Deterministically Deterring Timing Attacks in Deterland

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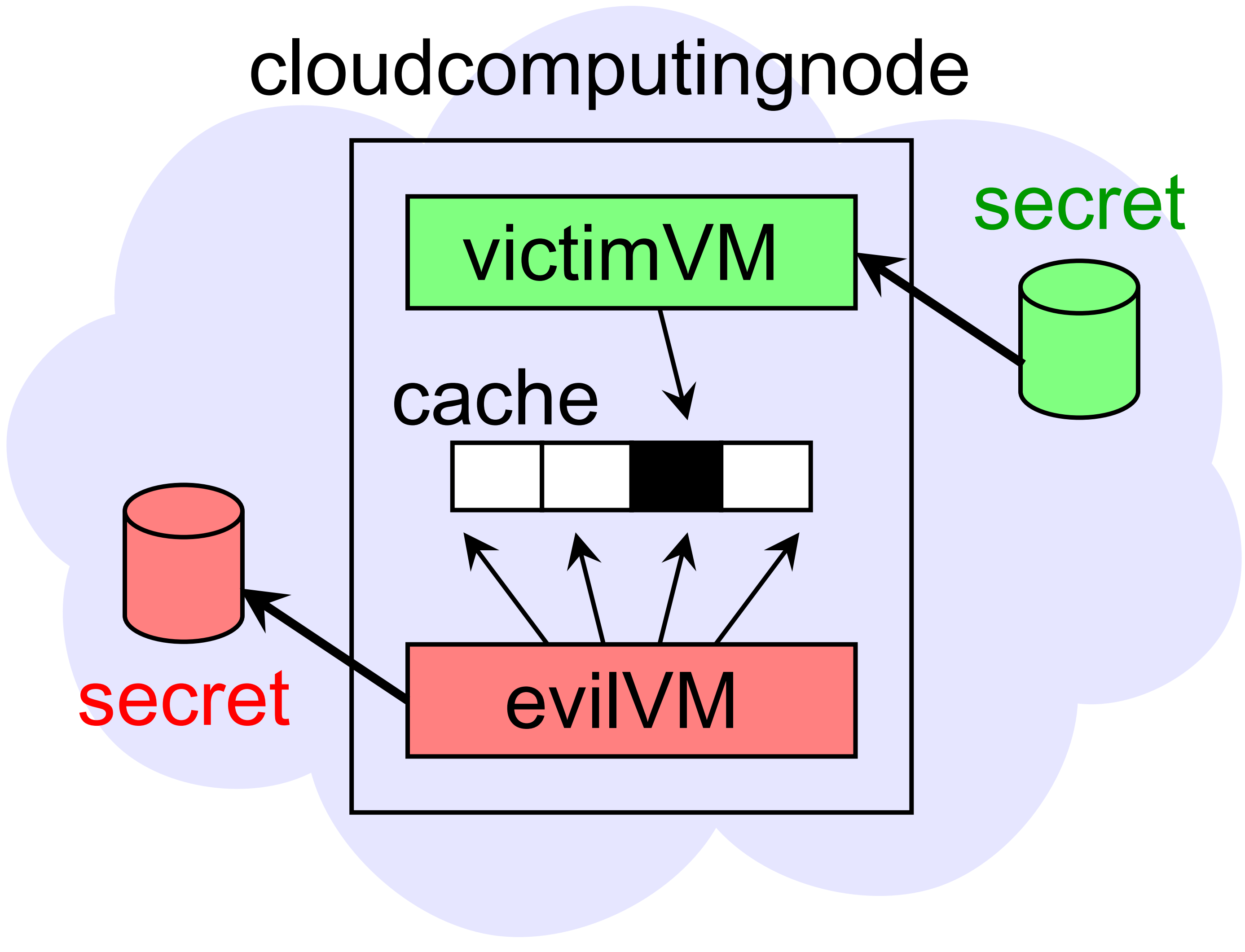
Timing Attacks via Shared Hardware Resources



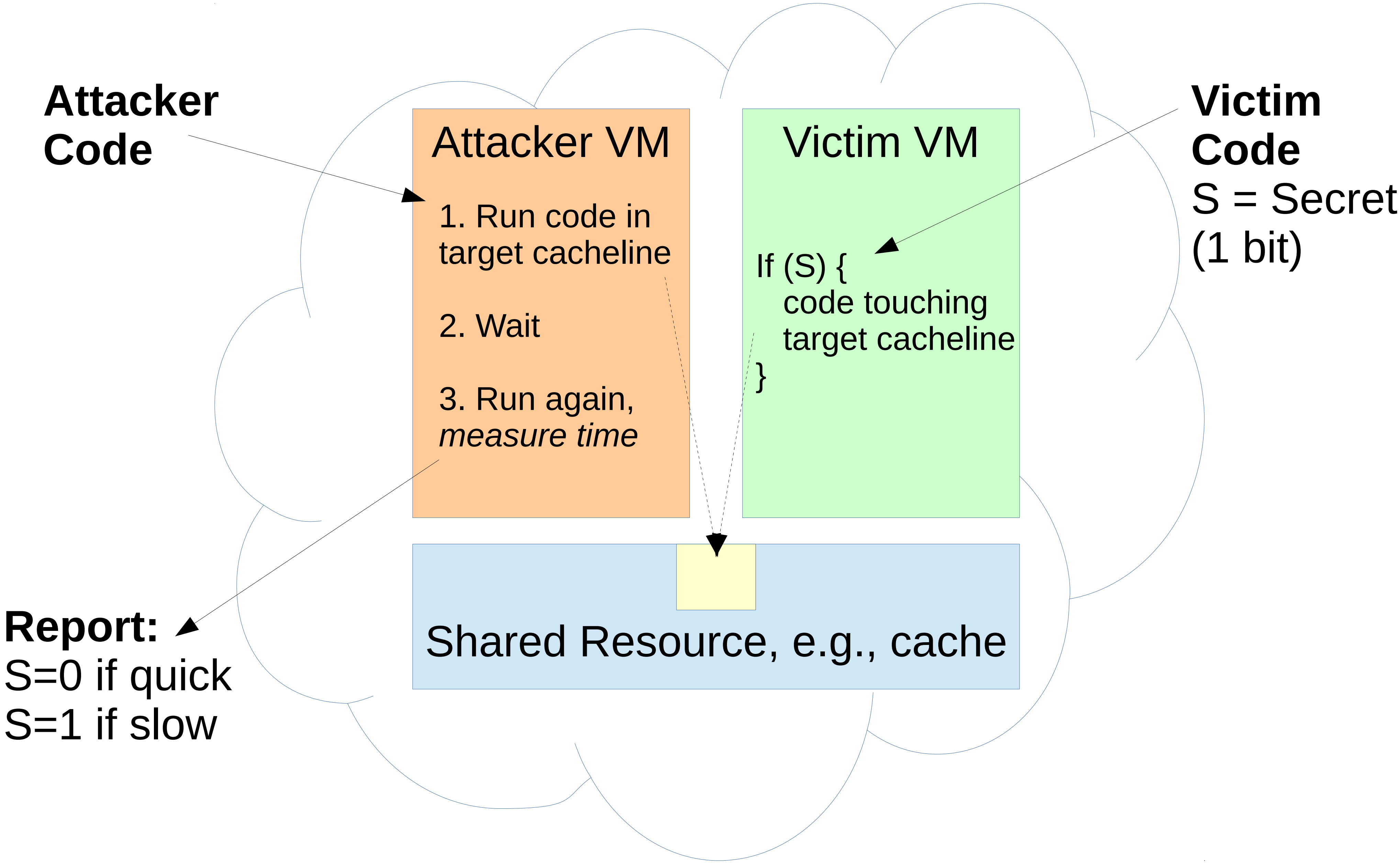
Talk Outline

- Background: Attacks and Mitigation in the Cloud
- Design: Hypervisor-Secure Mitigation
- Implementation: Deterland Hypervisor
- Preliminary Results: It Works (at a Cost)
- Conclusion

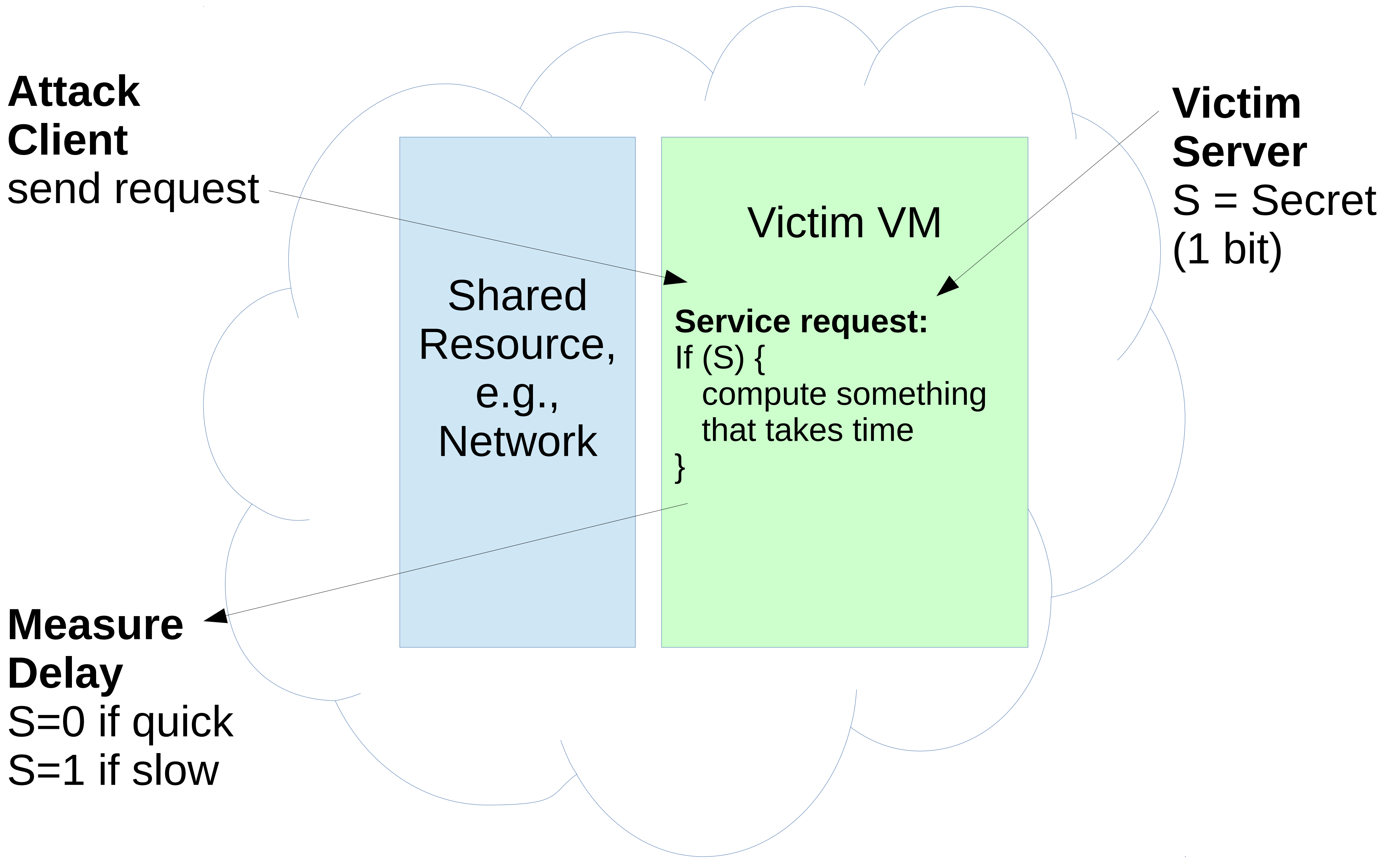
Timing Attack Background

- **Internal or Local Attacks:**
  - Attacker controls VM co-resident with victim
  - Operates from *within* the cloud environment
  - Ristenpart et al, “Get Off My Cloud” 2009
- **External or Remote Attacks:**
  - Attacker has *limited/no* control over guest VM
  - Operates from *outside* the cloud environment
  - Brumley/Boneh, “Remote timing attacks” 2005

Internal Attacks: Simplified Example



External Attacks: Simplified Example



Demonstrated Attacks

- Internal/Local attacks naturally easier
  - Through *many* resources:
    L1 code cache, L1 data cache, function units,
    branch target cache, last-level cache, …
  - Including cross-VM attacks in cloud environments
    [Zhang'12, Yarom'13, Irazoqui'14, …]
- But External/Remote attacks demonstrated too
  - e.g, remotely steal private RSA keys from
    non-constant-time SSL/TLS libraries
    [Bonneau'06, Brumley'10, Chen'10, …]

Why Pick On Cloud Computing?

Cloud computing **exacerbates vulnerabilities:**

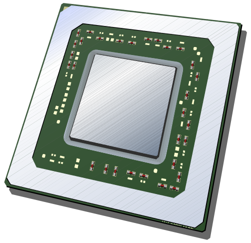
1. Mutually distrustful tasks *routinely co-resident*
2. Clouds introduce *massive parallelism*
3. Cloud-based timing attacks *won't get caught*
4. Partitioning defeats *elasticity of the cloud*

Aviram et al., “Determinating Timing Channels in Compute Clouds” [CCSW '10]

Timing Channel Mitigation

Timing channels require: [Wray 91]

- A *resource* that the victim process may (inadvertently) modulate



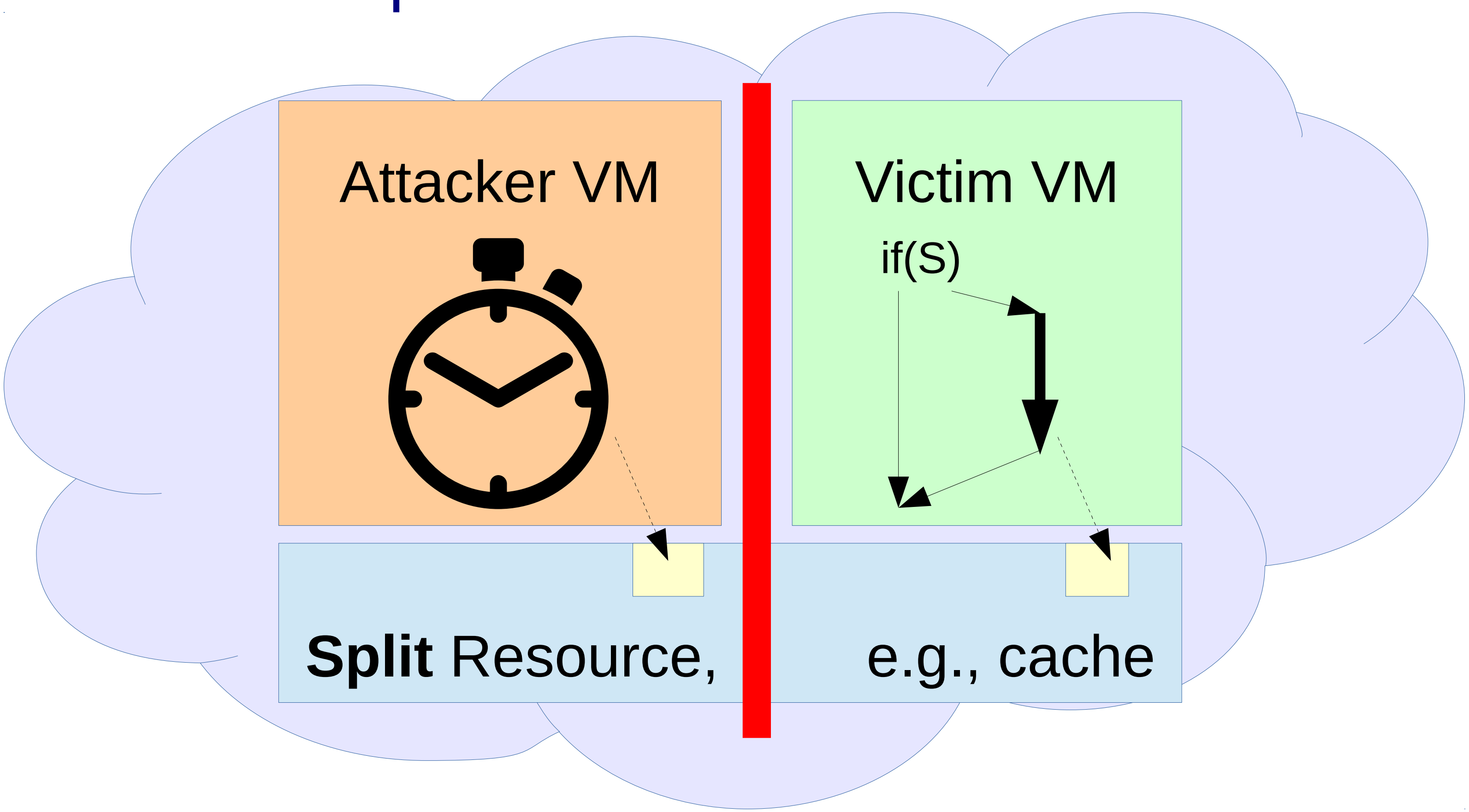
- A *reference clock* enabling the attacker to observe, extract the modulated signal

Remove either → no timing channel.

Approach 1: Eliminate Modulation

(a) by statically partitioning hardware resources

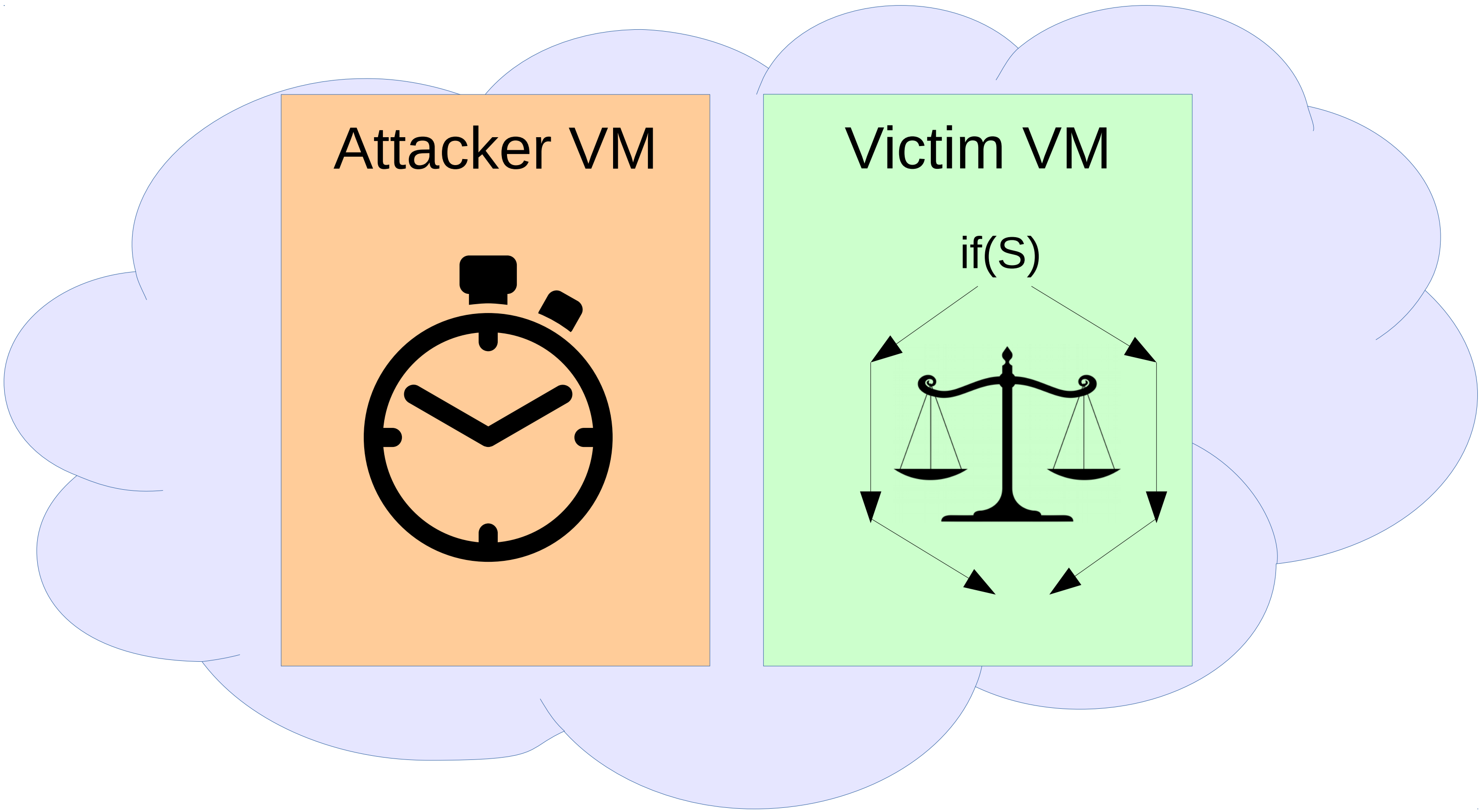
- Generalizes over **code**, must modify **hardware**
- Incompatible with **cloud business model**



Approach 1: Eliminate Modulation

(b) via constant-time code execution

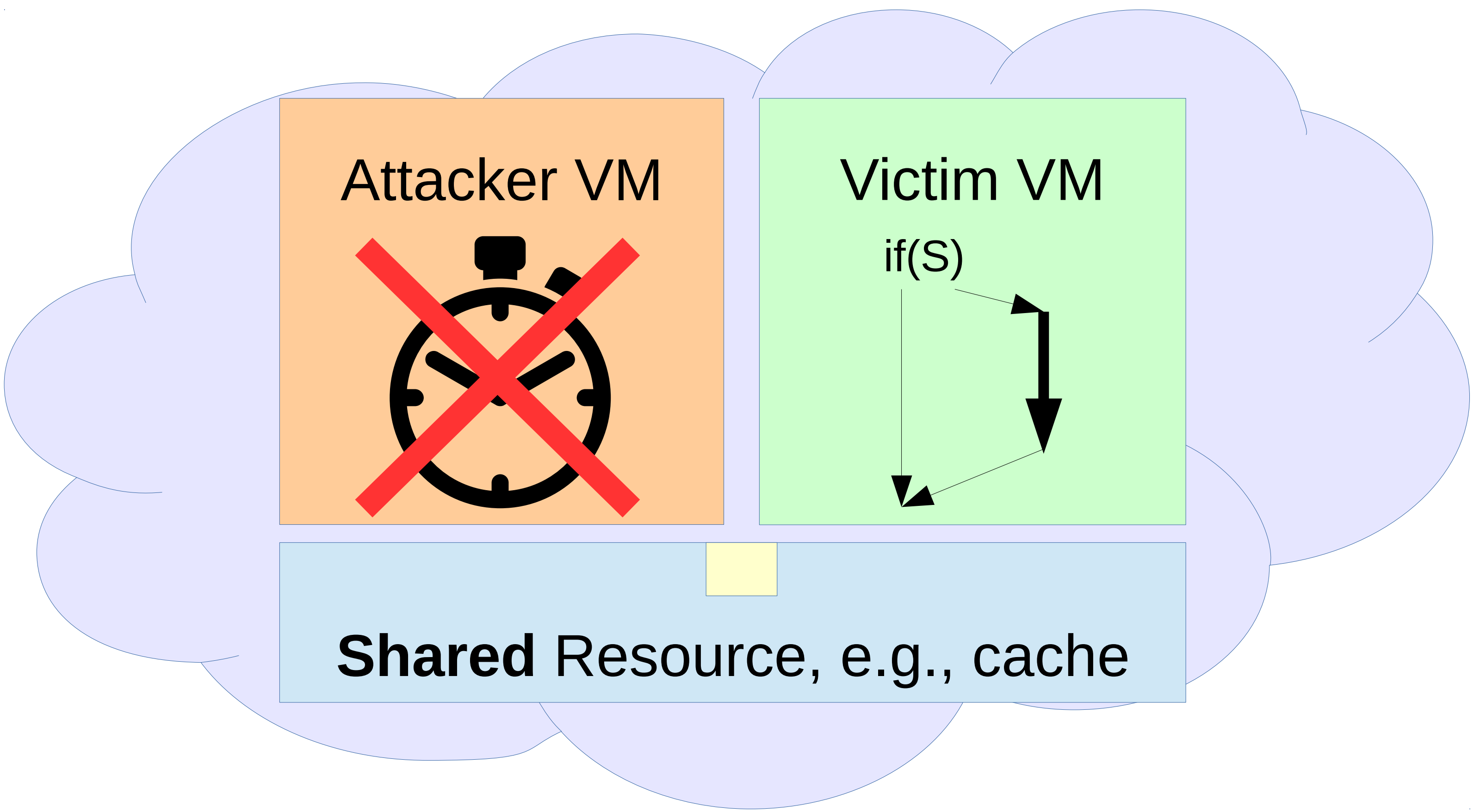
- General **hardware**, but specialized **code**
- Difficult to write, broken by “smart” compilers



Approach 2: Deny Reference Clocks

If attack VM can't **tell time**, can't **measure time**

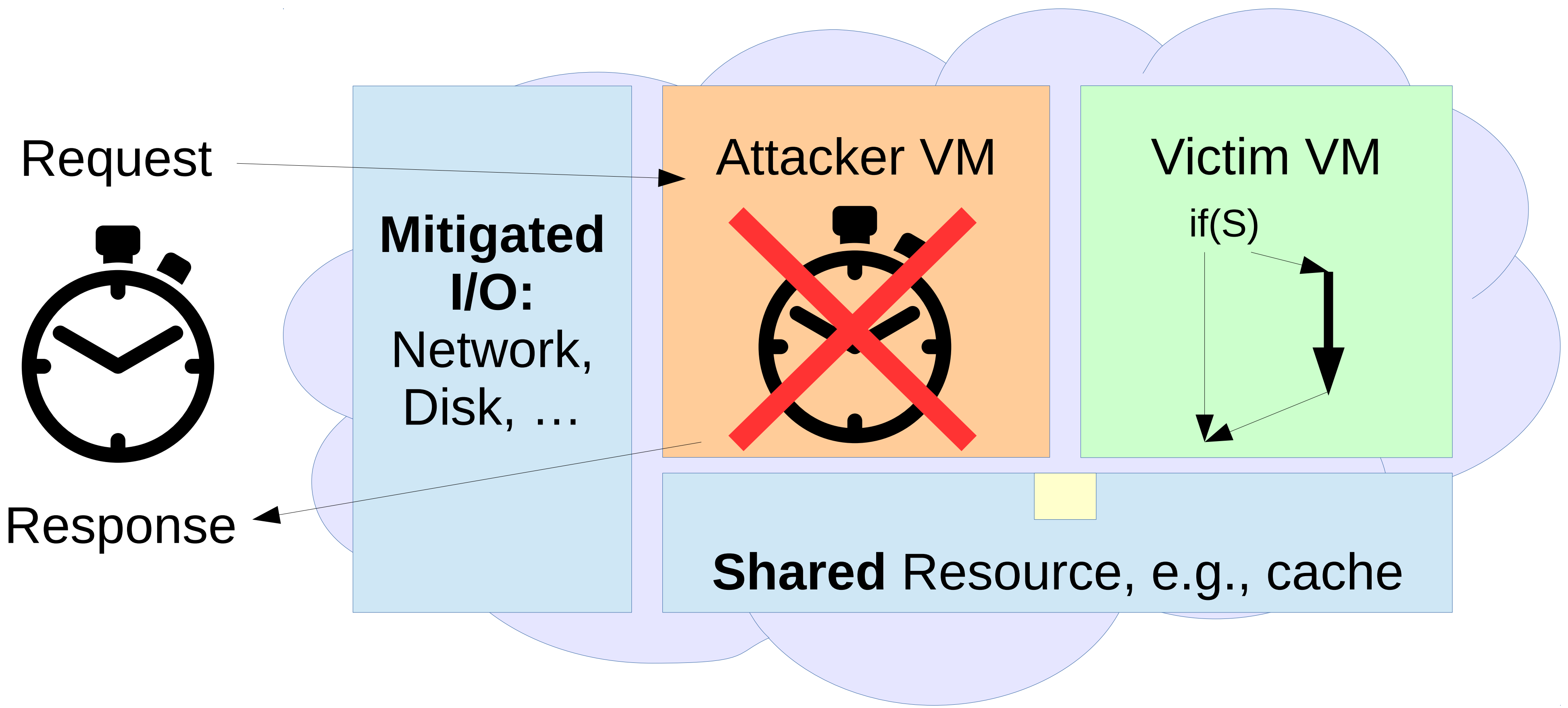
- At least not locally, **internal** to cloud



Approach 2: Deny Reference Clocks

Attacker can still **measure time remotely**

- But we **mitigate** to rate-limit external leakage



Deterministic Mitigation

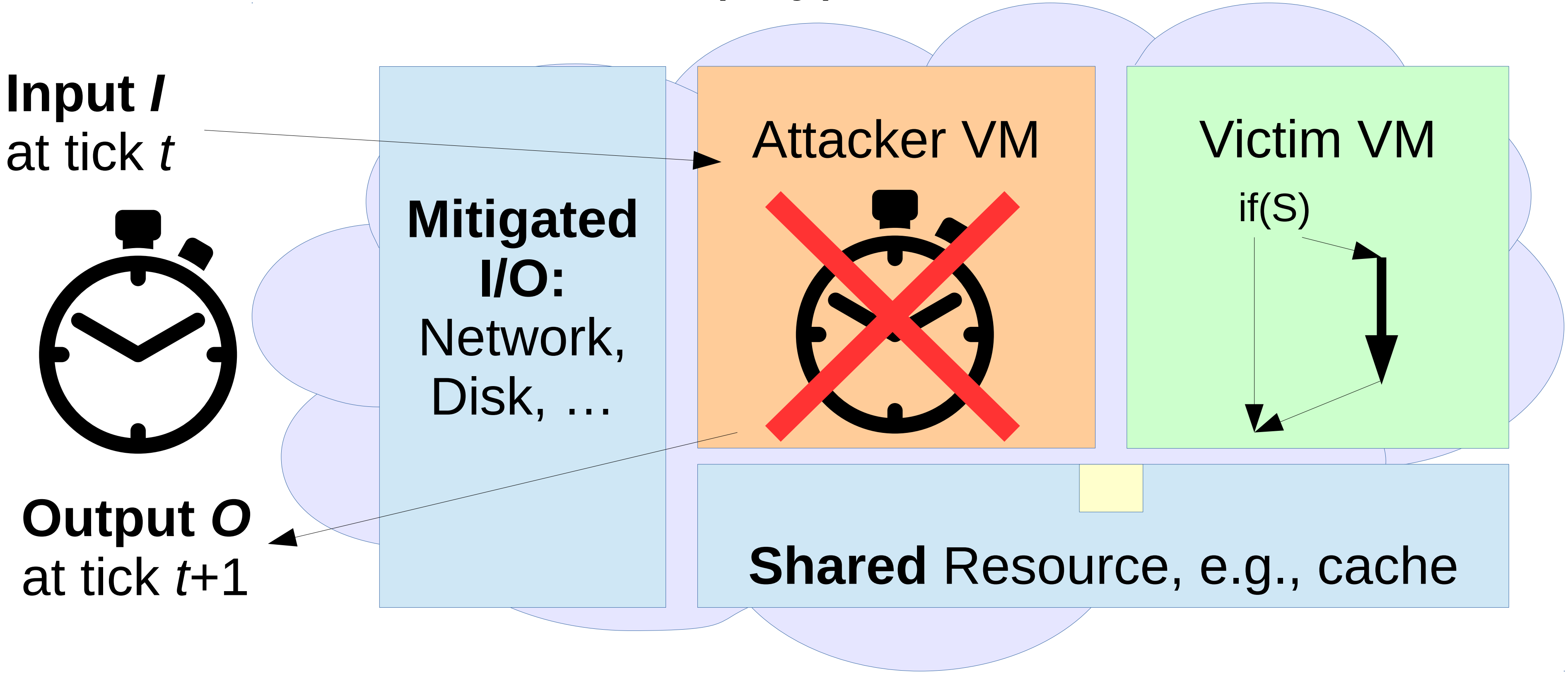
- Variants proposed independently by:
  - [Aviram'10] – Determinator basis, cloud focus
  - [Askarov'10] – PL basis, formal analysis
  - [Stefan'12] – PL basis, Haskell/Monads prototype
- No prior prototype of *general mitigation* compatible with *existing* apps & Oses

Talk Outline

- Background: Attacks and Mitigation in the Cloud
- **Design: Hypervisor-Secure Mitigation**
  - Timing-Channel Mitigation Overview
  - System-enforced Determinism in Deterland
  - Practical hypervisor-enforced mitigation
- Implementation: Deterland Hypervisor
- Preliminary Results: It Works (at a Cost)
- Conclusion

Overly-Simplified Example

- Batch operation, known worst-case exec time
  - Attacker submits input *I*, cloud computes pure *f*(*I*), always returns result *exactly* 1 "clock-tick" later because *f* limited to (say) 1M instructions



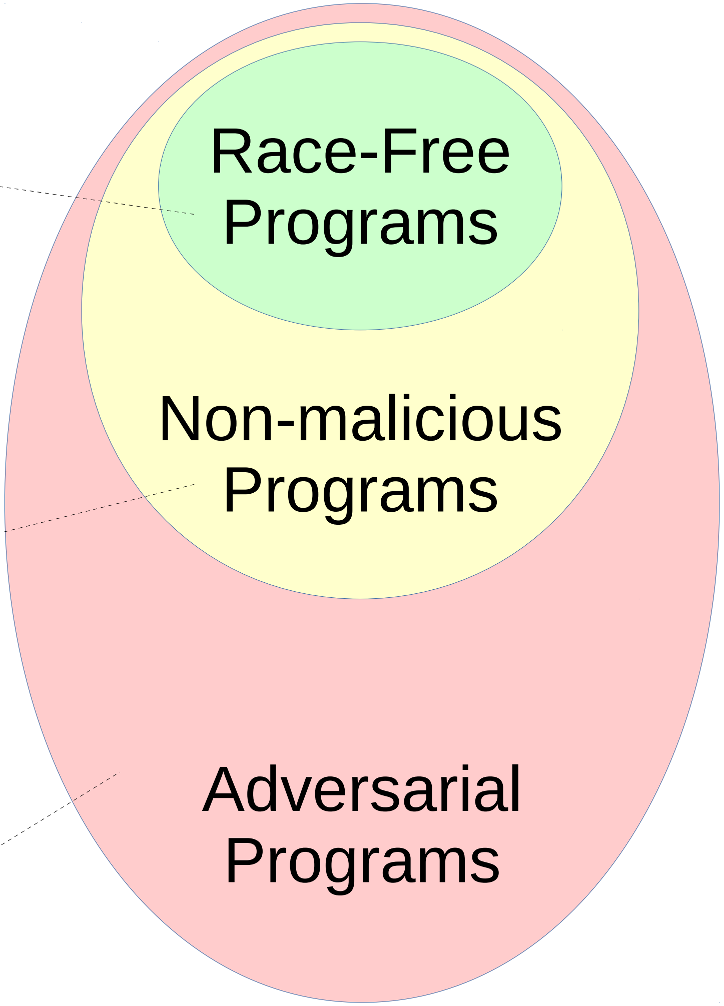
Overly-Simplified Example

Intuitive reasoning (formalized by Askarov):

- Attacker can learn leaked info only via either **content** of output ***O*** or **timing** of its production
  - If ***O*** is a **pure function** of its explicit input, ***O = f(I)***, then ***O*** cannot depend on nondeterministic timing
    - Principle: **determinism** closes **internal** timing channels
  - If ***O*** is always produced after **the same delay**, then timing of ***O*** cannot reveal any information
    - Principle: **constant delay** closes **external** channels

What Type of Determinism?

- **Weak Determinism:**
  typically library-implemented,
  works on *race-free* code
  [Grace, Kendo, …]
- **Strong Determinism:**
  typically library-implemented,
  works on *non-malicious* code
  [CoreDet, Dthreads, …]
- **Secure Determinism:**
  system-enforced,
  works on *adversarial* code
  [Determinator, Deterland]



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  [Determinator, Deterland]

Insufficient for Timing Channel Mitigation

Adversarial Programs

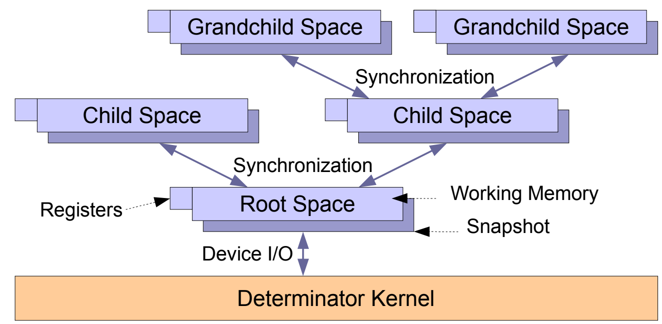
Mitigation requires Secure, **System-Enforced Determinism**

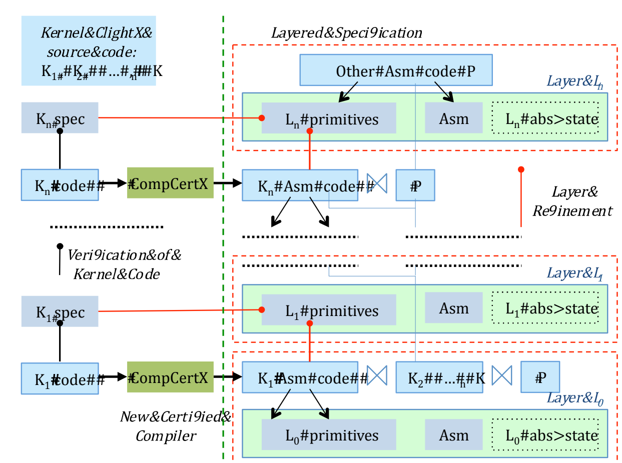
- If attacker-controlled VM can **escape** determinism enforcement, attacker can tell time → high-rate internal timing channel leak
- Most **any** source of nondeterminism is usable, e.g., launch thread that increments-and-spins
- Deterland **must**
  - Prevent unsynchronized cross-thread interaction
  - Prevent malicious escape from deterministic sandbox

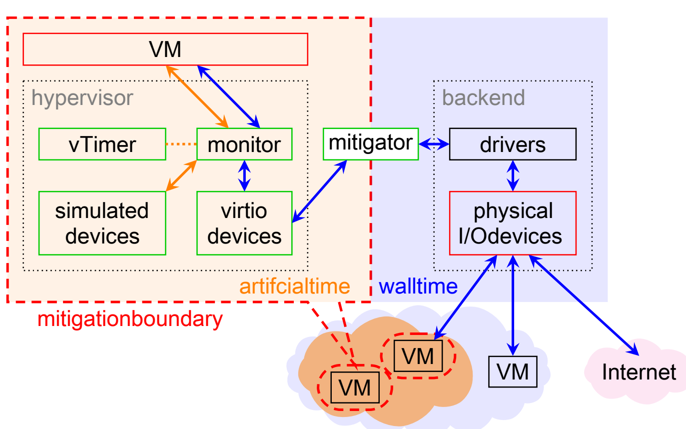
```
int bogoTime = 0

thread QuasiTimer {
   while (true) {
      bogotime++
   }
}
```

Deterland Hypervisor

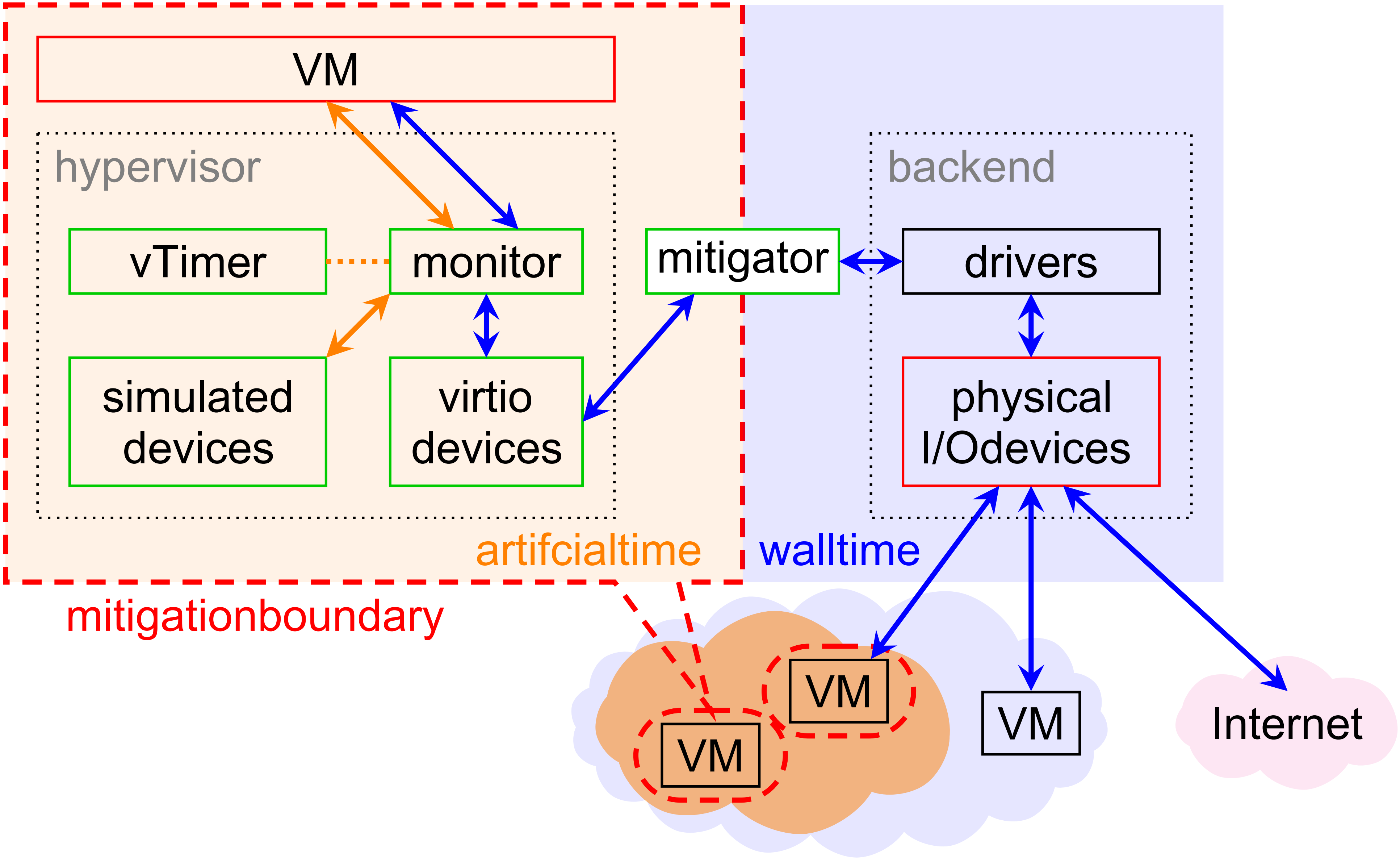
- Based on CertiKOS, based on Determinator
- Designed to be simple, formally verifiable hypervisor
  - CertiKOS is largely verified, but Deterland isn't (yet)





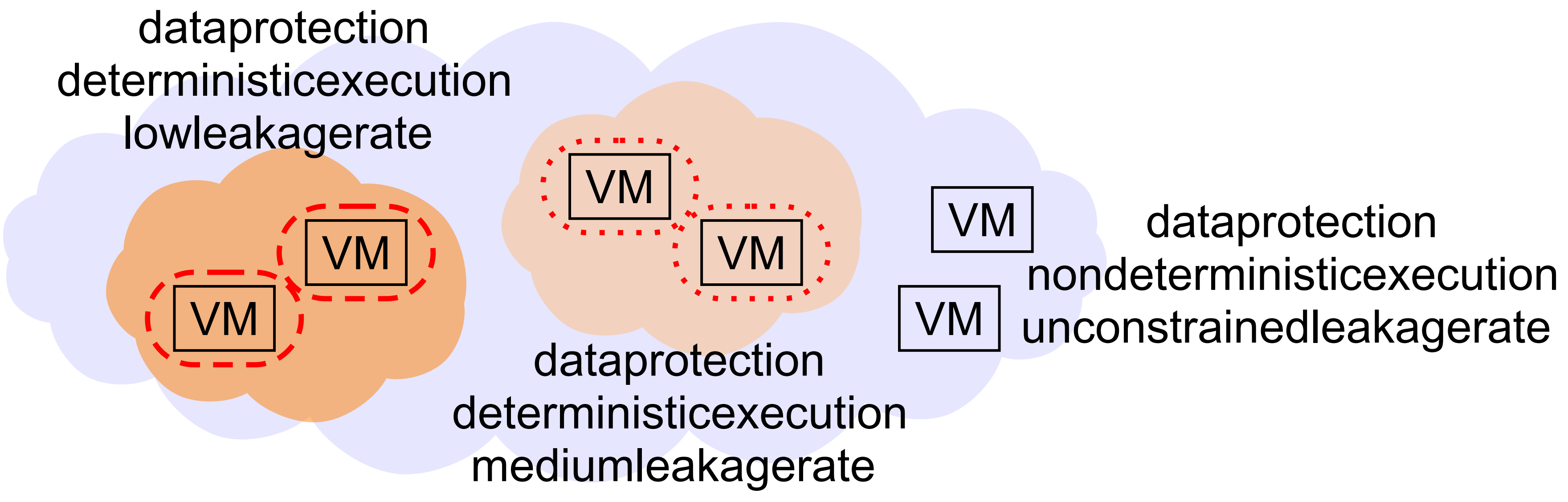


Deterland Hypervisor Architecture



Deterland Cloud Architecture

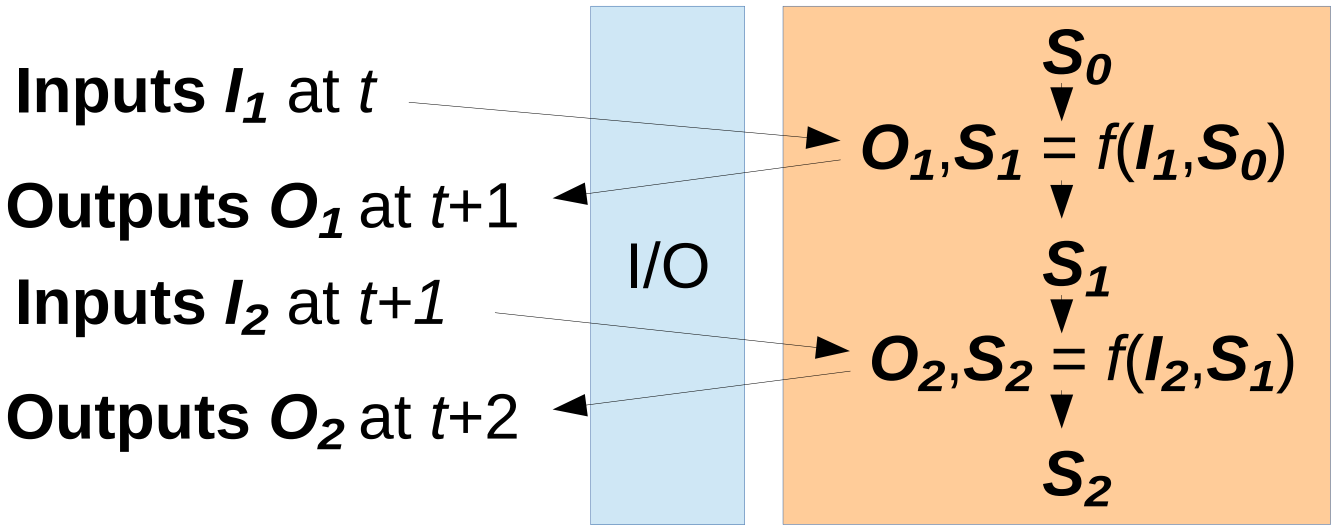
- Cloud provider offers different classes of VMs with different timing mitigation parameters
  - Only VMs with **same mitigation parameters** directly share physical machines



Mitigation for Interactive I/O

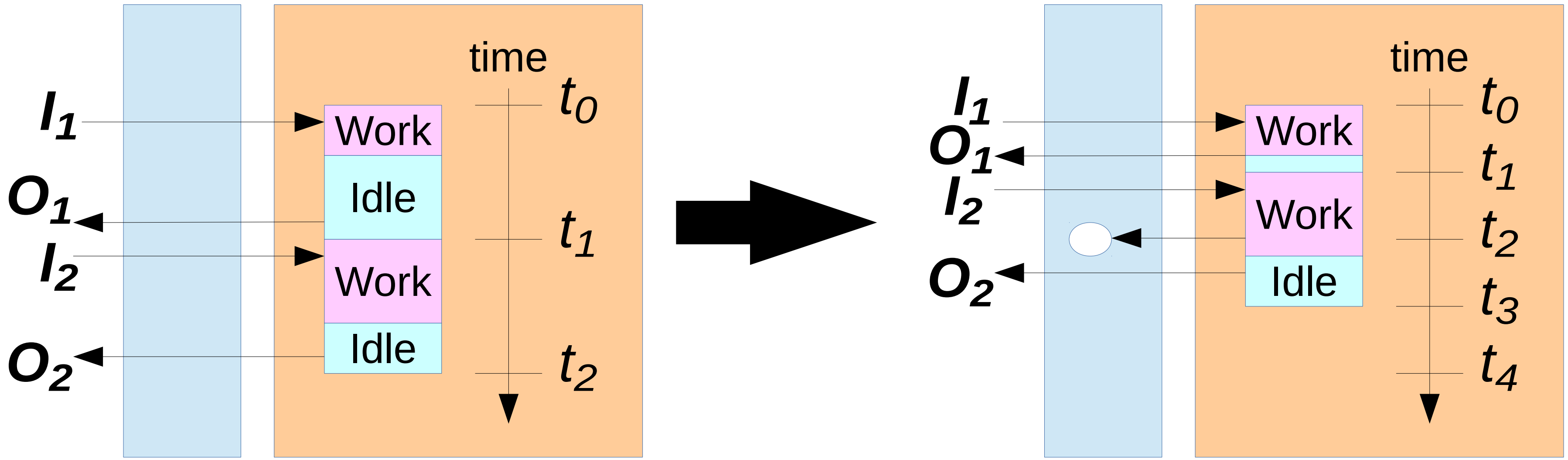
Intuition: "interactive operation" is just a series of small batch operations

- Cloud customer (e.g., attacker) can submit **one** new "batch input" per mitigation clock tick
  - Safe to maintain guest VM state across ticks
  - Safe to combine several inputs into one clock tick



Relax Worst-Case Execution Time

- Don't require *every* input to be done in 1 tick
  - “Easy-to-execute” ticks waste CPU capacity
- Instead, output delay is *integral number* of ticks
  - Extra ticks are “bubbles”, which **can leak info**
  - But can leak **at most one bit per tick**



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Implementation Summary

- Works, runs unmodified Linux (Ubuntu) guests
  - Deterministically emulates PIT, RDTSC timing
  - Virtio-based disk, network devices supported
- Limitation (inherited from CertiKOS): currently only one guest VM per physical core
  - Not fundamental, just per-core scheduler missing
- Limitation: one virtual core per guest VM
  - Much harder to solve efficiently, deterministically
- Workaround: “scale-out” across many single-core guests on each multi-core machine

Counting Instructions

- Challenge: x86 hardware can't trigger precise exception or VMexit after given # of instructions
  - Solution: imprecise performance counters plus single-stepping from “undershoot” to exact point
  - Classic technique used in ReVirt, etc.
- Works, but **slow**: major CPU cost per trigger
  - Amortizable if Deterland clock ticks are long, but long clock ticks are bad for I/O latencies
  - Historical architectures (e.g., PA-RISC) had precise instruction-counting; maybe future CPUs could too?

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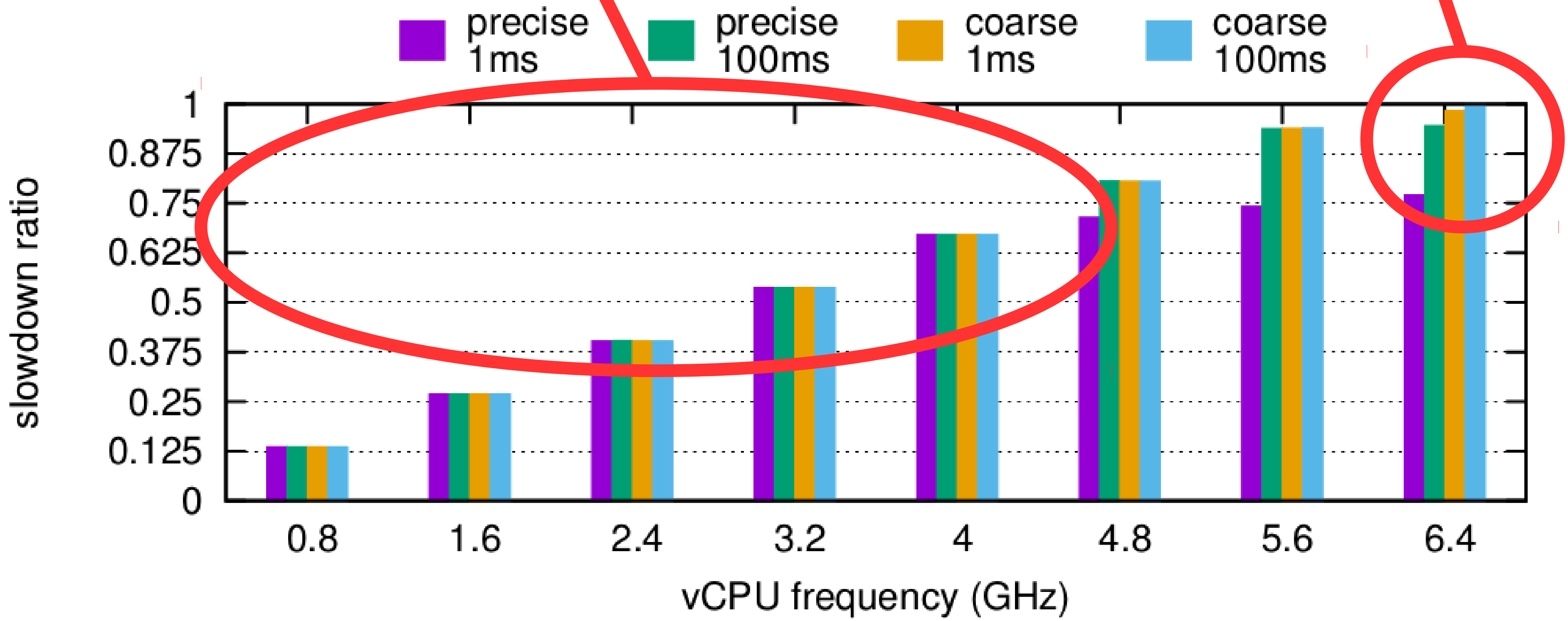
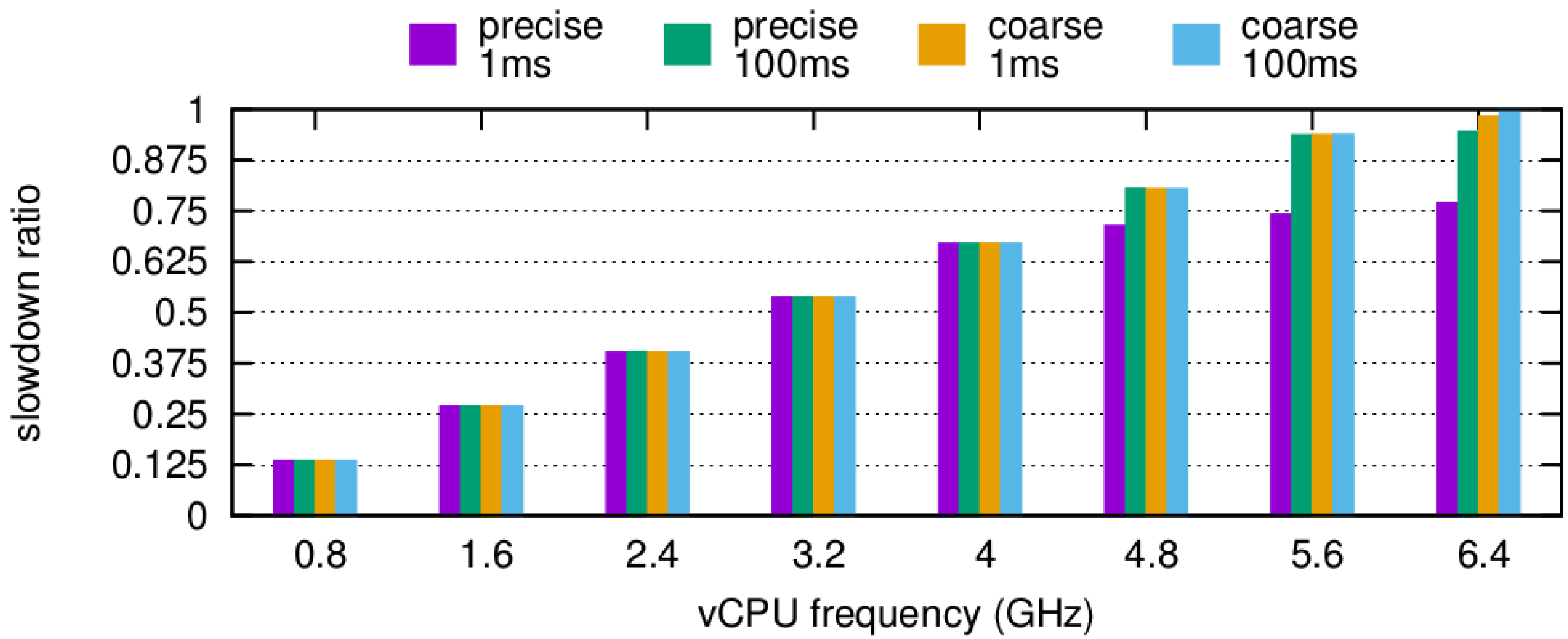
CPU-intensive Microbenchmark

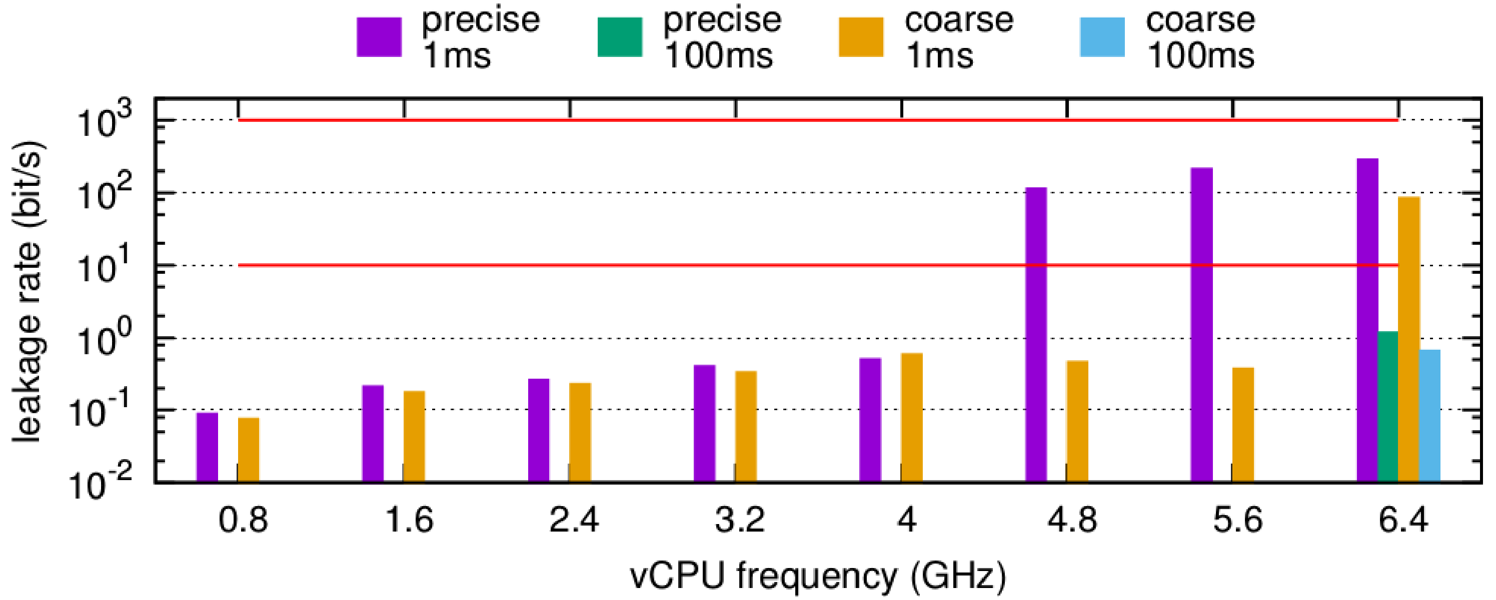
Otherwise we pay the “real-time tax” of underutilization

Load overhead if we *keep the CPU busy*

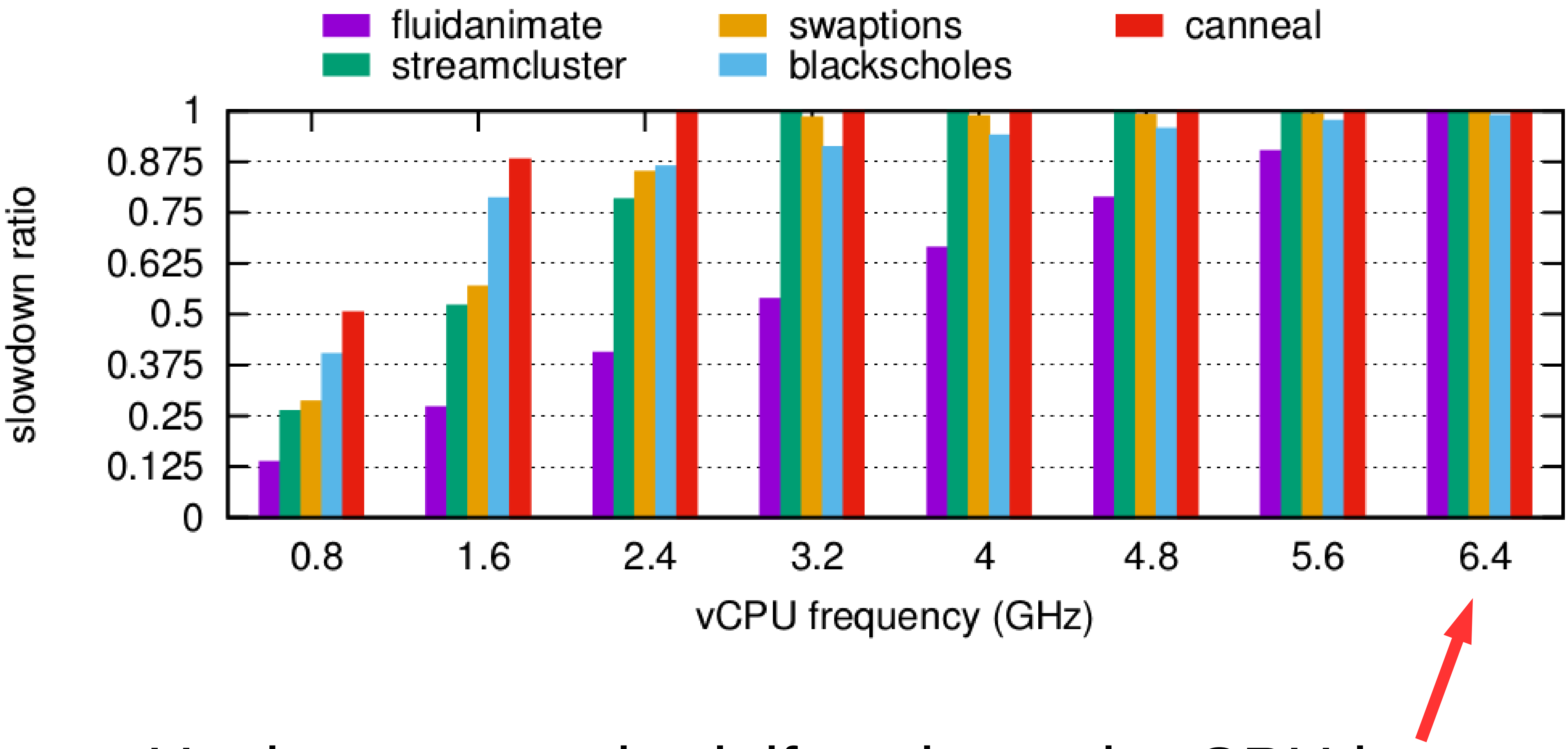


Performance vs Leakage Bound



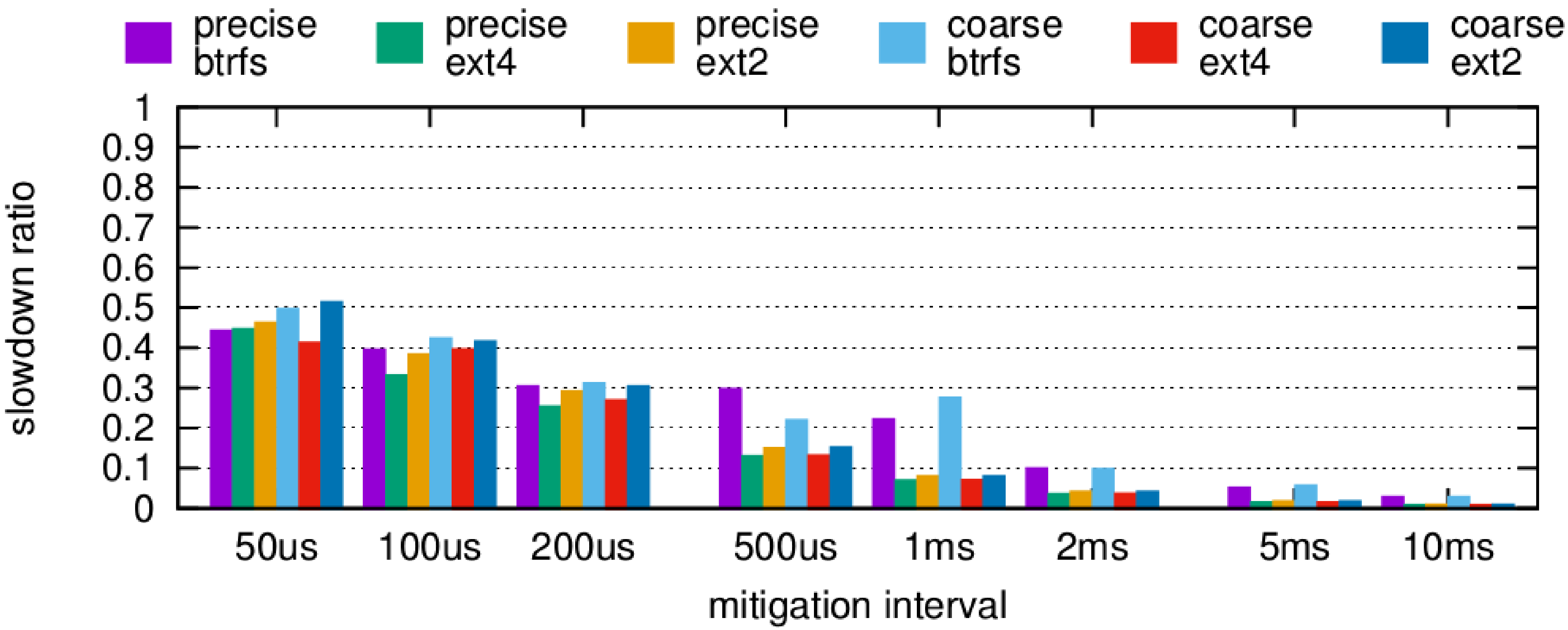


Real Compute-intensive Workloads



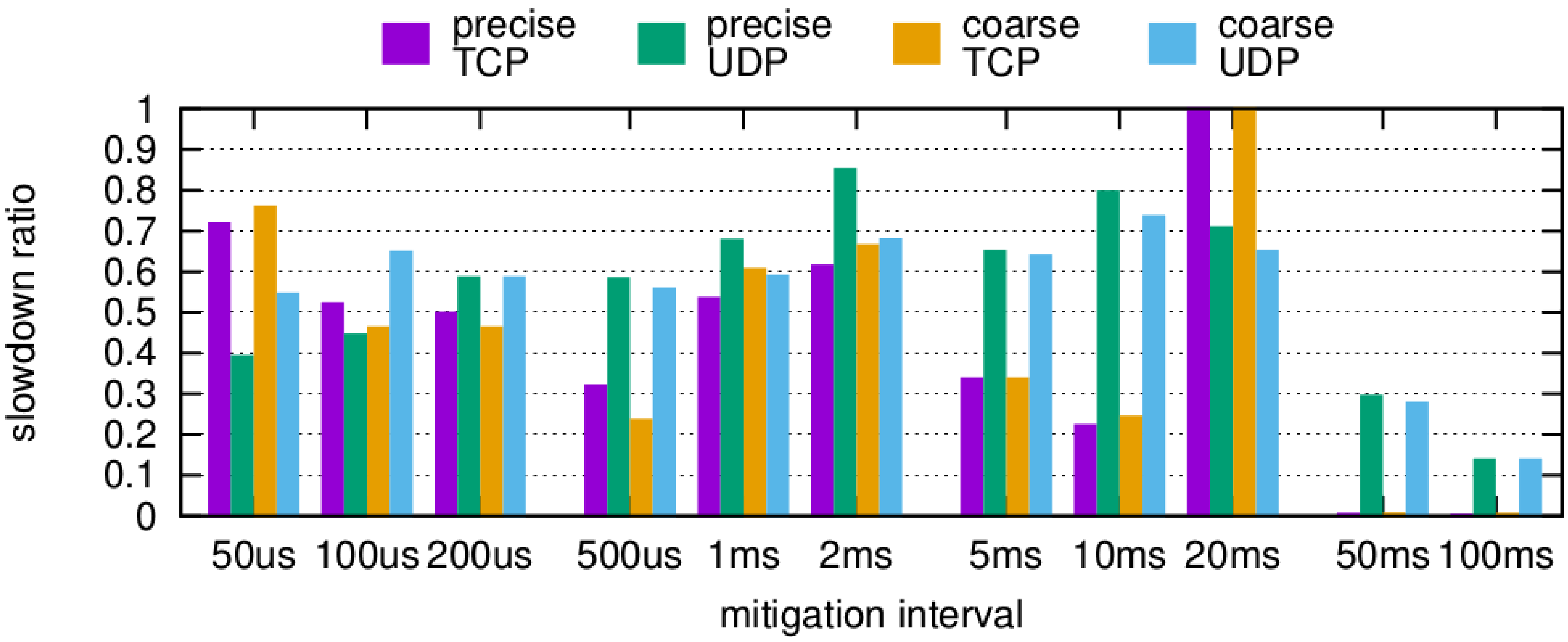
Upshot: not too bad, if we keep the CPU busy

Filesystem Benchmark



- Mitigation hurts I/O-intensive work (of course)
  - Heavily dependent on mitigation interval
  - Possible solution: deterministic disk/FS access

Network-intensive Benchmark



- Main problem: mitigation of guest TCP stack
  - Congestion control highly sensitive to timing
  - Possible solution: move TCP stack out to hypervisor

Potential Future Optimizations

- Mitigating all I/O is unnecessary in principle:
  - Deterministic intra-cloud, inter-guest networking
  - Deterministic intra-cloud disk access
- Mitigate at higher levels of abstraction:
  - Move TCP, congestion control out of guest VM
  - Move filesystem, disk drivers out of guest VM
- Determinate but don't mitigate:
  - Enforced determinism alone eliminates *local* attacks
  - Mitigation needed only to rate-limit *remote* attacks
    - Can disable if remote attack risk is deemed remote

Compiler/Hardware Opportunities

- Deterministic instruction counting is costly
  - Potential alternative: lightweight code rewriting?
  - Long-term: why oh why doesn't hardware do this?
- Instruction count is also a poor model for “deterministic time”
  - Falsely pretends all instructions about equally hard
  - Potential alternative: deterministic cost models?
  - Long-term: hardware support for cost models?

Conclusion

- First hypervisor implementing timing channel mitigation for existing unmodified OSes, apps
  - General I/O mitigation model for virtio devices
  - Usable performance for CPU-intensive loads, currently high costs for I/O-intensive loads
- Just first step, many improvements possible

More info: http://dedis.cs.yale.edu/cloud/

Code: git@dedis.cs.yale.edu:verikos tifc rtl