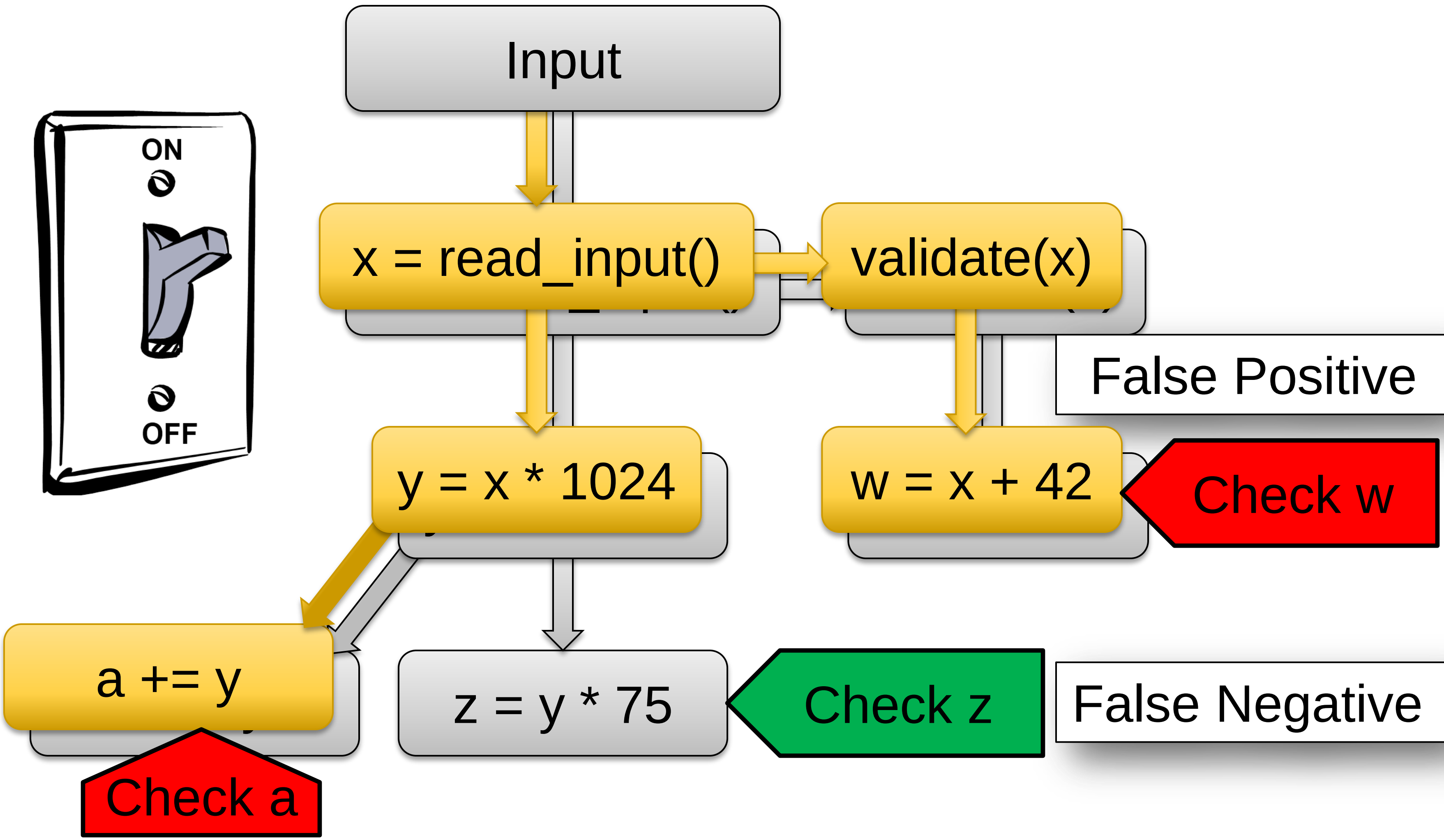
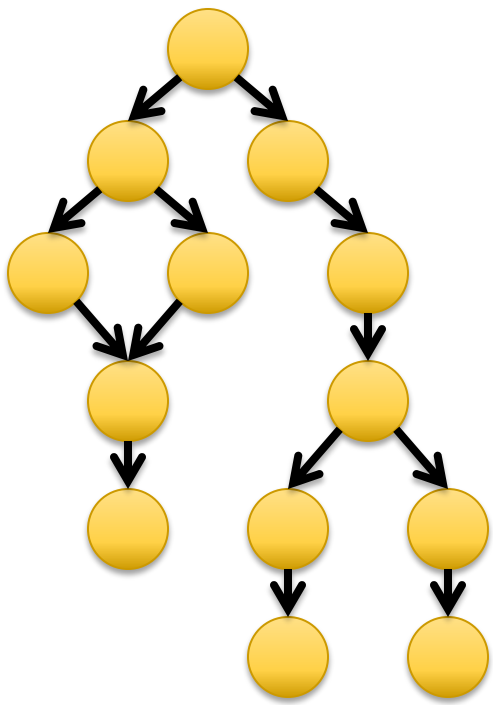


Our Solution: Sample Data, not Code

- Sampling must be aware of meta-data



- Remove meta-data from skipped dataflows
  - Prevents false positives

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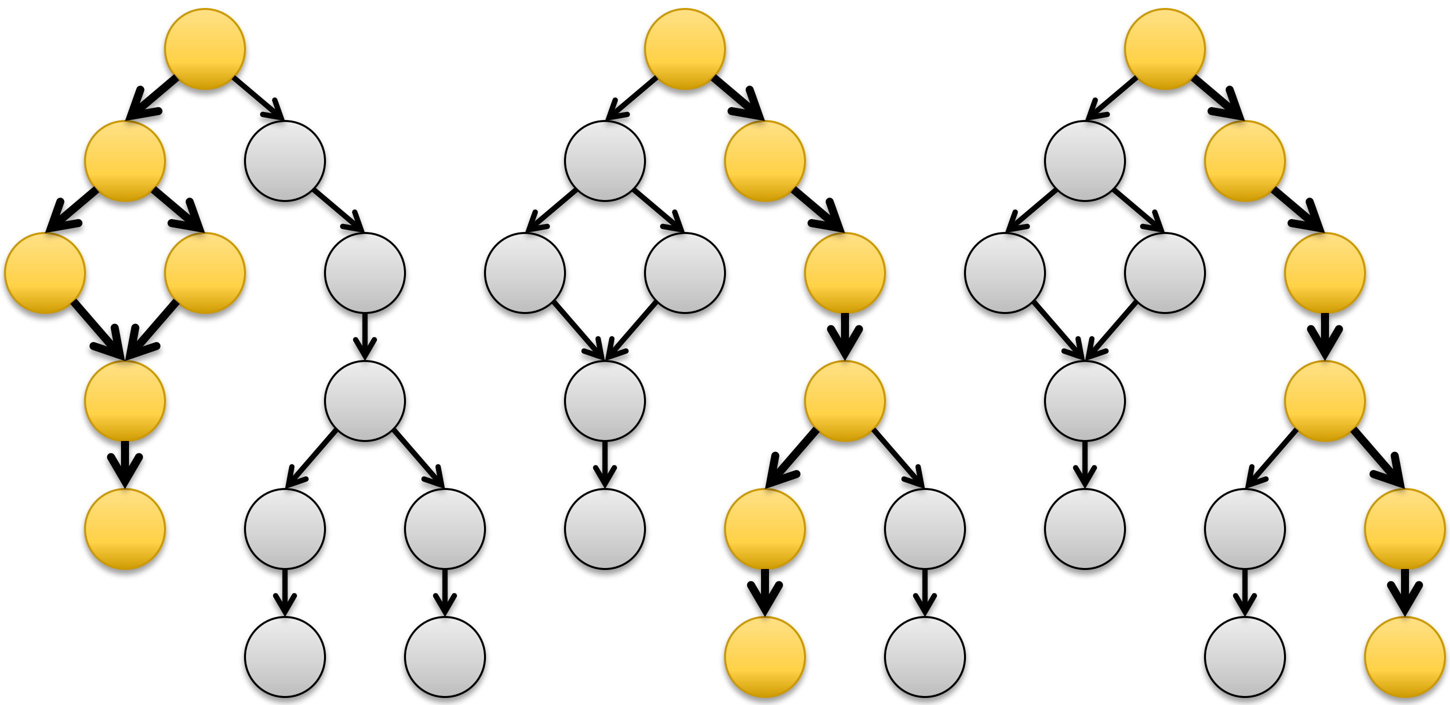

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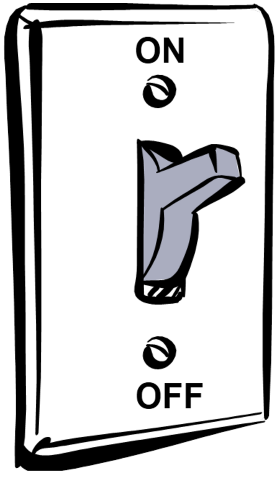
Dataflow Sampling Example

Input



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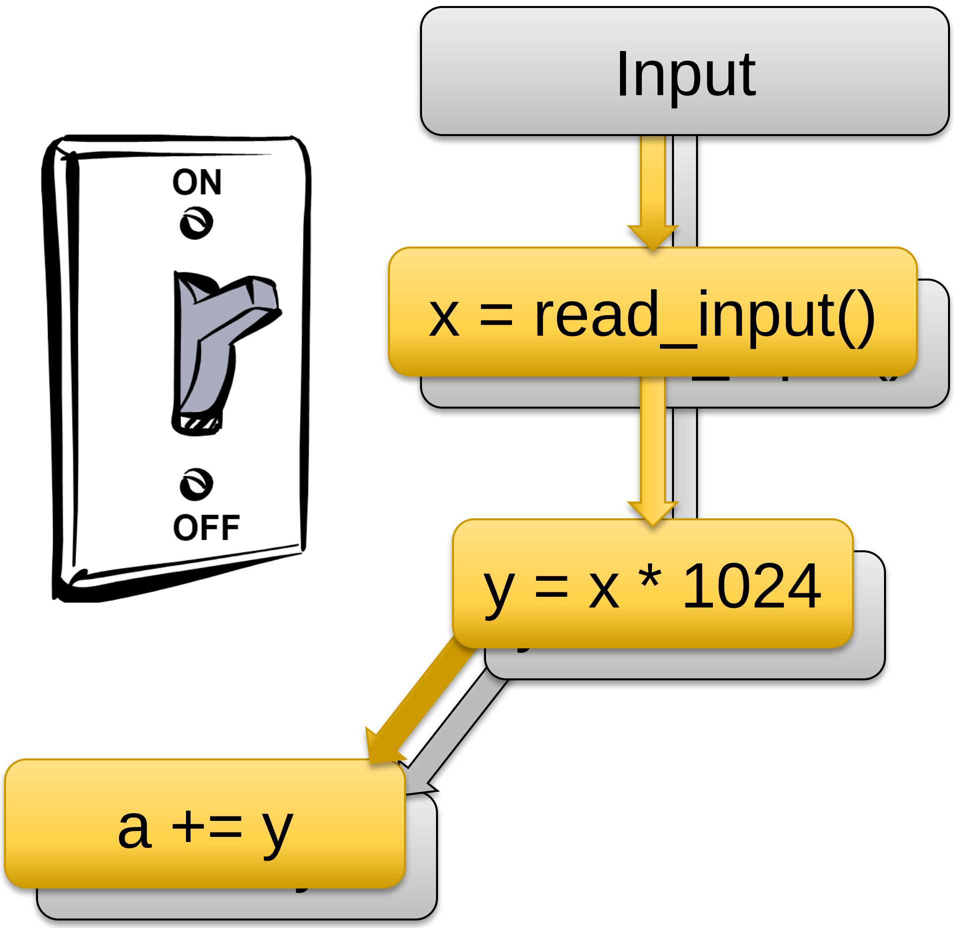

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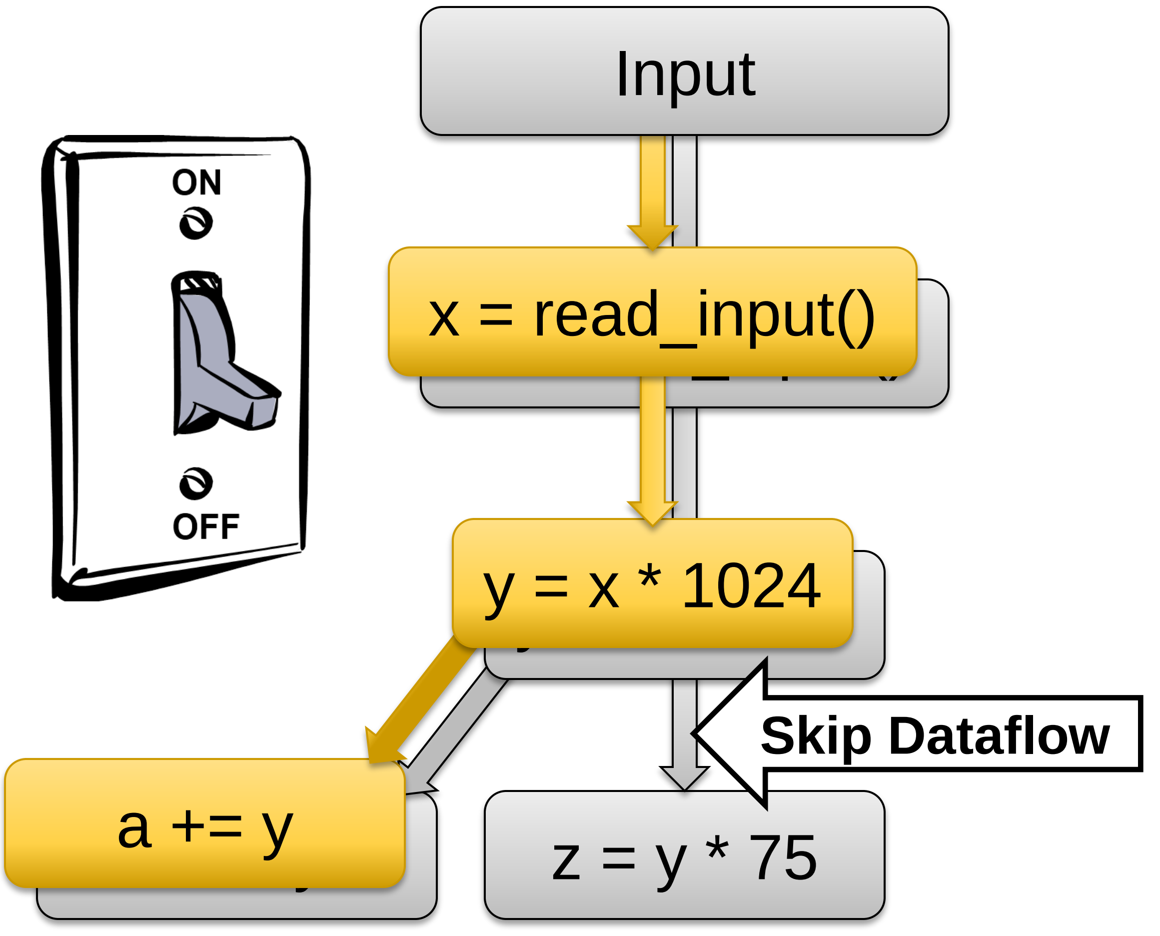

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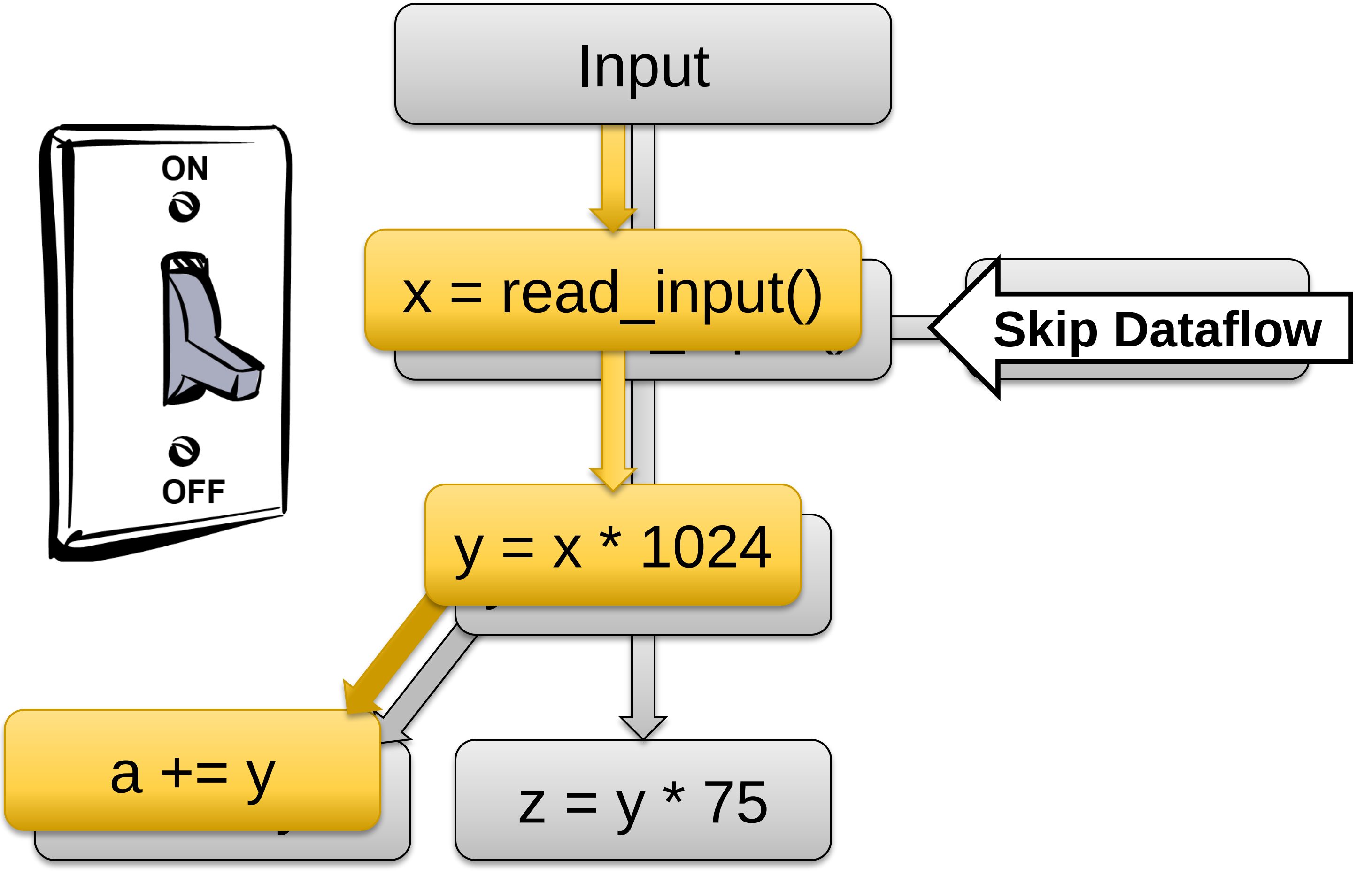

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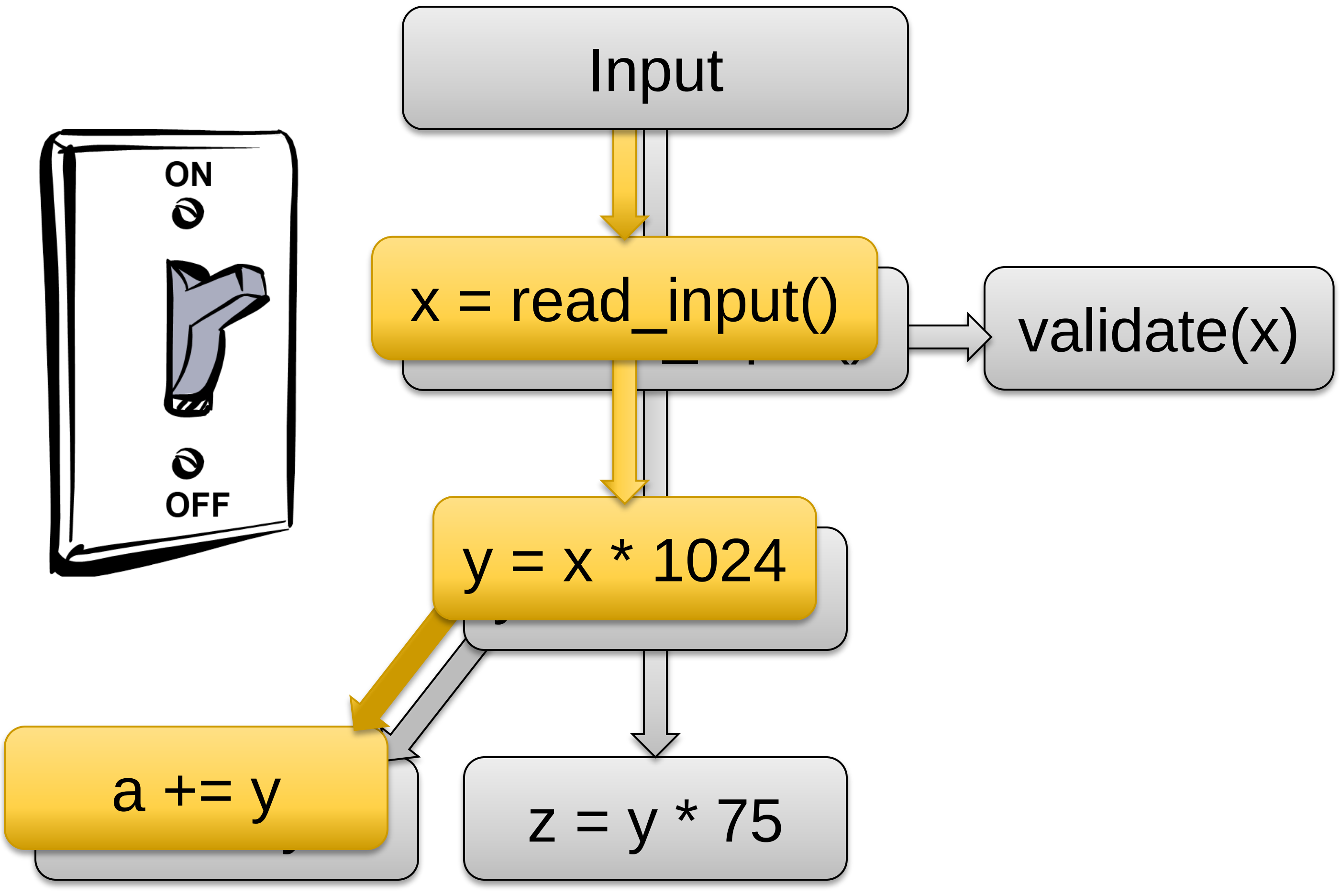
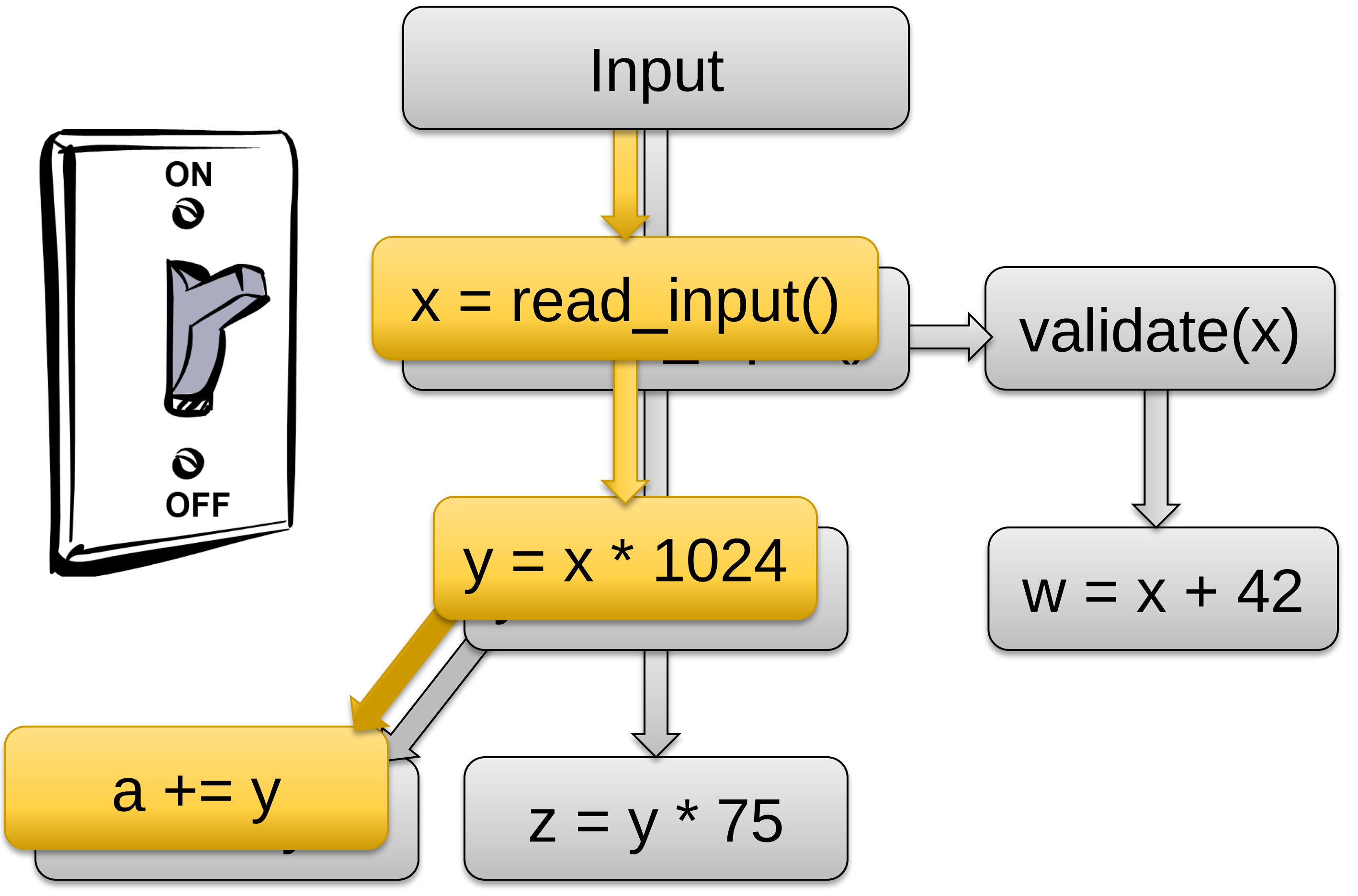
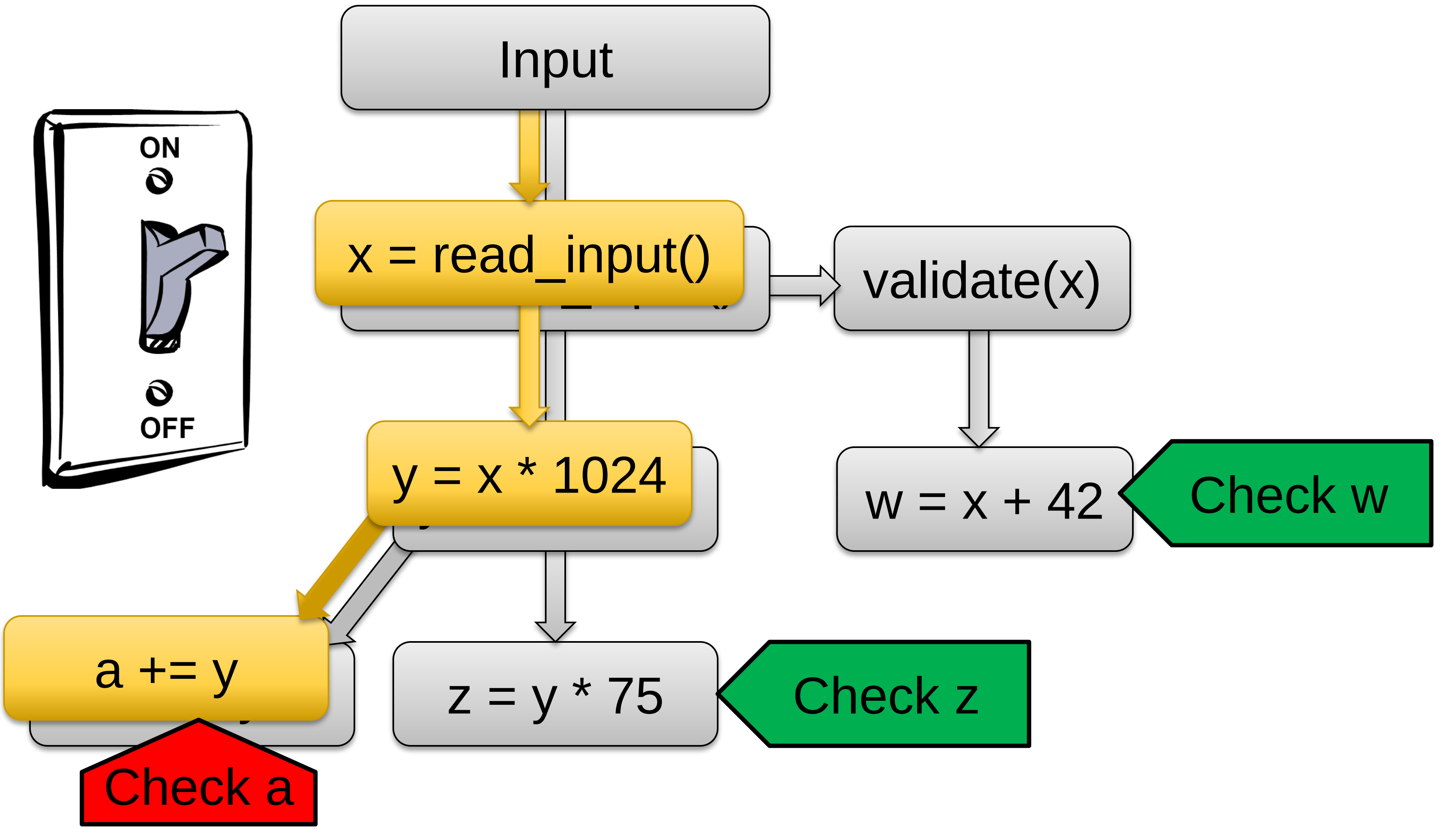


Dataflow Sampling Example



Dataflow Sampling Example



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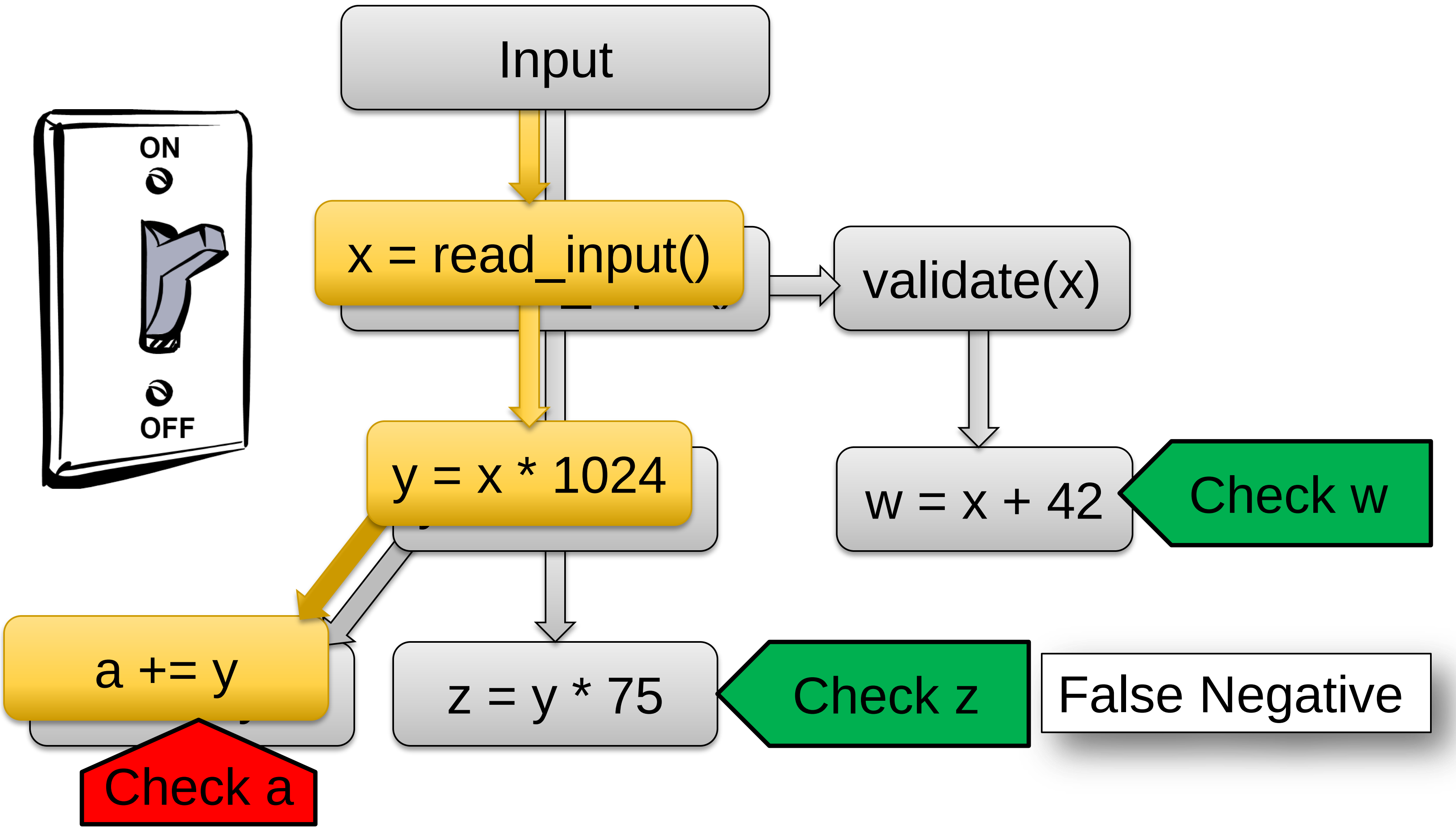
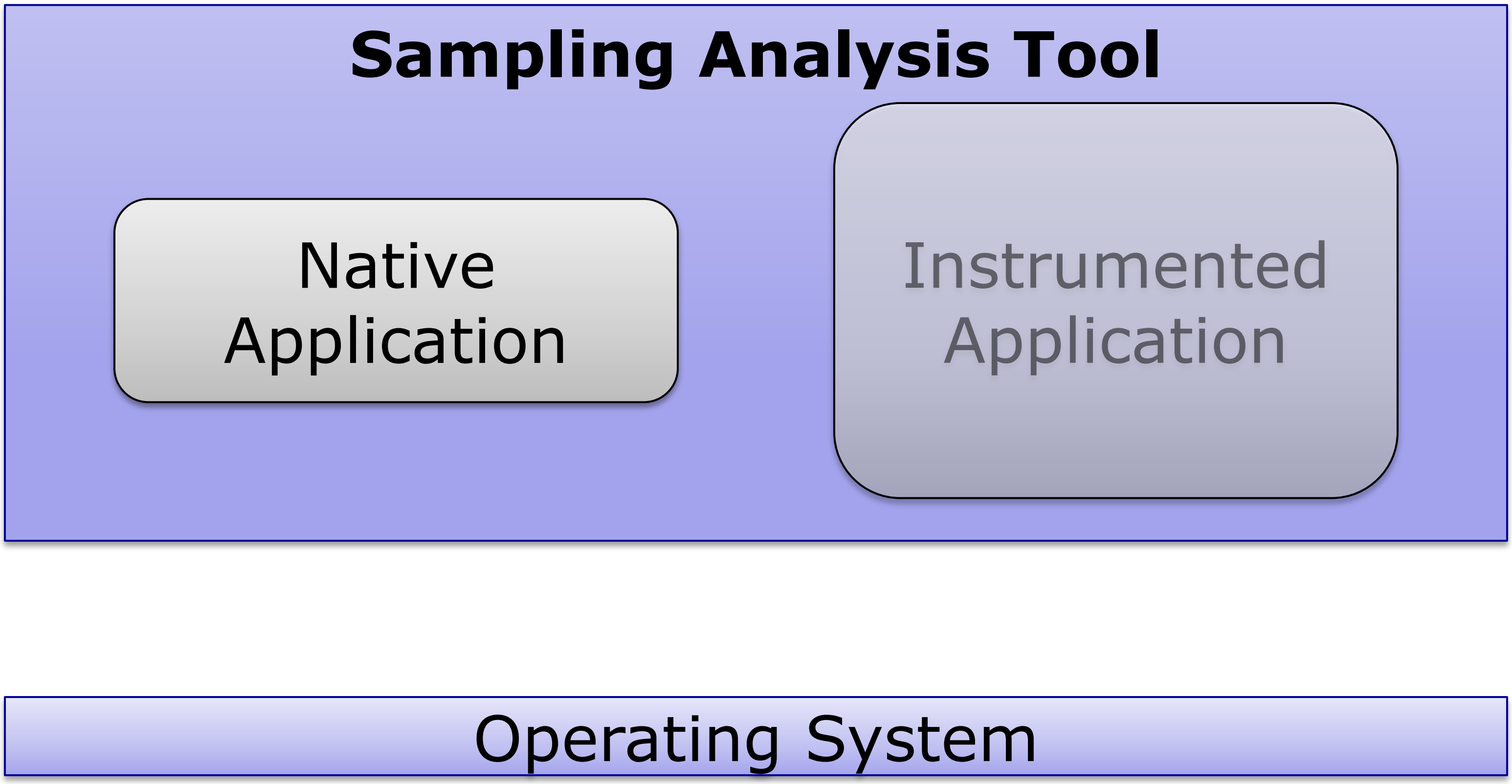


Dataflow Sampling

- **Remove** dataflows if execution is too slow



Dataflow Sampling

- **Remove** dataflows if execution is too slow

Sampling Analysis Tool

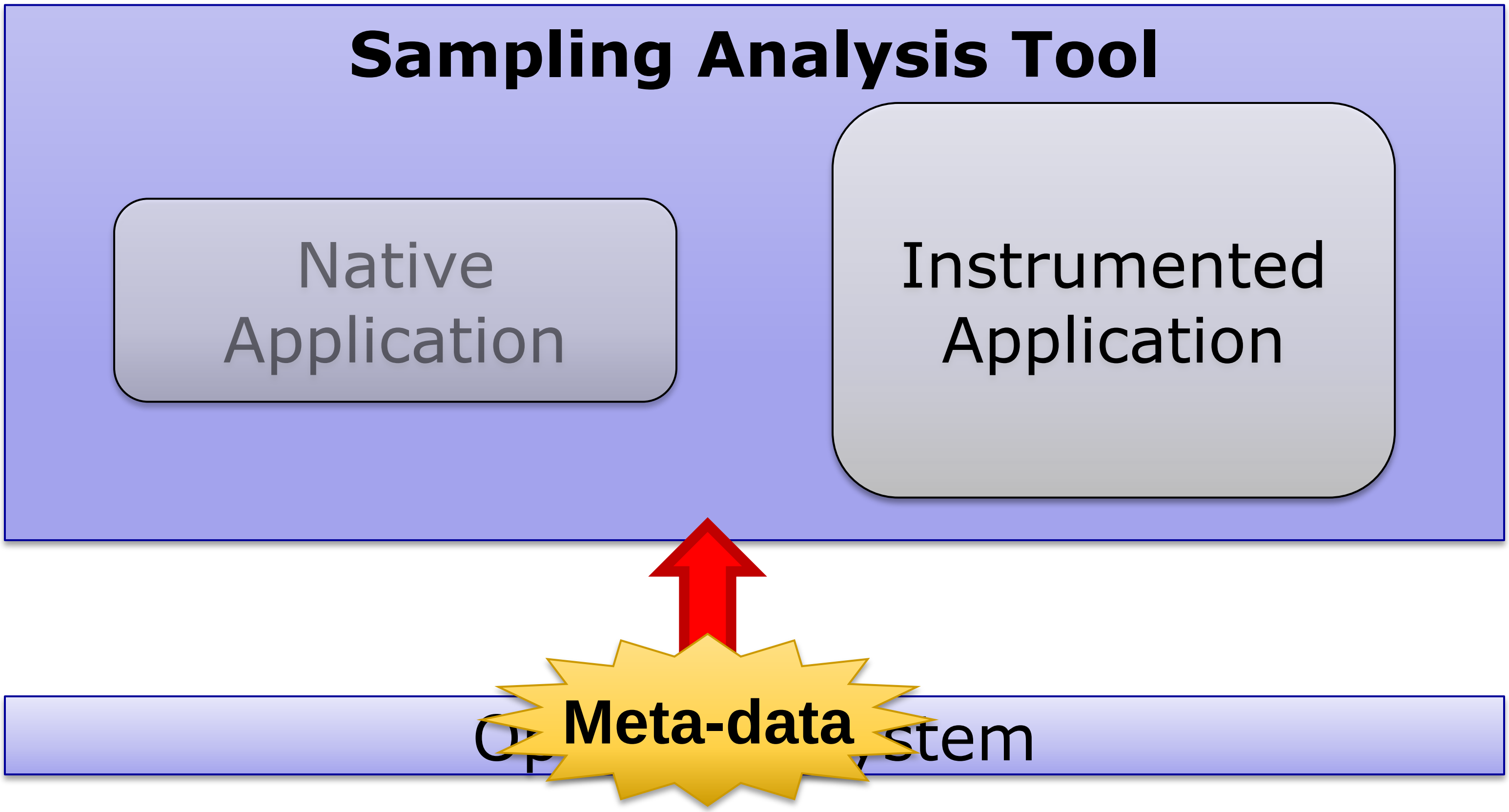
Native Application

Instrumented Application

Operating System

Dataflow Sampling

- **Remove** dataflows if execution is too slow



Dataflow Sampling

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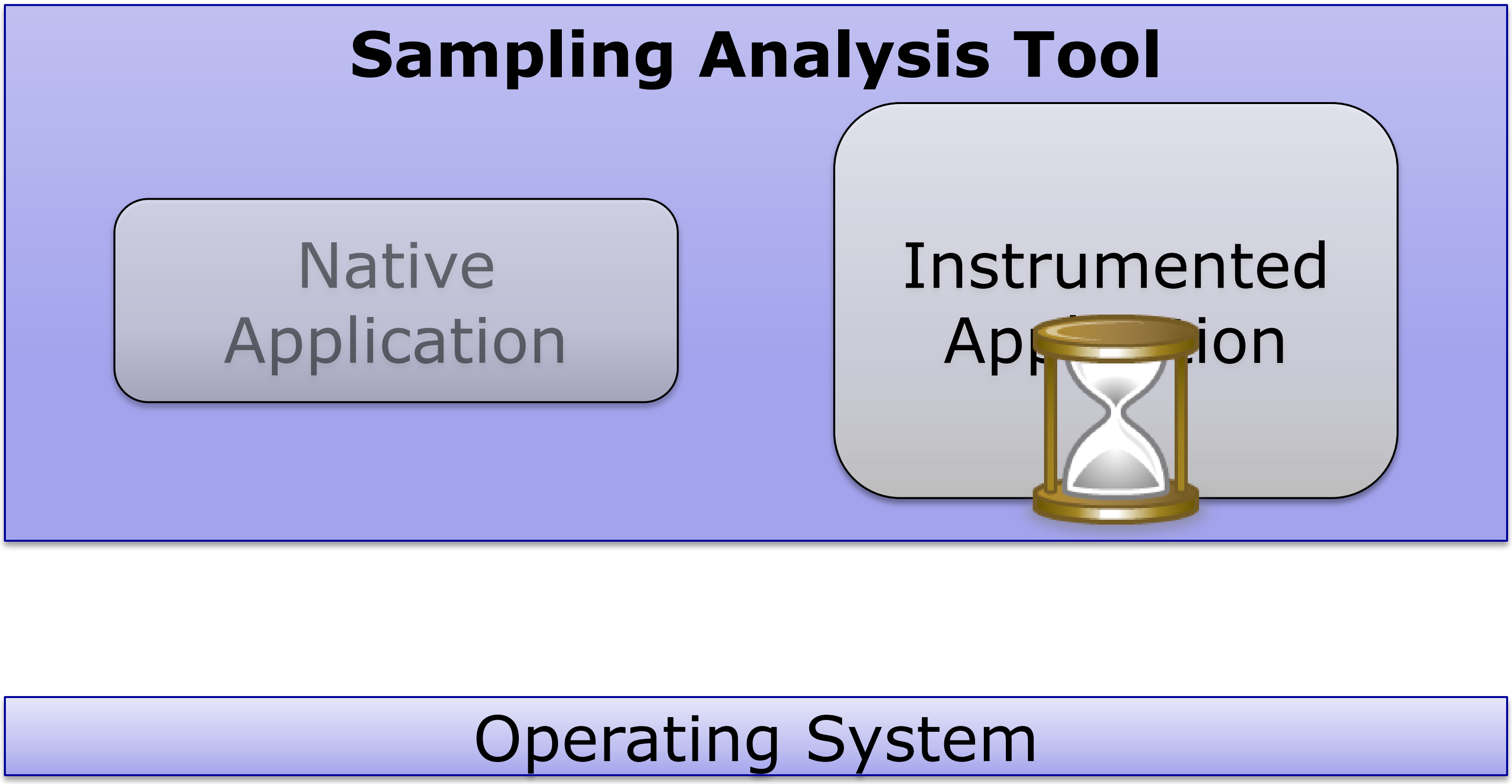

Dataflow Sampling

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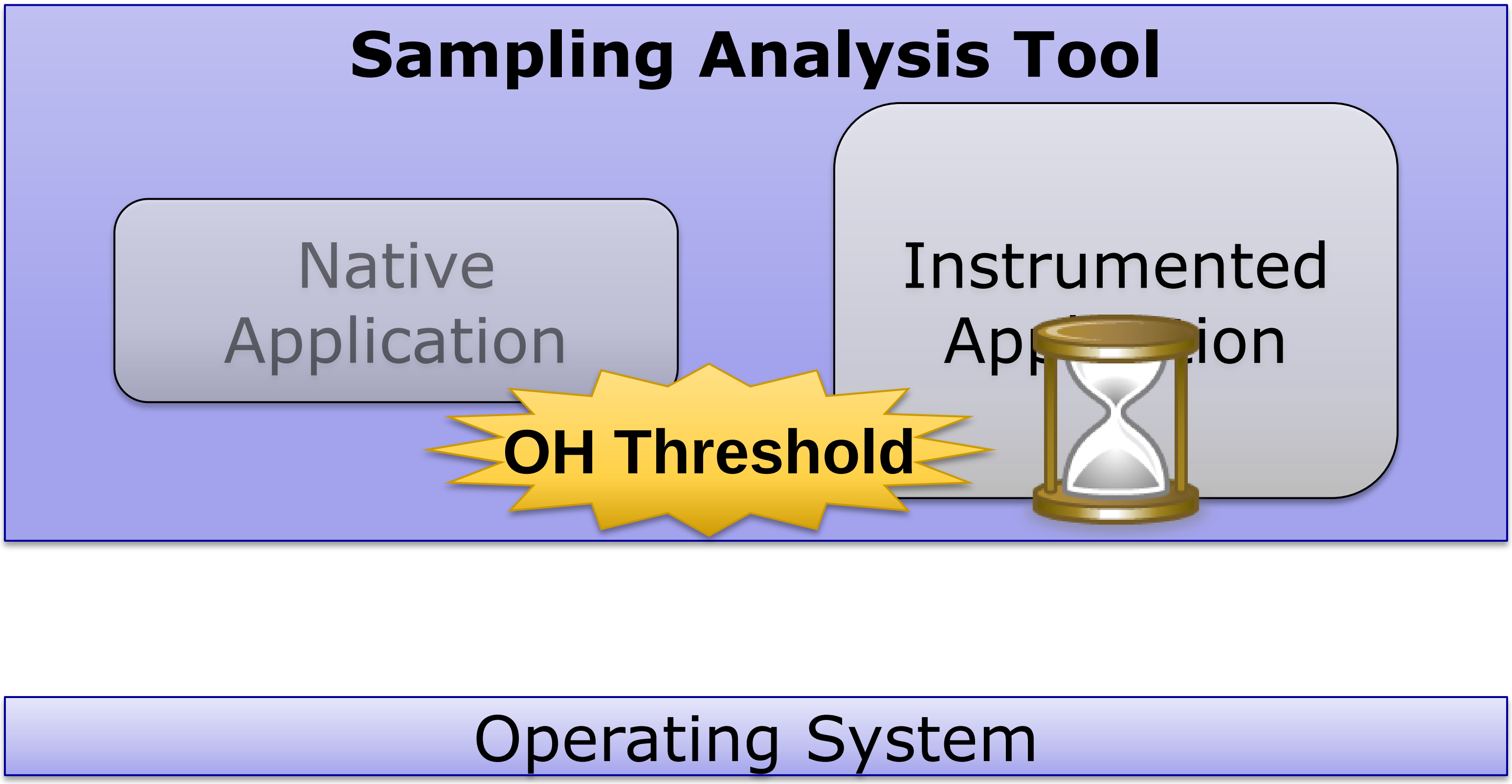

Dataflow Sampling

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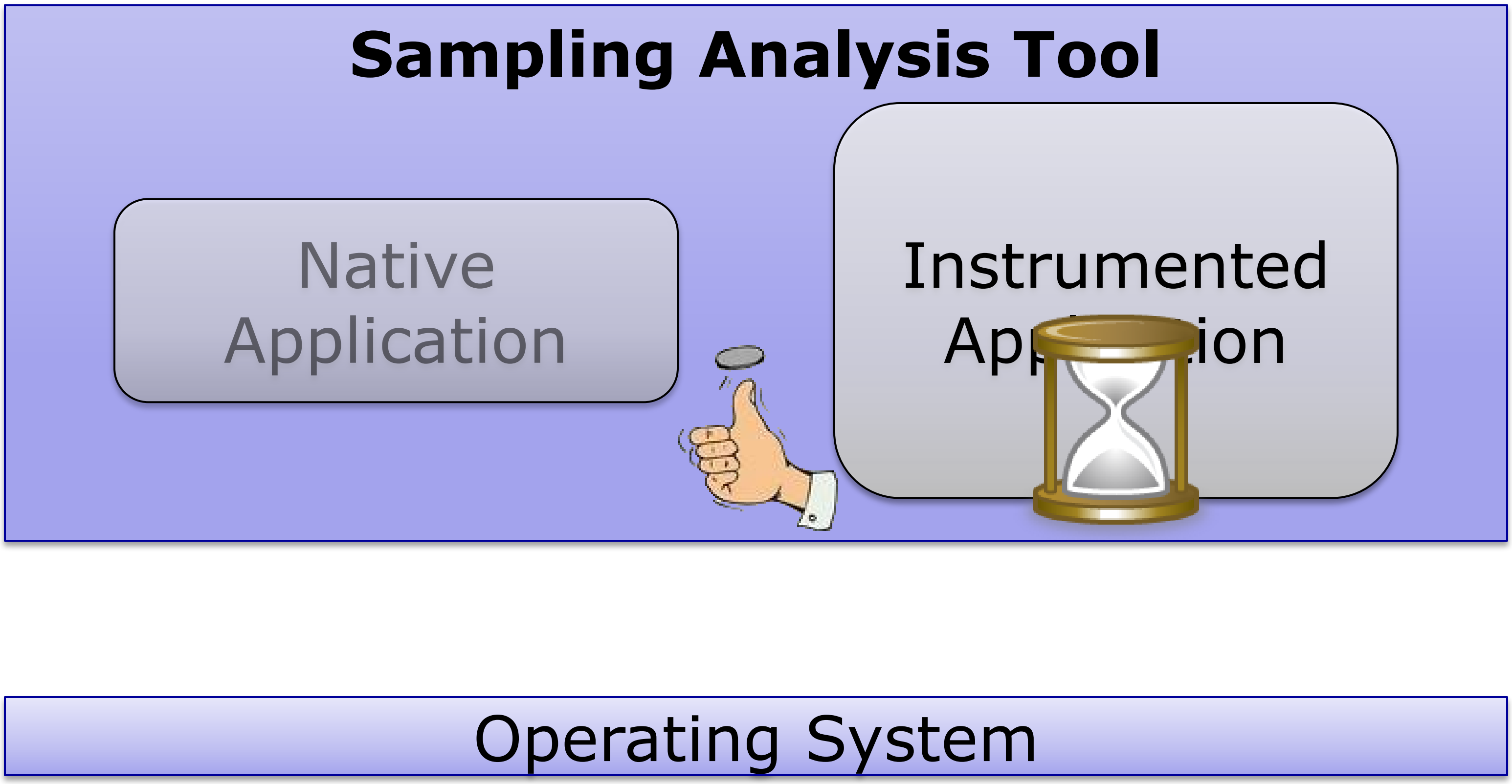

Dataflow Sampling

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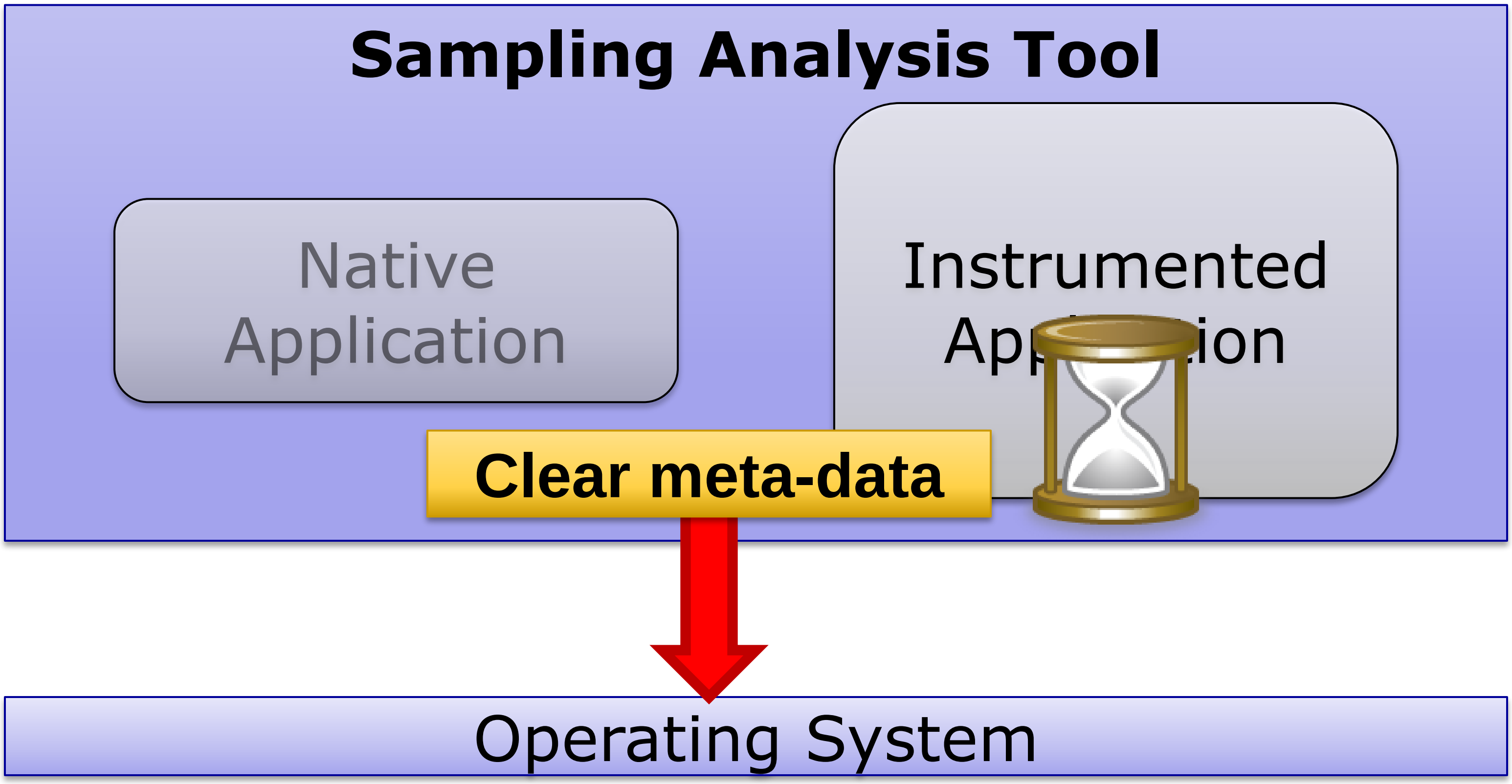

Dataflow Sampling

- **Remove** dataflows if execution is too slow

Sampling Analysis Tool

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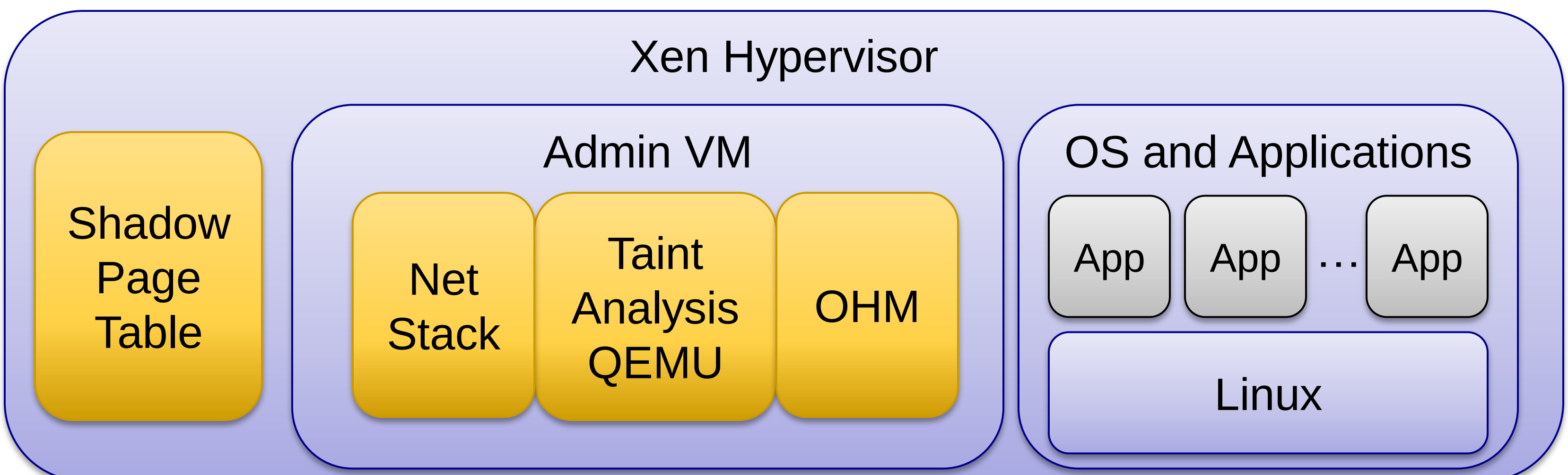
Prototype Setup

- Taint analysis sampling system
  - Network packets untrusted
- Xen-based demand analysis
  - Whole-system analysis with modified QEMU
- Overhead Manager (OHM) is user-controlled

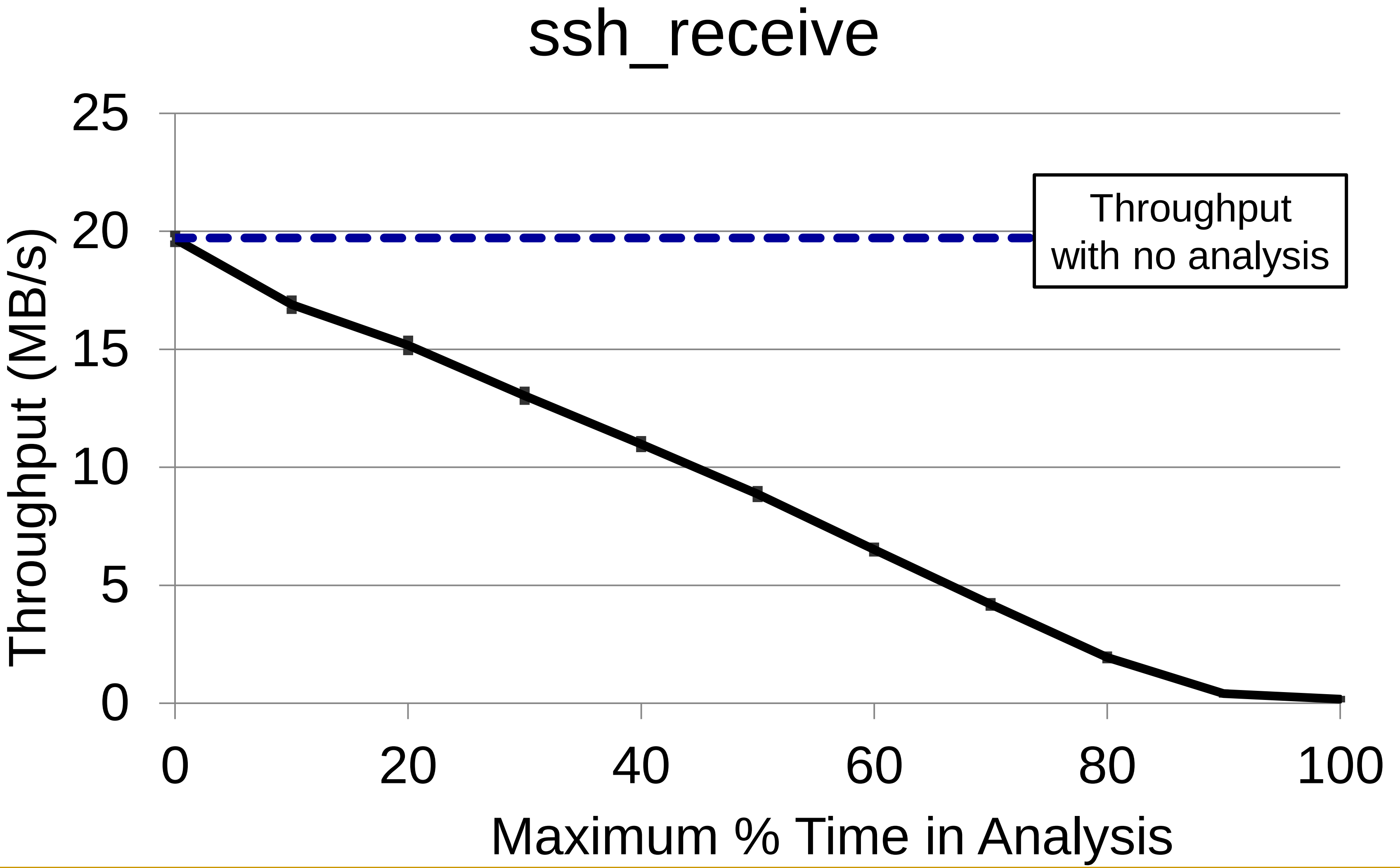


Benchmarks

- Performance – Network Throughput
  - *Example:* ***ssh_receive***
- Accuracy of Sampling Analysis
  - Real-world Security Exploits

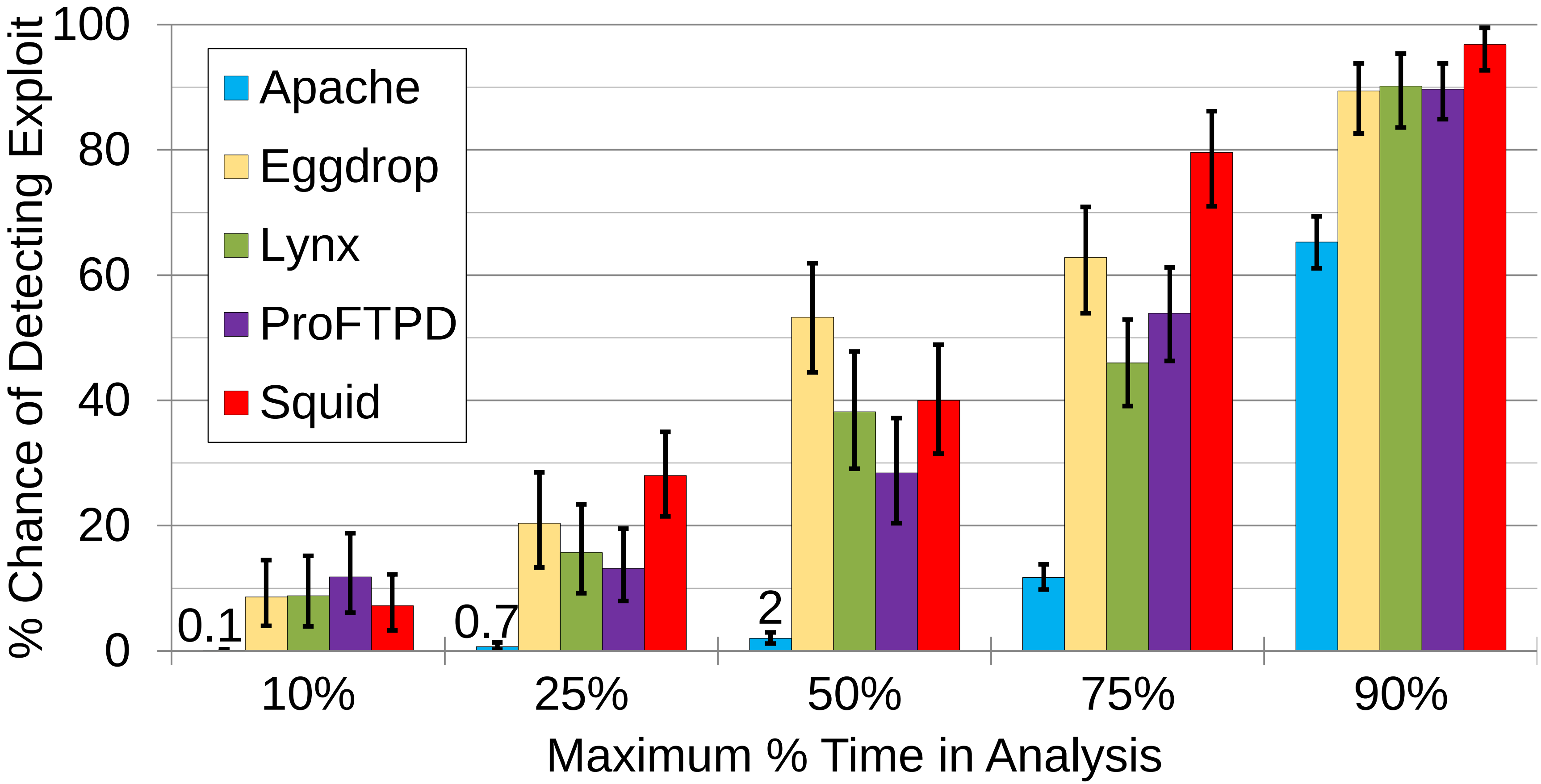
Name	Error Description
Apache	Stack overflow in Apache Tomcat JK Connector
Eggdrop	Stack overflow in Eggdrop IRC bot
Lynx	Stack overflow in Lynx web browser
ProFTPD	Heap smashing attack on ProFTPD Server
Squid	Heap smashing attack on Squid proxy server

Performance of Dataflow Sampling



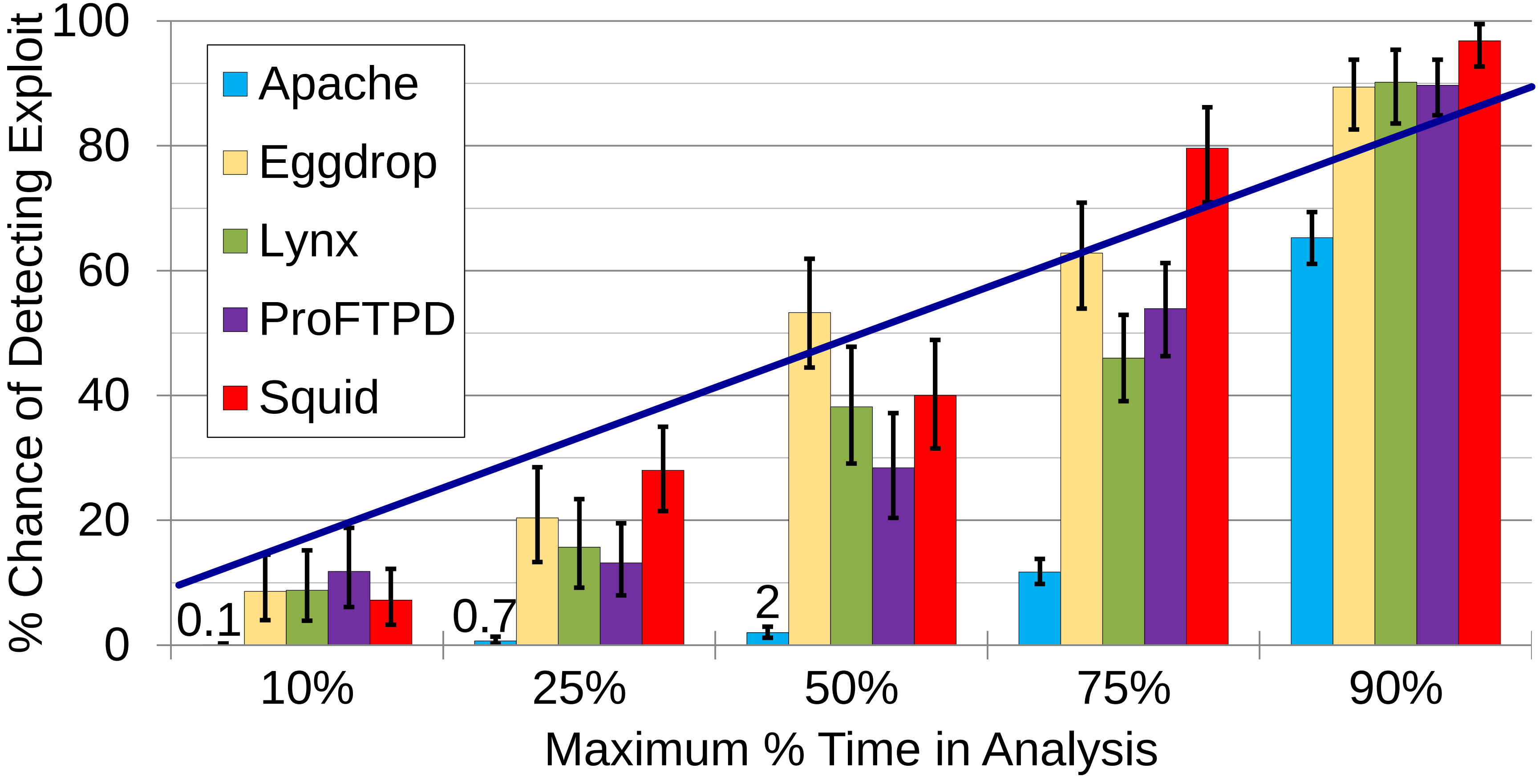
Accuracy with Background Tasks

ssh_receive running in background



Accuracy with Background Tasks

ssh_receive running in background



BACKUP SLIDES

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