DAGguise

Mitigating Memory Controller Side Channels

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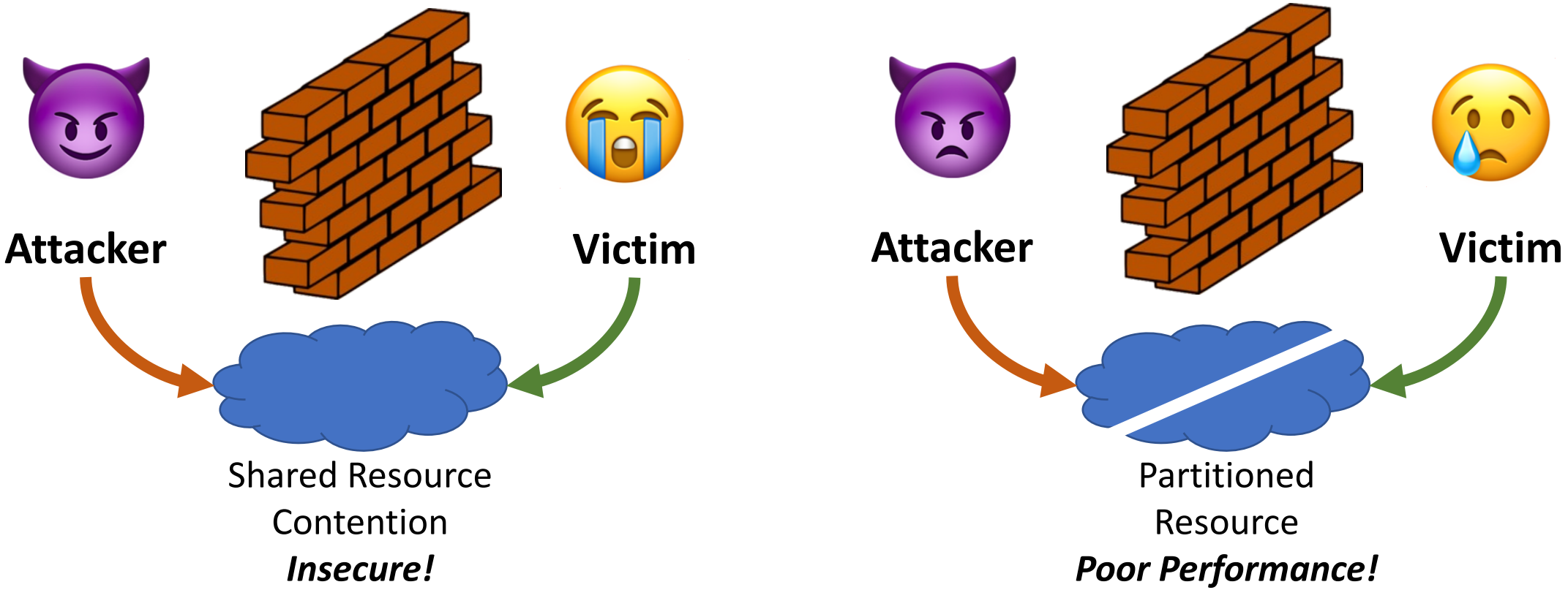
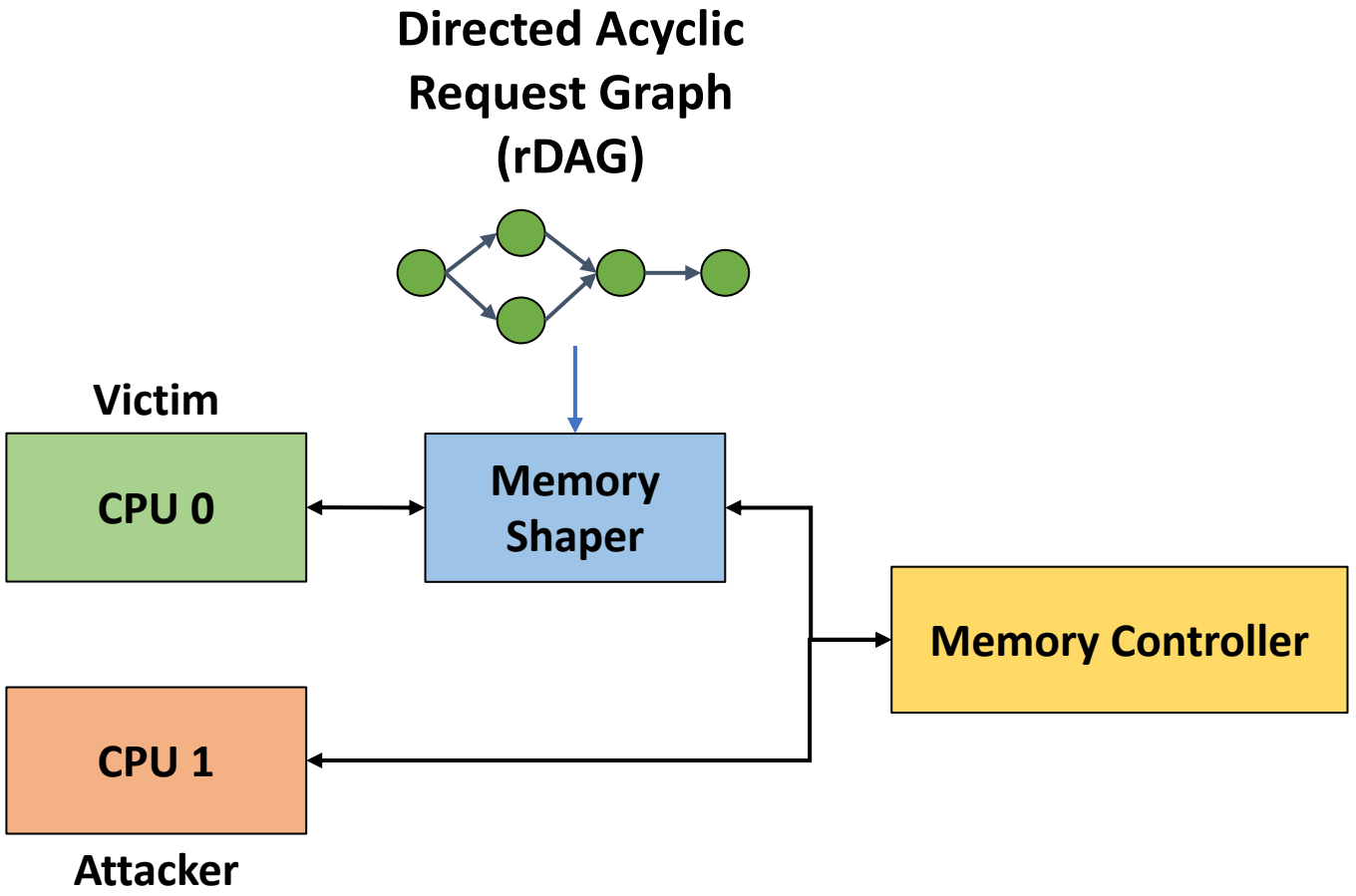
ASPLOS 2022 (Session 3A)

Microarchitectural Side-Channels



<u>Key Defense Tradeoff:</u> Security vs. Performance

DAGguise Key Idea



DAGguise achieves:

✓ **Formally-Verified Security**

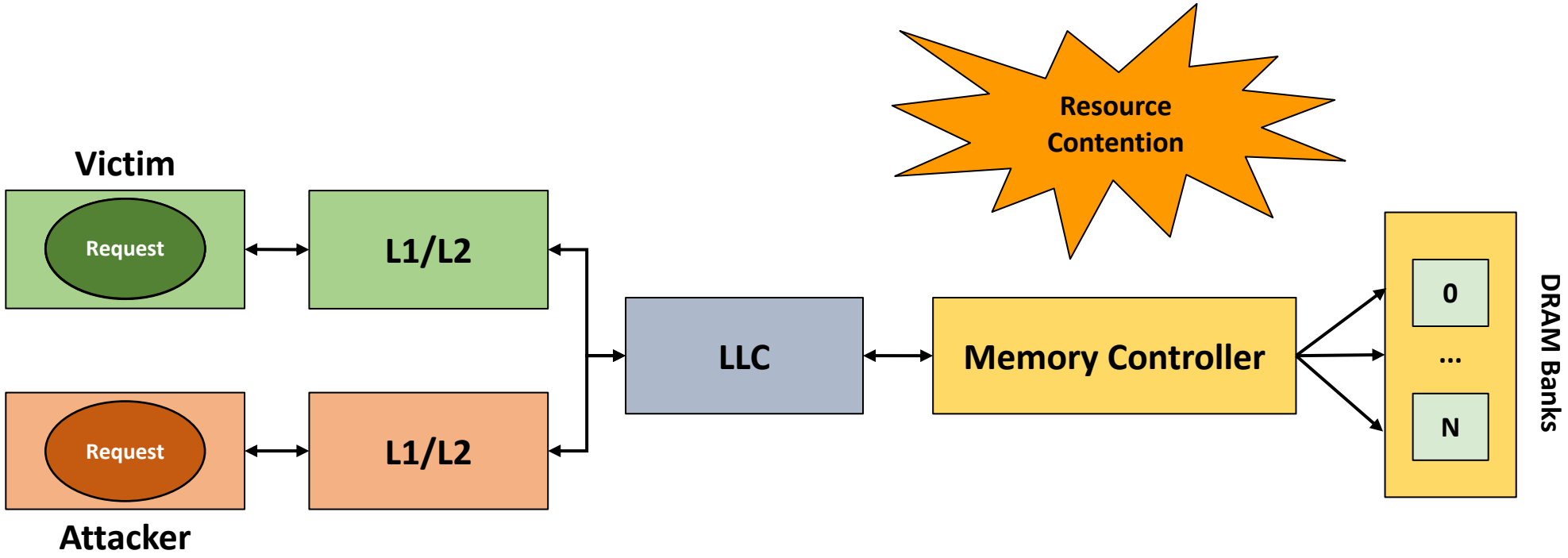
and

✓ **Good Performance**

Outline

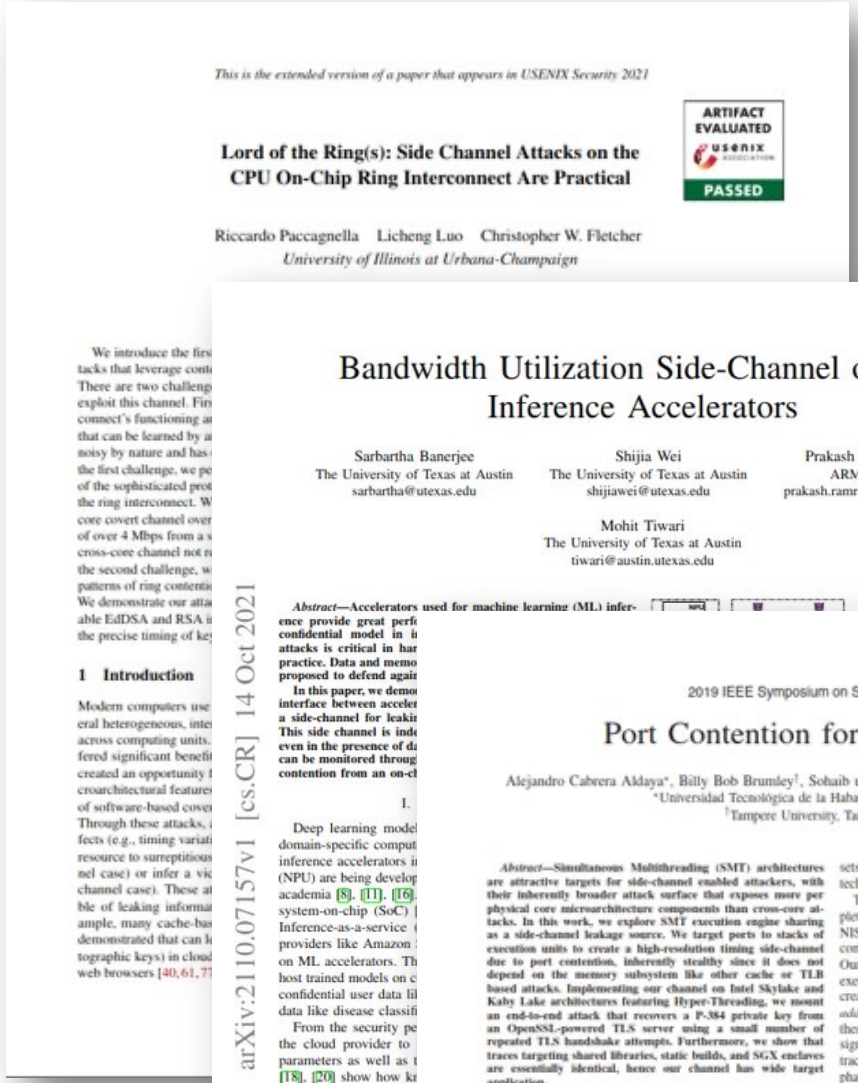
- Memory Controller + Scheduler-based Side Channels
- Existing Approaches
  - Static Partitioning
  - Traffic Shaping
- DAGguise
  - Directed Acyclic Request Graphs (rDAGs)
- Security + Performance Evaluation
- Generalizability

Memory Controller Side Channels



This is a class of "*scheduler-based*" side channels!

Scheduler-Based Side Channels



This is the extended version of a paper that appears in USENIX Security 2021

Lord of the Ring(s): Side Channel Attacks on the CPU On-Chip Ring Interconnect Are Practical

ARTIFACT EVALUATED usenix PASSED

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arXiv:2110.07157v1 [cs.CR] 14 Oct 2021

Bandwidth Utilization Side-Channel on ML Inference Accelerators

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2019 IEEE Symposium on Security and Privacy

Port Contention for Fun and Profit

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DRAMA: Exploiting DRAM Addressing for Cross-CPU Attacks

Peter Pessl, Daniel Gruss, Clémentine Maurice, Michael Schwarz *and* Stefan Mangard
Graz University of Technology, Austria

SMoTherSpectre: Exploiting Speculative Execution through Port Contention

Atri Bhattacharyya* EPFL
Alexandra Sandulescu† IBM Research – Zurich
Matthias Neugschwandtner† IBM Research – Zurich
Alessandro Sorniotti† IBM Research – Zurich
Babak Falsafi* EPFL
Mathias Payer* EPFL
Anil Kurmus† IBM Research – Zurich

arXiv:1903.01843v3 [cs.CR] 26 Sep 2019

Session 10D: VulnDet 2 + Side Channels 2 CCS'18, October 15-19, 2018, Toronto, ON, Canada

Rendered Insecure: GPU Side Channel Attacks are Practical

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ABSTRACT

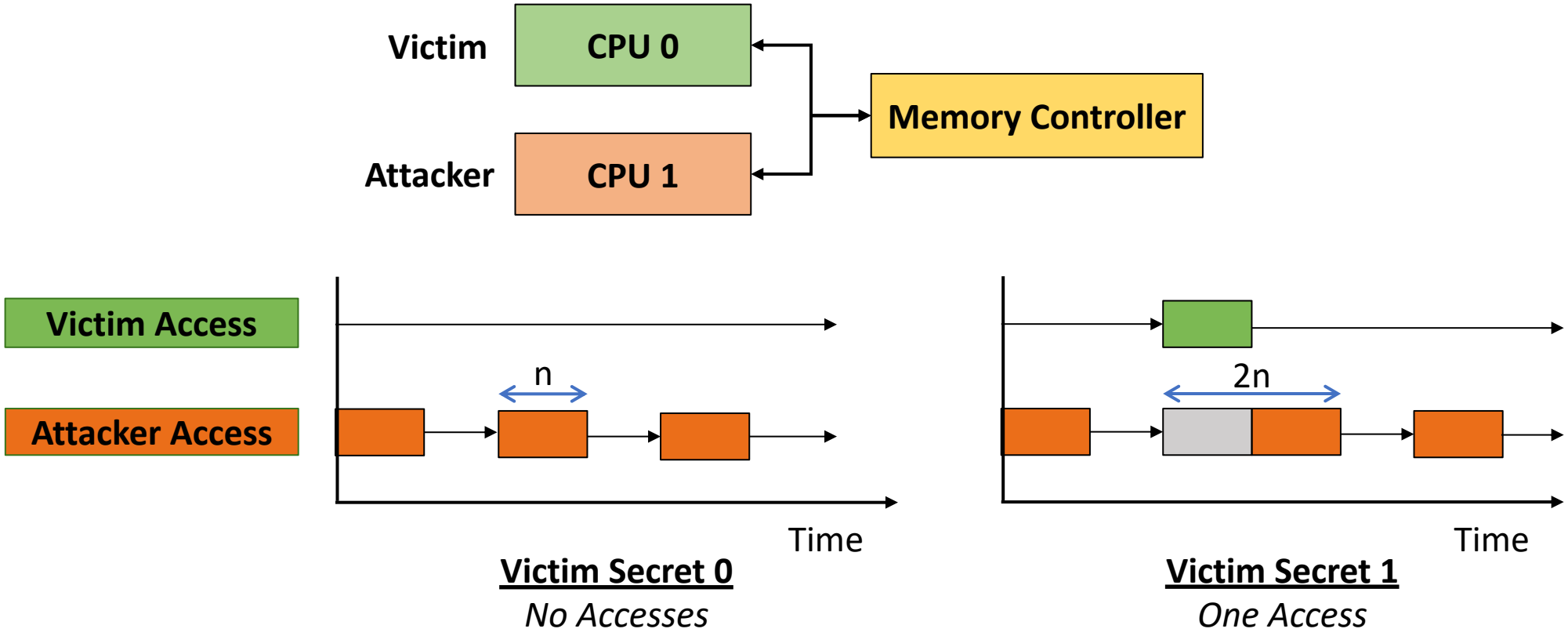
Graphics Processing Units (GPUs) are commonly integrated with computing devices to enhance the performance and capabilities of graphical workloads. In addition, they are increasingly being integrated in data centers and clouds such that they can be used to accelerate data intensive workloads. Under a number of scenarios the GPU can be shared between multiple applications at a fine granularity allowing a spy application to monitor side channels and attempt to infer the behavior of the victim. For example, OpenGL and WebGL send workloads to the GPU at the granularity of a frame, allowing an attacker to interleave the use of the GPU to measure the side-effects of the victim computation through performance counters or other resource tracking APIs. We demonstrate

1 INTRODUCTION

Graphics Processing Units (GPUs) are integral components to most modern computing devices, used to optimize the performance of today's graphics and multi-media heavy workloads. They are also increasingly integrated on computing servers to accelerate a range of applications from domains including security, computer vision, computational finance, bio-informatics and many others [52]. Both these classes of applications can operate on sensitive data [25, 31, 57] which can be compromised by security vulnerabilities in the GPU stack.

Although the security of GPUs is only starting to be explored, several vulnerabilities have already been demonstrated [46, 49, 55, 58, 63, 71, 74]. Most related to this paper, Luo et al. demonstrated a

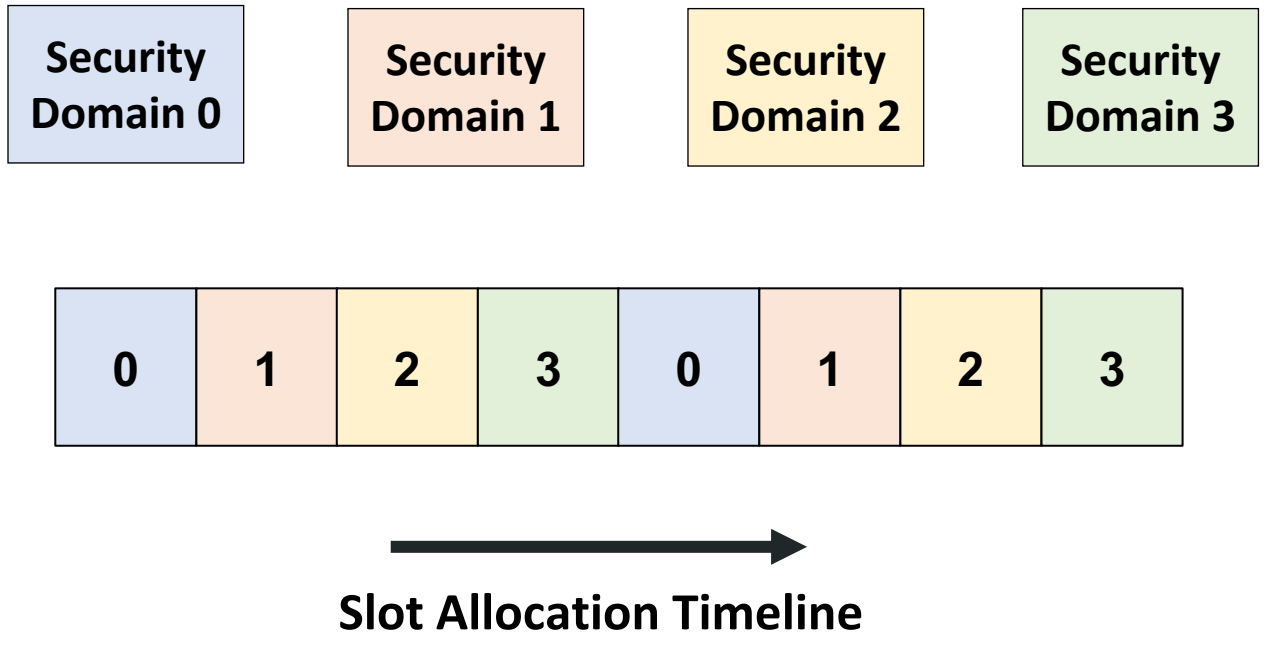
Timing Attack Example



The attacker uses its *own* latencies to leak information!

Static Partitioning in Time

Use a Round Robin, No-Skip Arbitration Policy



✓ **Secure**

Static partitioning, no leakage

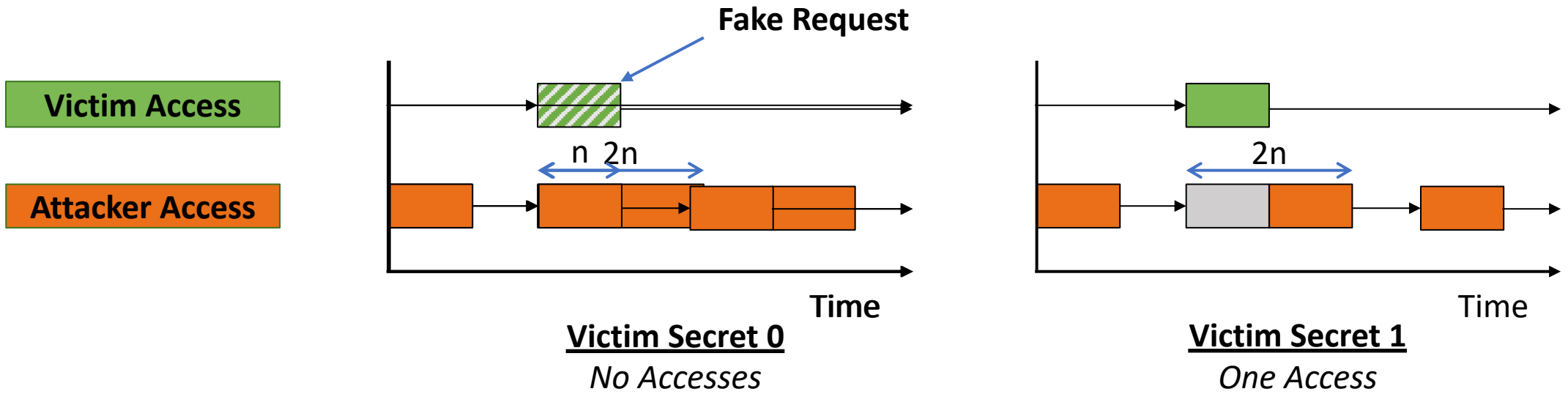
✗ **Bad Performance**

Poor bandwidth utilization!

Avoiding Information Leakage in the Memory Controller with Fixed Service Policies (Shafiee et al., Utah, ISCA 2015)

Traffic Shaping

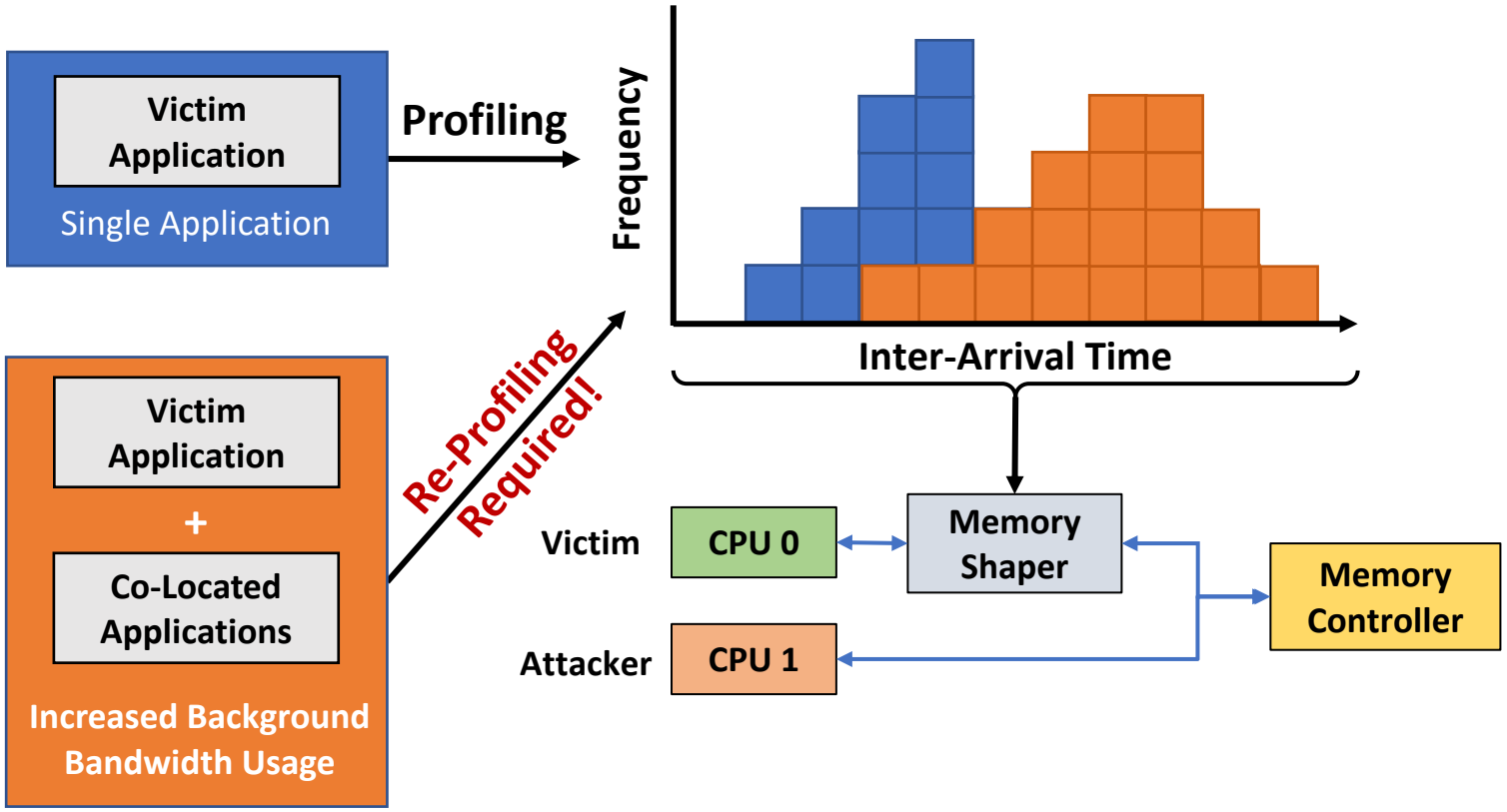
Shaping Strategy: Delay victim's existing requests and add fake requests



How do we do this for real applications without significant costs?

Camouflage's Traffic Shaping Strategy

Shape memory requests to a secret-independent *timing distribution*



✓ Good Performance

Dynamic sharing of the memory controller

✗ Insecure

Ordering or bank information can reveal the secret

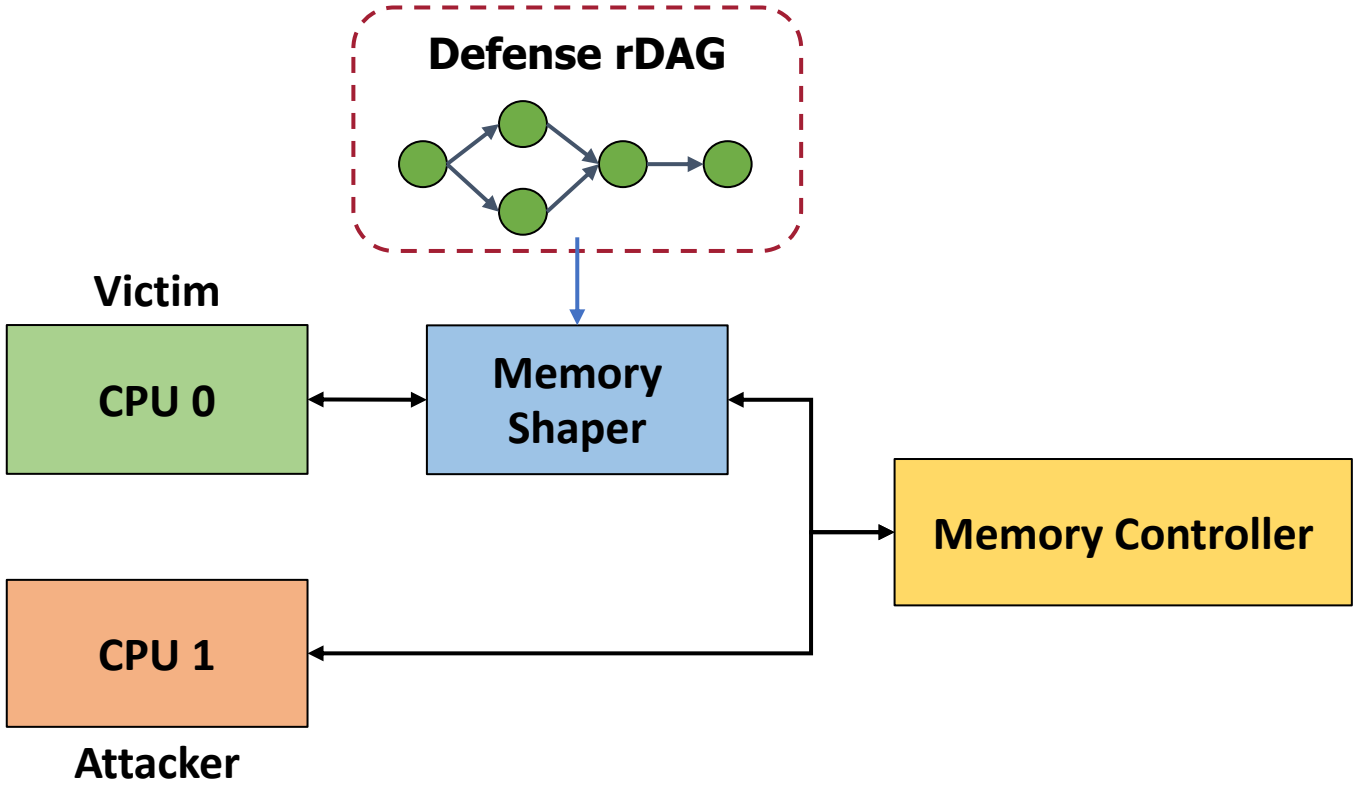
✗ Expensive Profiling

Ideal shaping distribution depends on co-running applications

Camouflage: Memory Traffic Shaping to Mitigate Timing Attacks (Zhou et al., Princeton, HPCA 2017)

DAGguise's Traffic Shaping Strategy

Shape memory requests to a secret-independent
Directed Acyclic Request Graph (rDAG)

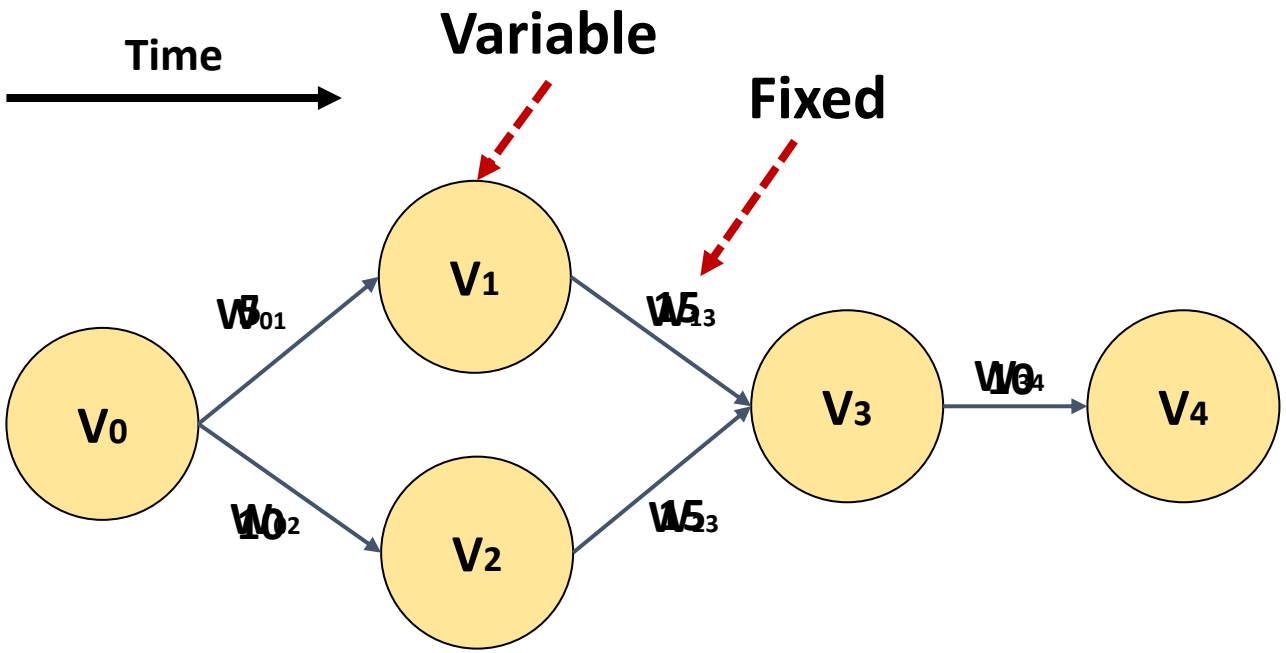


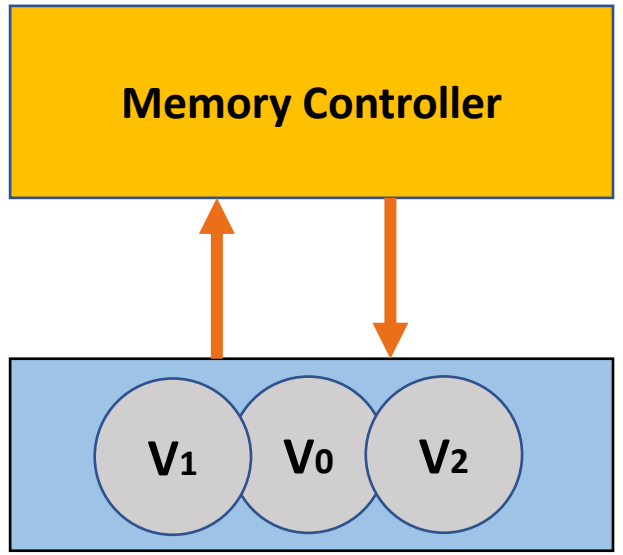
✓ Secure

✓ Good Performance

✓ Profile Victim Alone

Directed Acyclic Request Graphs





Vertices

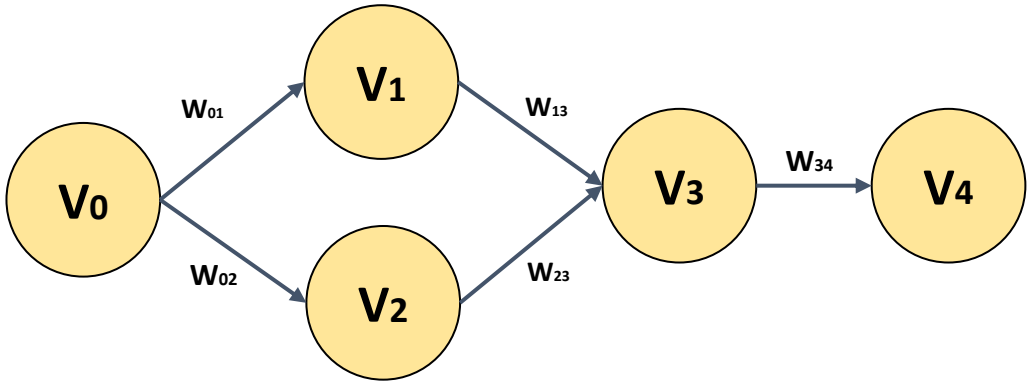
Memory requests with ***variable*** latency

Edges

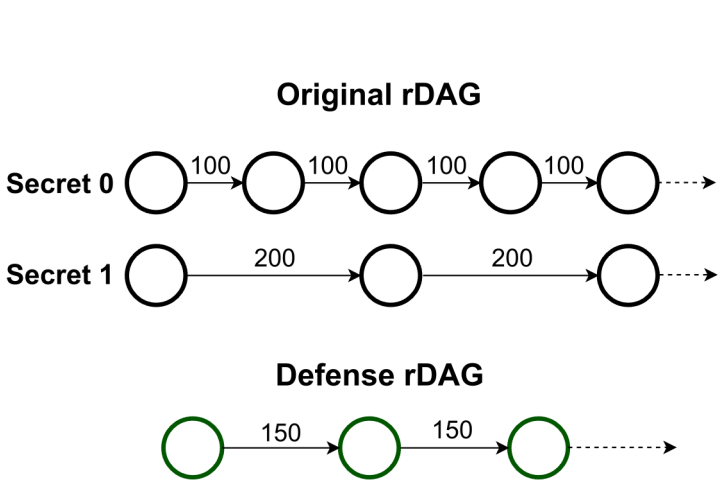
Dependencies between memory requests with ***fixed*** latency

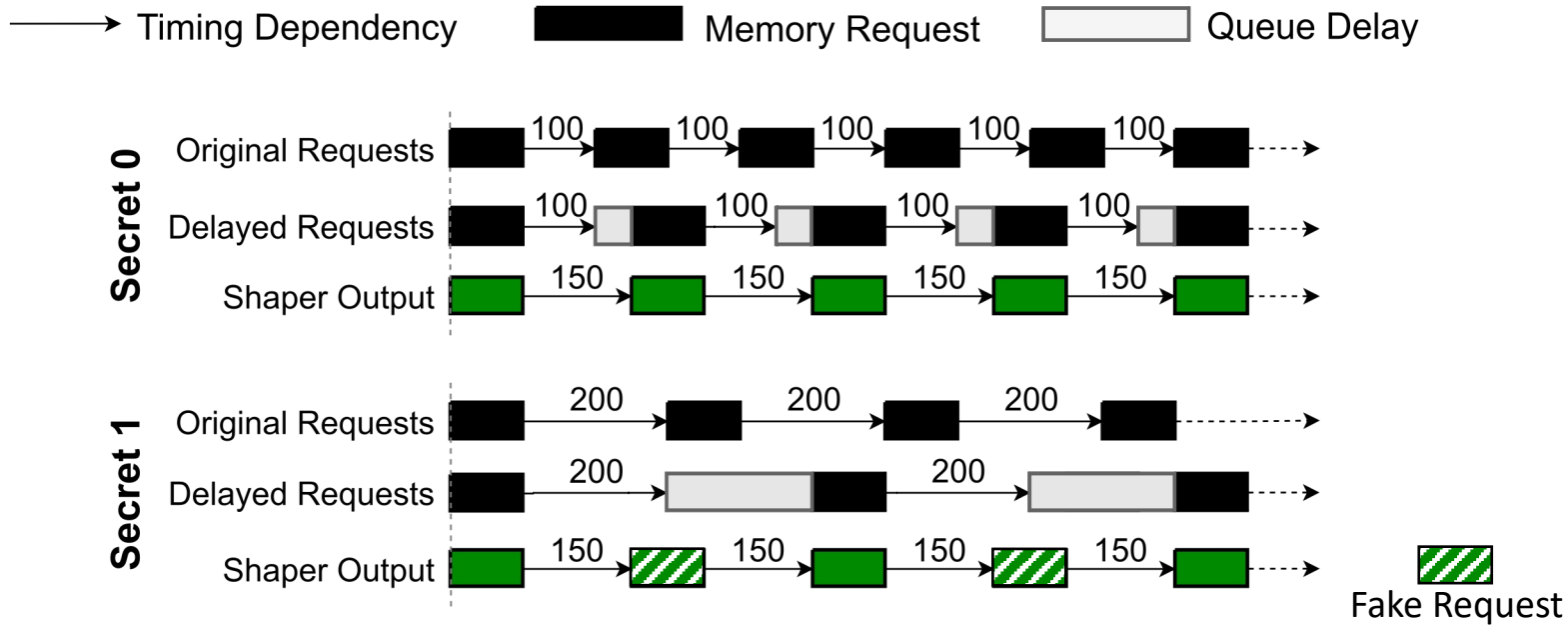
Why shape requests to an rDAG?

- ✓ **Security**
  - Shaping to a secret-independent defense rDAG makes victim request patterns *indistinguishable*
  - Defense rDAGs are public and are the only thing an attacker can recover
- ✓ **Performance**
  - Allows for *dynamic* sharing of memory resources in the memory controller
- ✓ **Profiling Cost**
  - Does not require knowledge of co-located applications



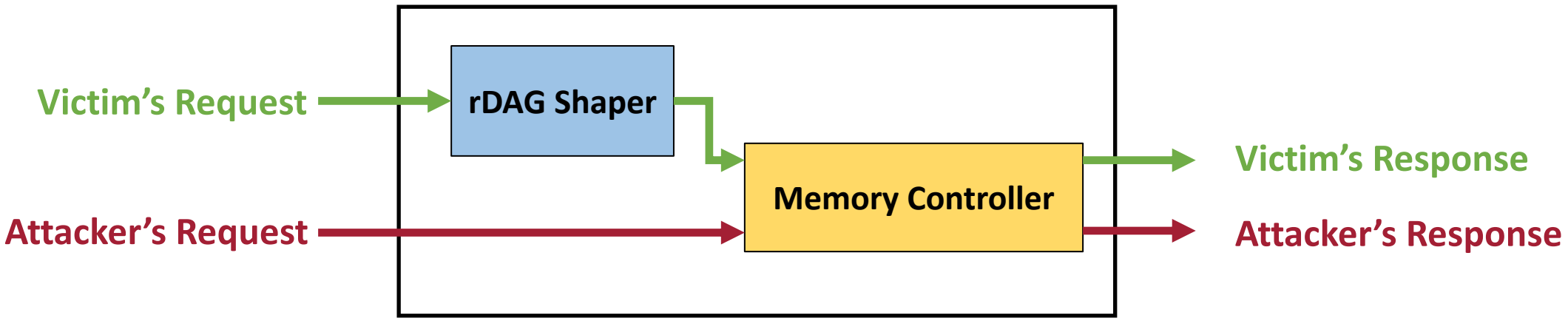
Simple Shaping Example





The shaper output is always the same, *no matter the secret*!

Indistinguishability Property



The attacker's observations should be *independent* from victim's request pattern

Indistinguishability Property

- Attacker's observation is independent from victim's request pattern
  - Given an attacker's request pattern, the attacker has an identical observation when contending with **ANY** victim's request pattern
  - This holds for **ANY** attacker's request pattern

Attacker's Observations when Contending with Victim

Victim Request Patterns / Attacker Request Patterns	A	B	C	… …
X	Attacker's Response Pattern X			

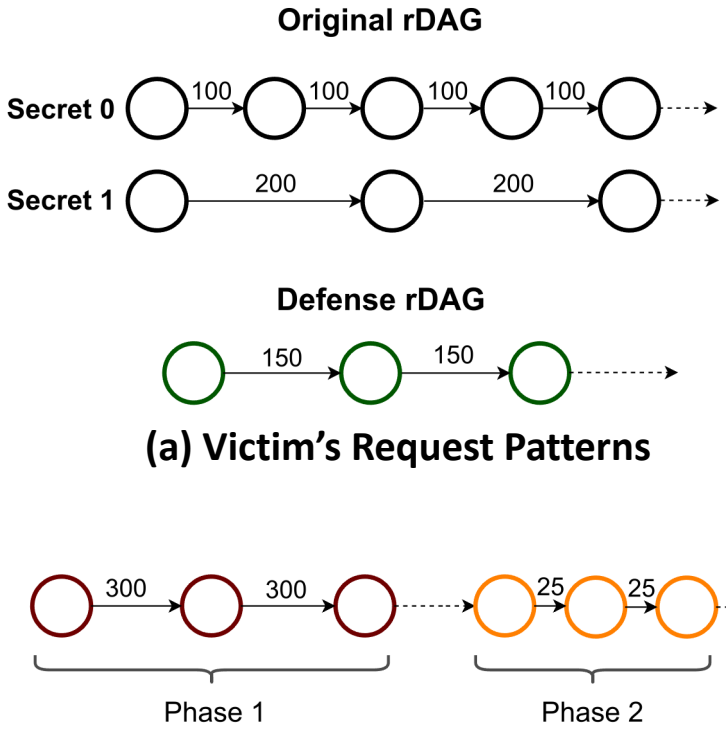
Formalization & Verification

- Formalize the indistinguishability property using state transitions

$$\begin{aligned} \mathrm{P}(S_0, n) := \;& \forall\ \mathrm{Req}_{Tx}, \mathrm{Req}'_{Tx},\ \ \forall\ \mathrm{Req}_{Rx} \\ & \textbf{if}\ \ S_0 \xrightarrow[\mathrm{Req}_{Tx},\mathrm{Req}_{Rx}]{\mathrm{Resp}_{Tx},\mathrm{Resp}_{Rx}} S_n \ \ \text{and}\ \ S_0 \xrightarrow[\mathrm{Req}'_{Tx},\mathrm{Req}_{Rx}]{\mathrm{Resp}'_{Tx},\mathrm{Resp}'_{Rx}} S'_n \\ & \textbf{then}\ \ \mathrm{Resp}_{Rx} = \mathrm{Resp}'_{Rx} \end{aligned}$$

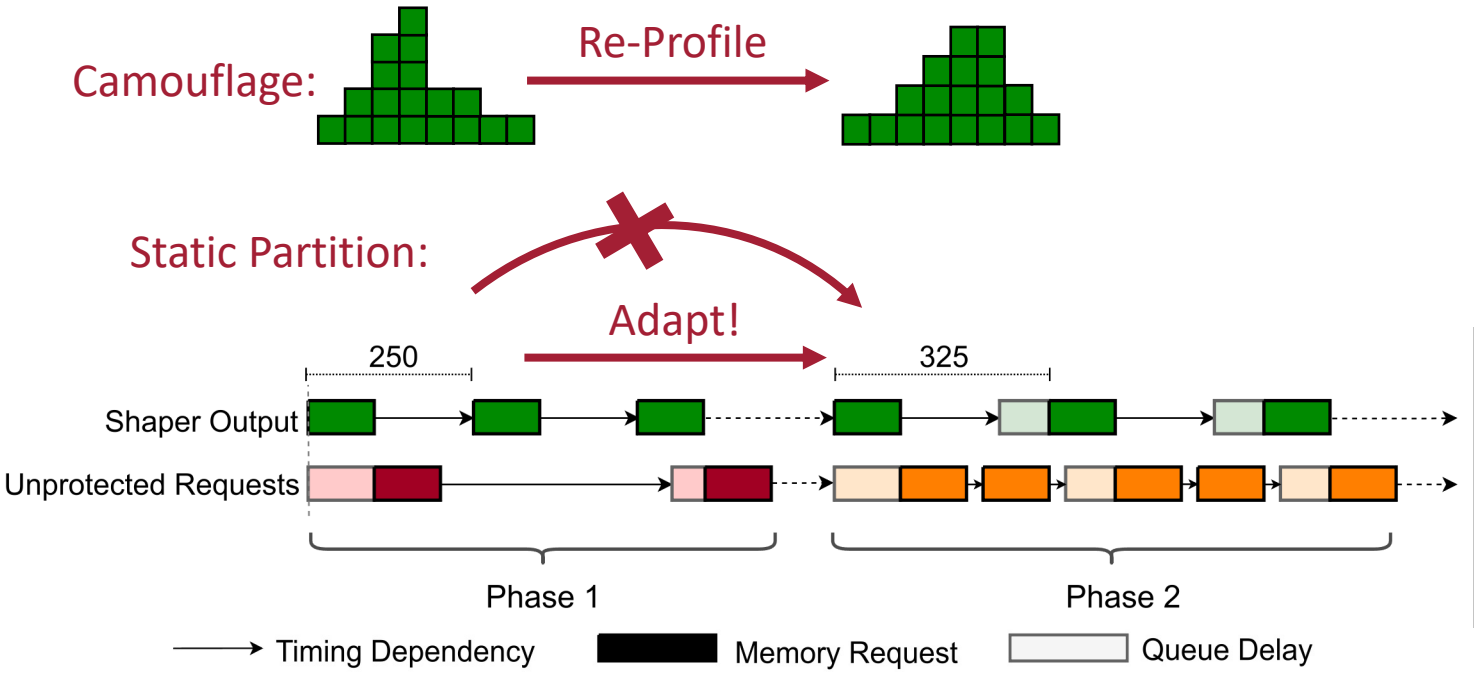
- Verification with *Rosette*:
  - First k cycles: symbolic execution
  - Arbitrary cycles: k-induction

rDAG Adaptivity



(a) Victim's Request Patterns

(b) Unprotected Program's Request Patterns

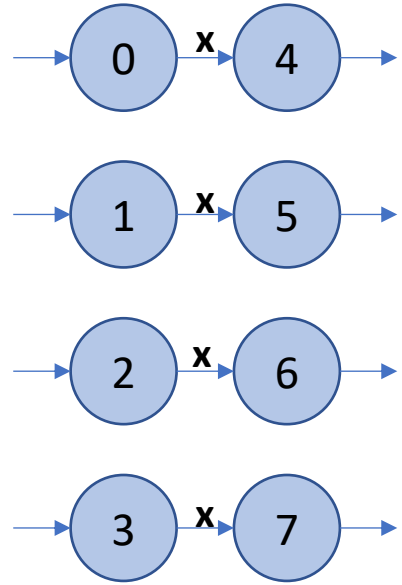


(c) Contention between Victim and Unprotected Program on Memory Controller

rDAG's adaptivity allows for better bandwidth utilization!

Offline Profiling Step

- Not for security, ***any*** secret-independent rDAG ensures security
- Low profiling cost
  - Victim is profiled ***alone***
  - Reduce search space by finding parameters for an rDAG *template*

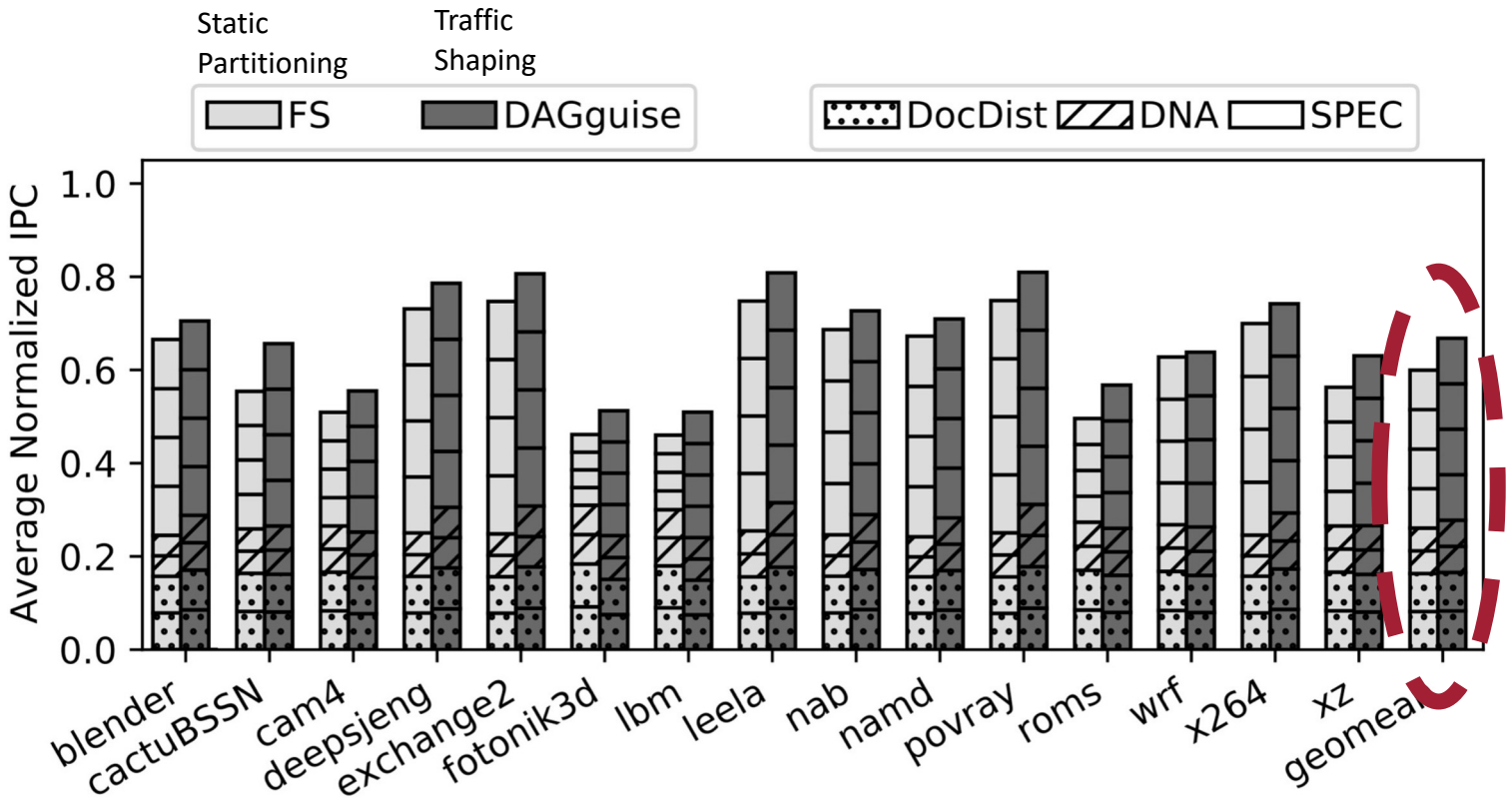


4-Parallel rDAG Template

Experimental Setup

- **Simulator:** gem5 and DRAMSim2
- **Architectural Specifications:**
  - 2 and 8 out-of-order CPU cores
  - 32KB L1i/d, 256kB L2, 1MB/core L3
- **Evaluated Configurations:**
  - DAGguise
  - Fixed Service (Bank Triple Alternation)
  - Baseline
- **Evaluated Applications:**
  - Unprotected SPEC benchmark(s) co-running alongside DAGguise protected application(s)

Experimental Results

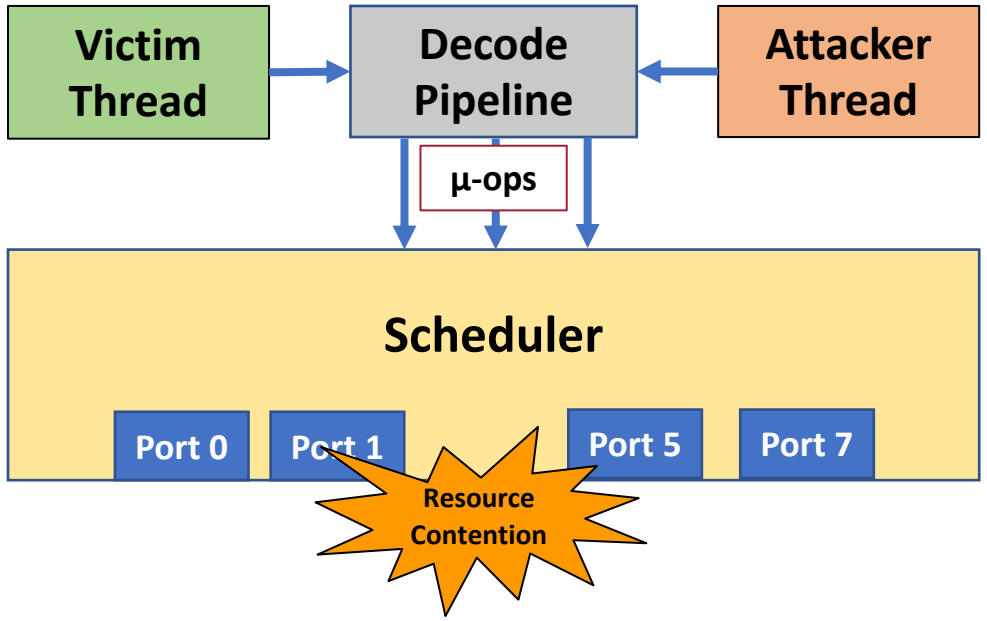


DAGguise's improves performance for both protected *and* unprotected applications!

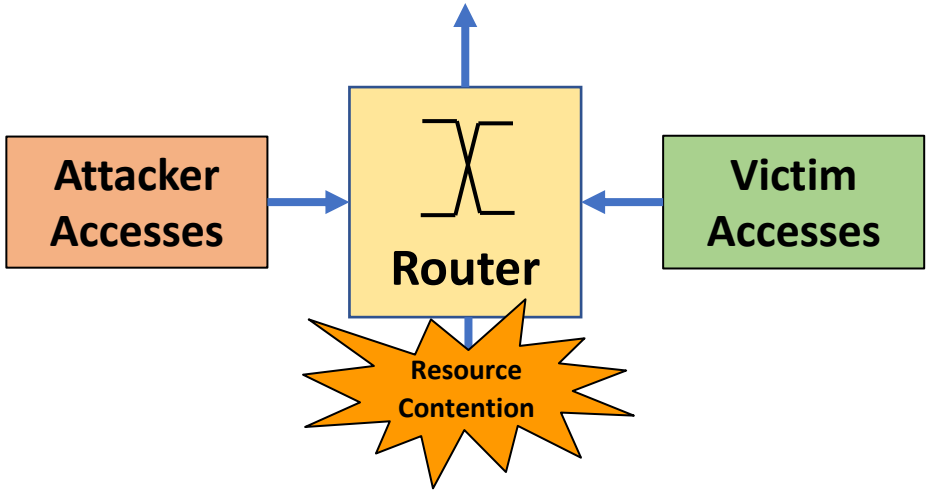
DAGguise achieves a 12% performance improvement over Fixed Service in an 8-CPU system

DAGguise Generalization

SMT Contention



Network on Chip Contention

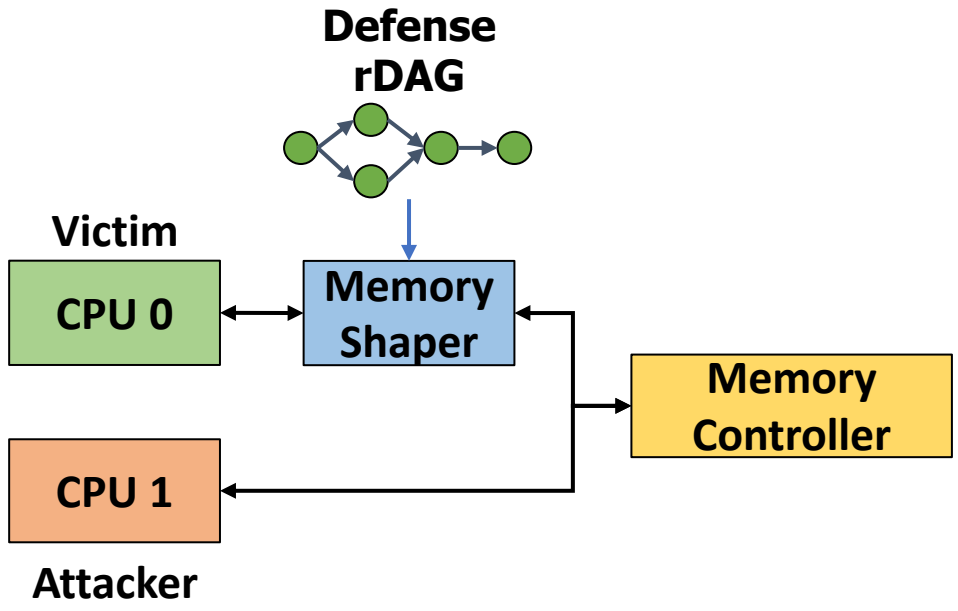


More in the Paper

- Implementation details of DAGguise shaper
- Formal security verification using symbolic execution and k-induction
- Detailed rDAG offline profiling process
- More performance and area overhead evaluation
- Generalizations to other scheduler-based side channels (e.g. port contention)

Conclusion

- DAGguise
  - A memory traffic shaper which:
    - Completely eliminates data leakage
    - Allows for dynamic contention
    - Requires only simple profiling
- rDAGs
  - A *general* and *adaptive* request representation
- A formal model of correctness using *Rosette*
- A generalized scheduler-based attack mitigation framework



DAGguise

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