Deterministically Deterring Timing Attacks in Deterland

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Talk Outline

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

Talk Outline

- **Background: Attacks and Mitigation in the Cloud**
  - The Timing Attack Problem
  - Why the Problem is Worse in the Cloud
  - Known Approaches to Mitigation
- Design: Hypervisor-Secure Mitigation
- Implementation: Deterland Hypervisor
- Evaluation: It Works (at a Cost)
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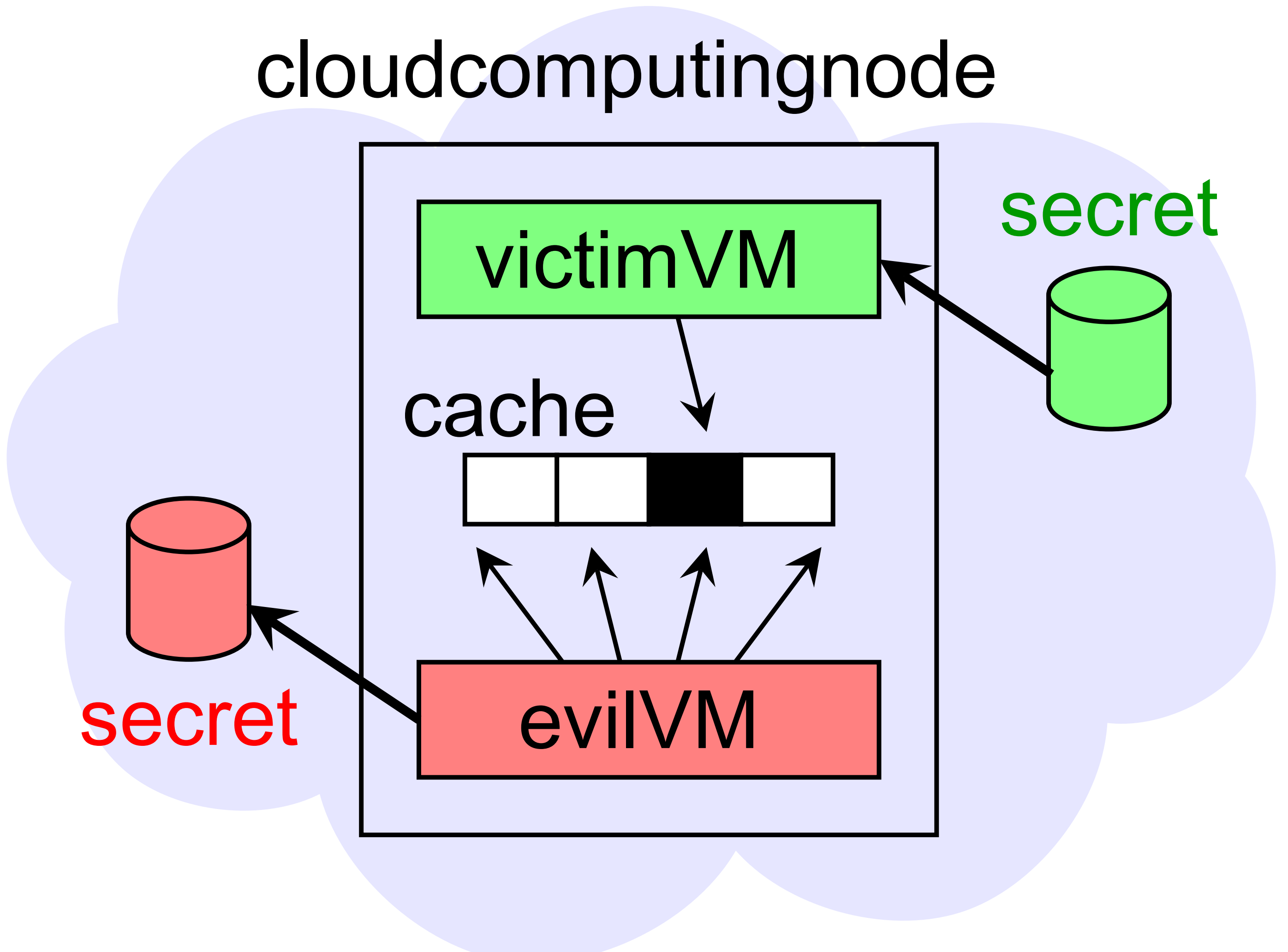
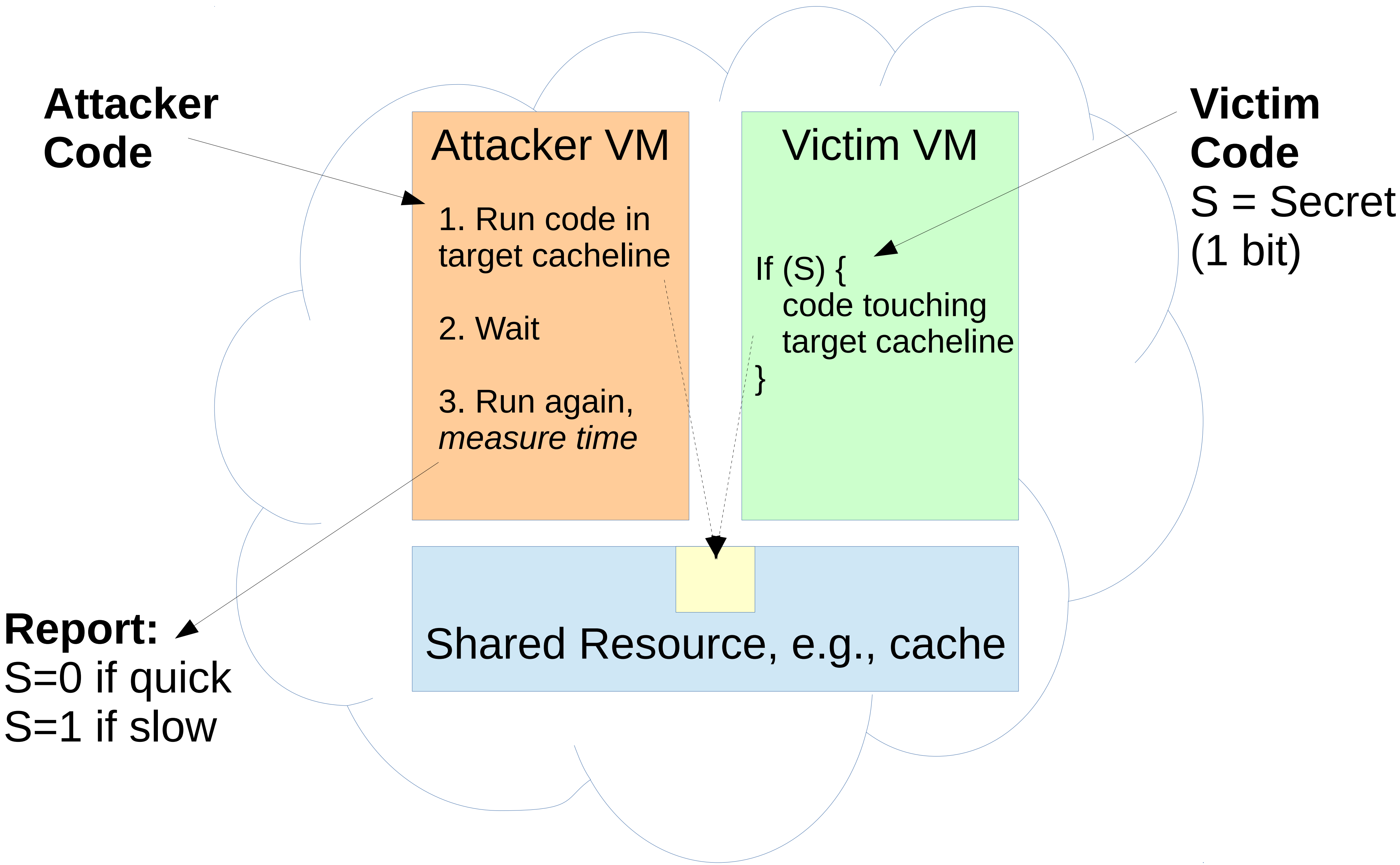
Timing Attacks via Shared Hardware Resources



Classes of Timing Attacks

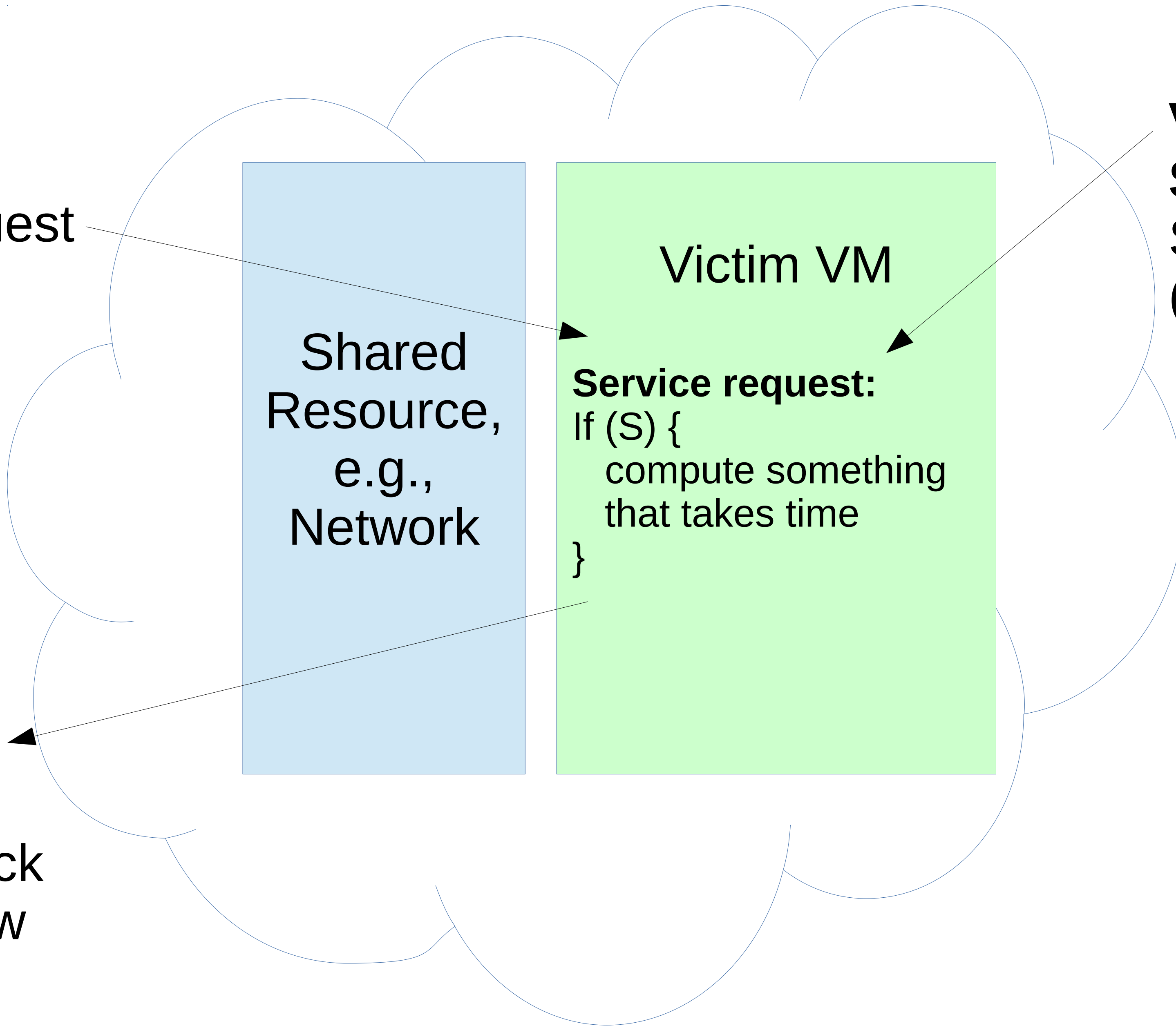
- **Internal or Local Attacks:**
  - Attacker has *full* control over guest VM co-resident with victim
  - Attack VM carries out attack autonomously from *within* the cloud environment
- **External or Remote Attacks:**
  - Attacker has *limited/no* control over guest VM
  - Attacker must carry out attack (partly) remotely from *outside* the cloud environment

Internal Attacks: Simplified Example



External Attacks: Simplified Example

Attack Client
send request



Victim Server
S = Secret
(1 bit)

Measure Delay
S=0 if quick
S=1 if slow

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*

1. Routine Co-Residency

On Private Infrastructure:

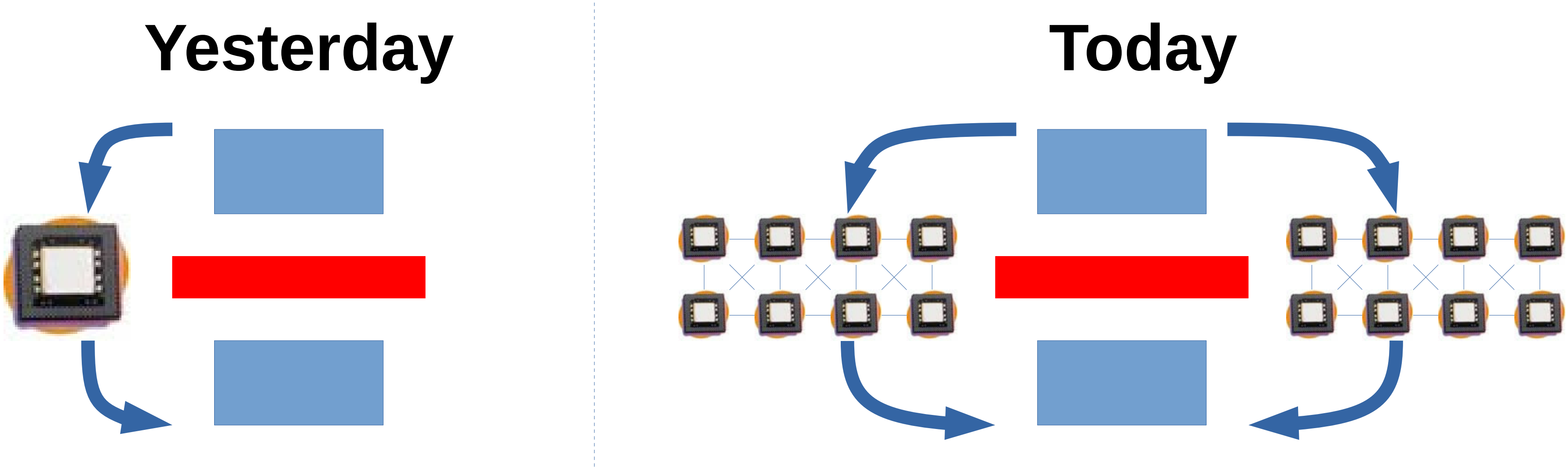
- Owner can manage all running software
- Attacker must **get code installed locally** (e.g., malware) before starting attack

On Cloud Infrastructure:

- Provider *doesn't* manage running guest apps
- Attacker simply buys CPU time to run attack
- No protection comprimised → no alarms

2. Massive Parallelism

- *All* shared resources create timing channels
  - CPUs, caches, interconnects, I/O devices, …
- Cloud jobs use *many* resources in parallel
  - Multiply attack surface by ***N***



3. Timing Attacks Won't Get Caught

On Private Infrastructure:

- Owner can *monitor* all running software (antiviral software, intrusion analysis, …)

On Cloud Infrastructure:

- Customer A *cannot* monitor customer B's apps
- Provider *can,* but probably doesn't want to
  - Not their job to ask questions
  - Might invite privacy lawsuits

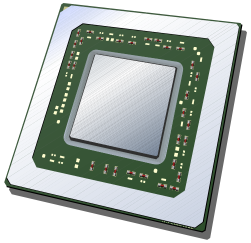
4. Partitioning is Infeasible

Current timing hardening approaches are either:

- *Specific to particular algorithms & resources*
  - Equalize AES path lengths, cache footprint, …
- *General but contrary to cloud business model*
  - **Partition** CPU cores, cache, interconnect, …
  - Can't oversubscribe, stat-mux resources
  - ➔ **Cloud loses its elasticity!**

Timing Channel Mitigation

Timing channels require: [Wray 91]



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

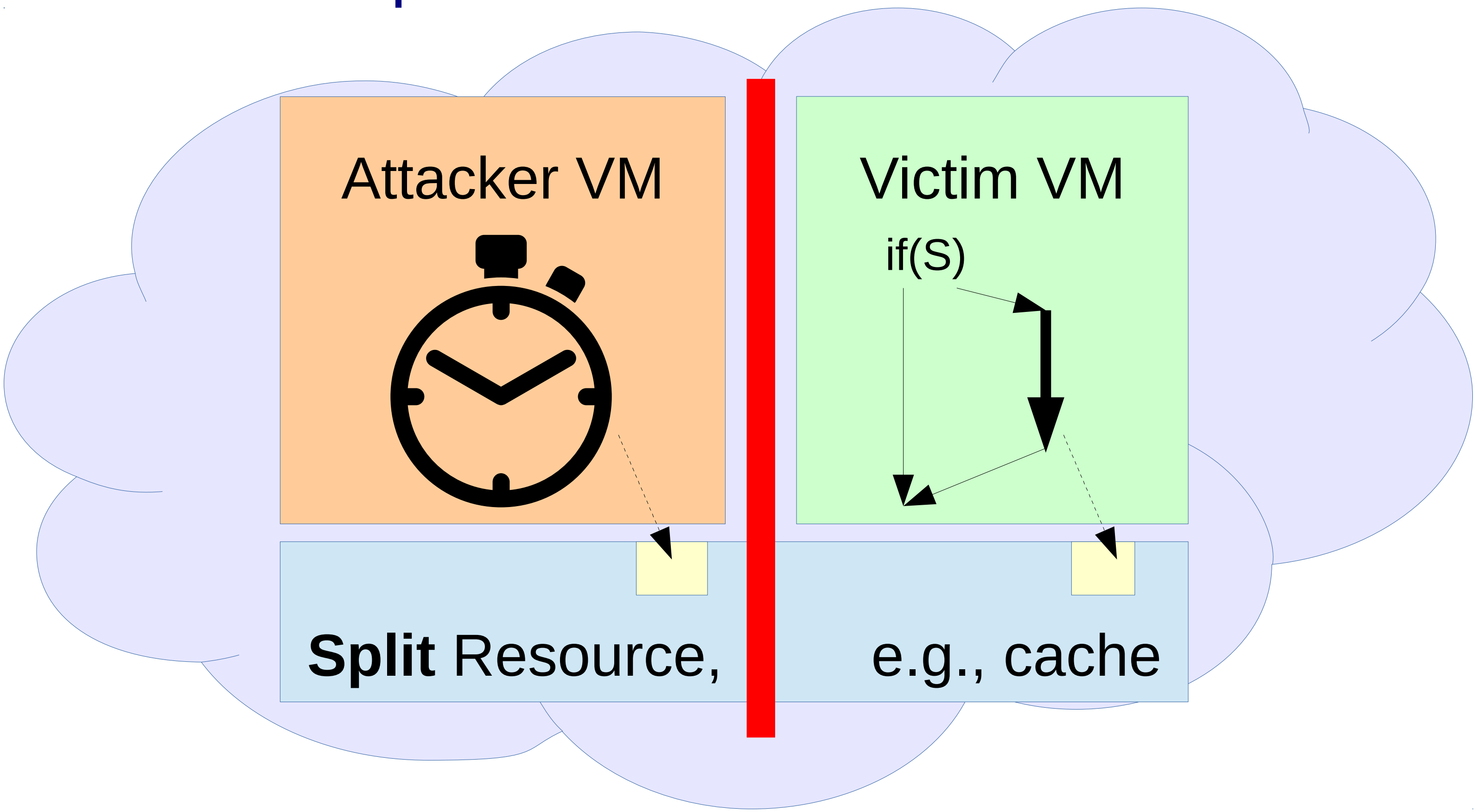
- A *reference clock* enabling the attacker to observe, extract the modulated signal

Remove either → no timing channel.

Approach 1: Eliminate Modulation

(a) by statically partitioning hardware resources

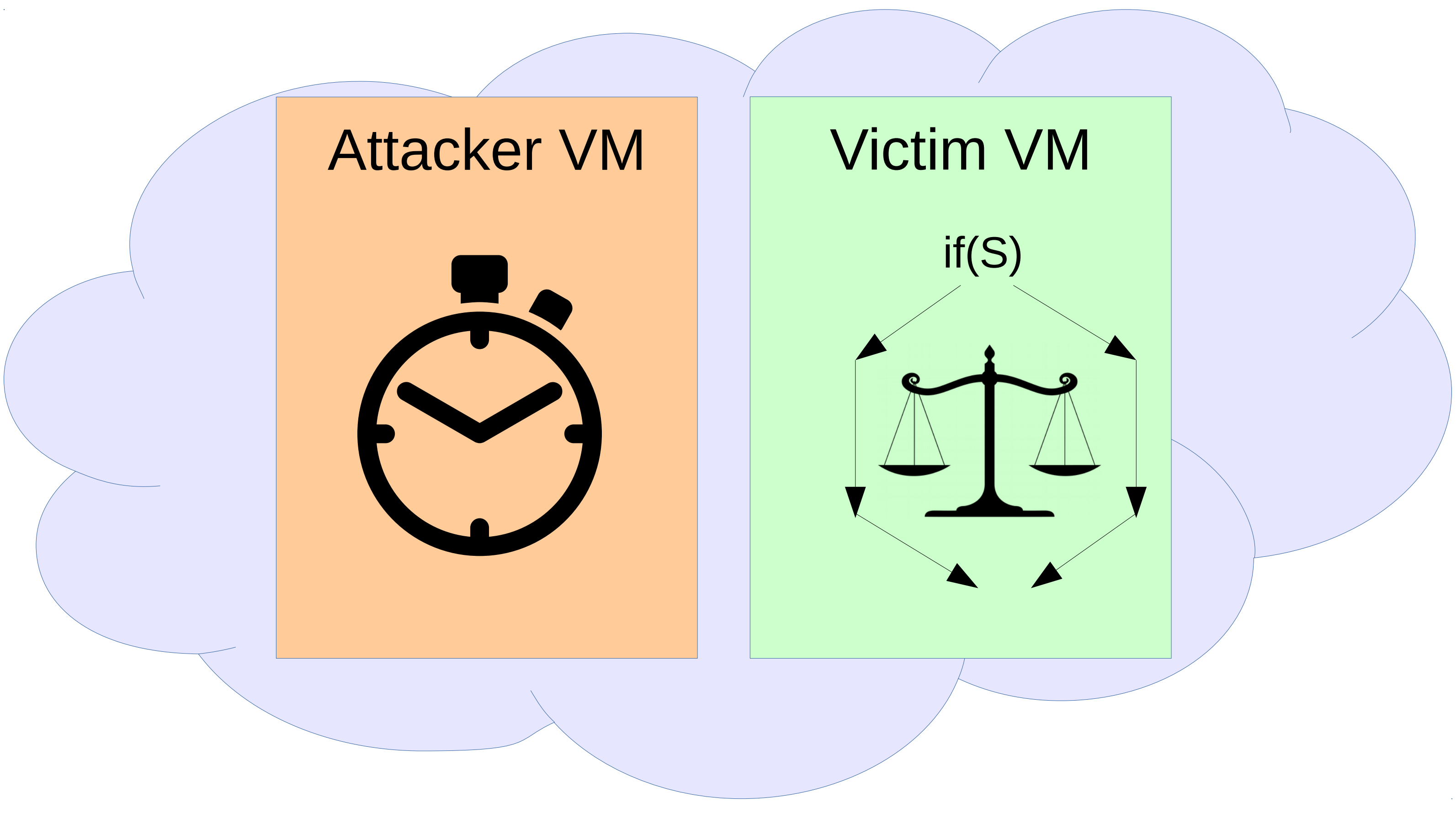
- Generalizes over **code**, must modify **hardware**
- Incompatible with **cloud business model**



Approach 1: Eliminate Modulation

(b) via constant-time code execution

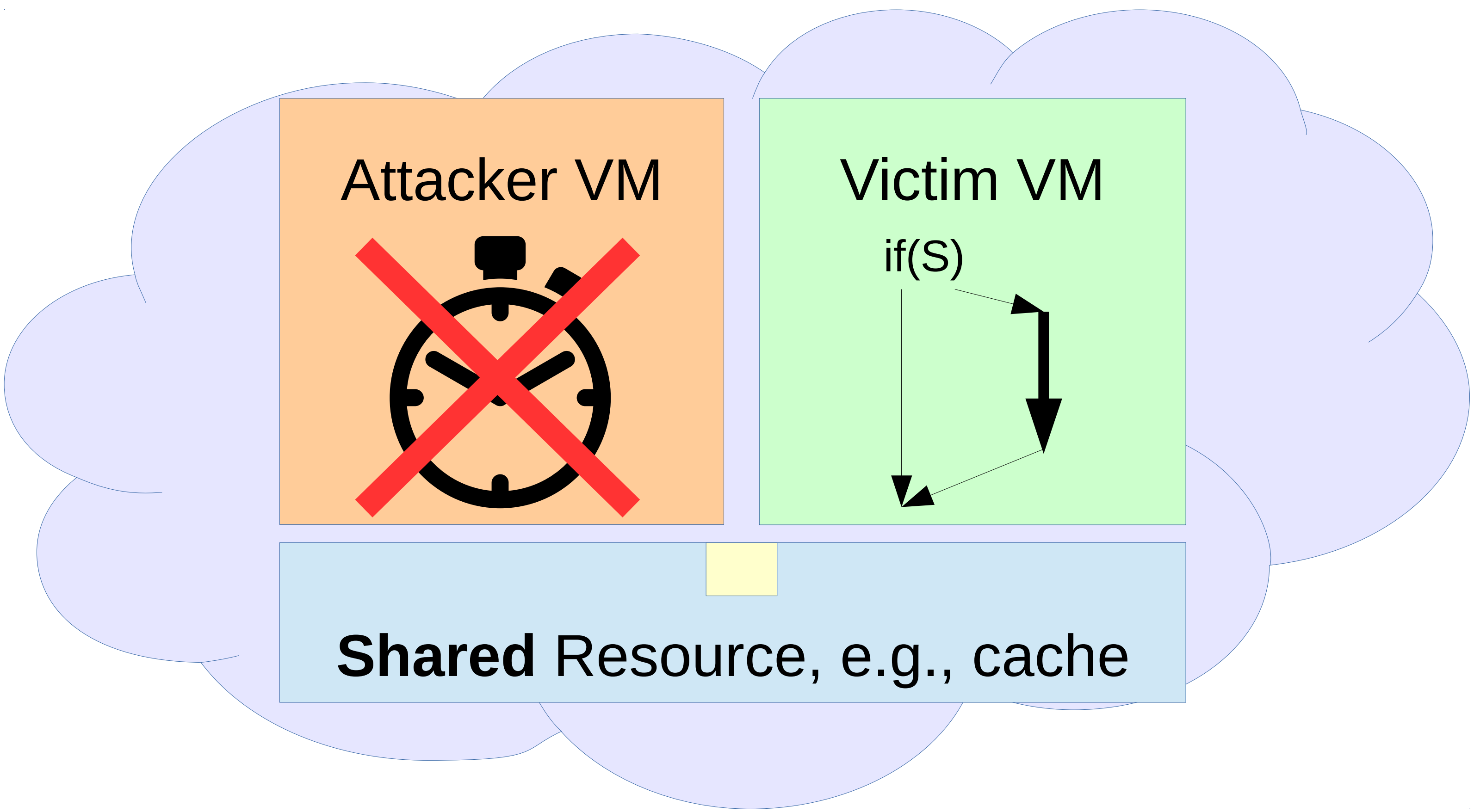
– General **hardware**, but specialized **code**



Approach 2: Deny Reference Clocks

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

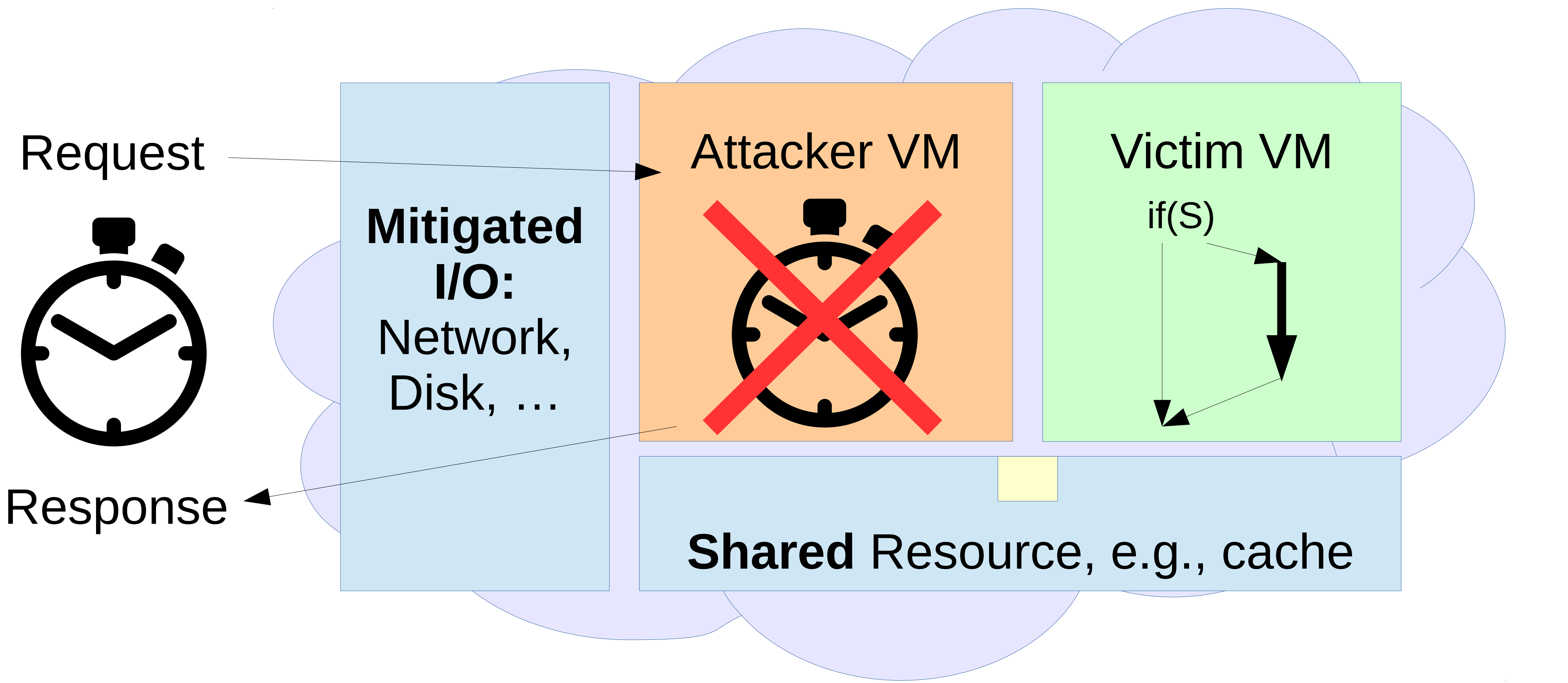
- At least not locally, **internal** to cloud



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
  - That's what's new!

Talk Outline

- Background: Attacks and Mitigation in the Cloud
- **Design: Hypervisor-Secure Mitigation**
  - Deterland cloud and hypervisor architecture
  - Hypervisor-enforced mitigation, step-by-step
- Implementation: Deterland Hypervisor
- Evaluation: It Works (at a Cost)
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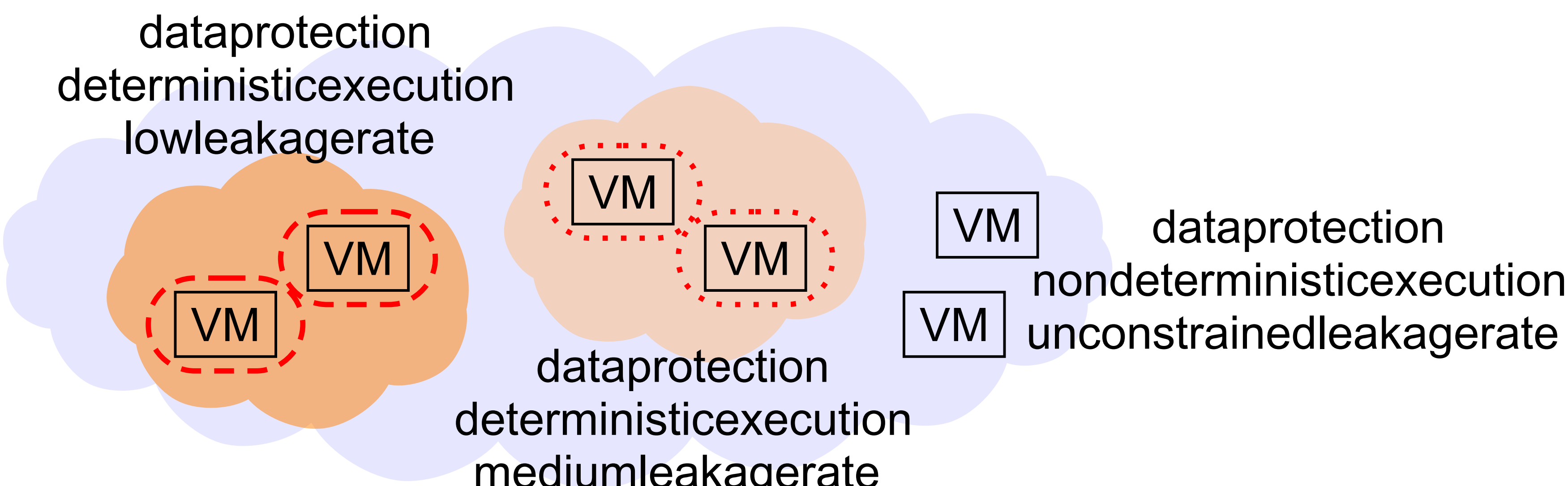
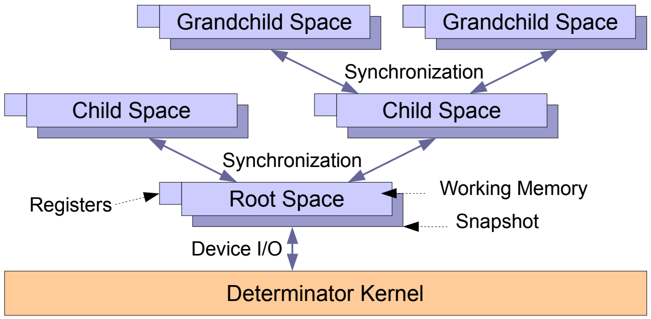
Deterland Cloud Architecture

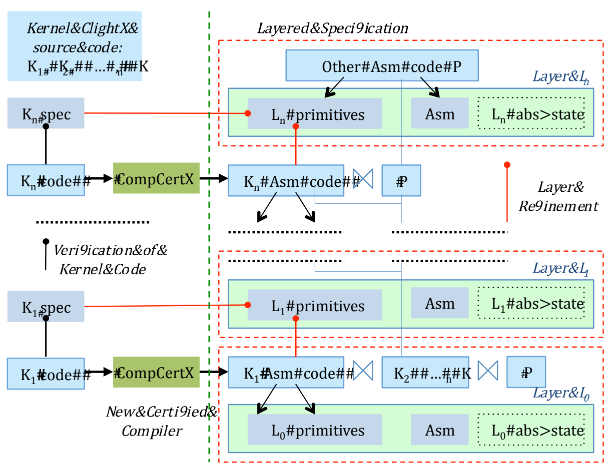
- Cloud provider offers different classes of VMs with different timing mitigation parameters
  - Only VMs with **same mitigation parameters** directly share physical machines

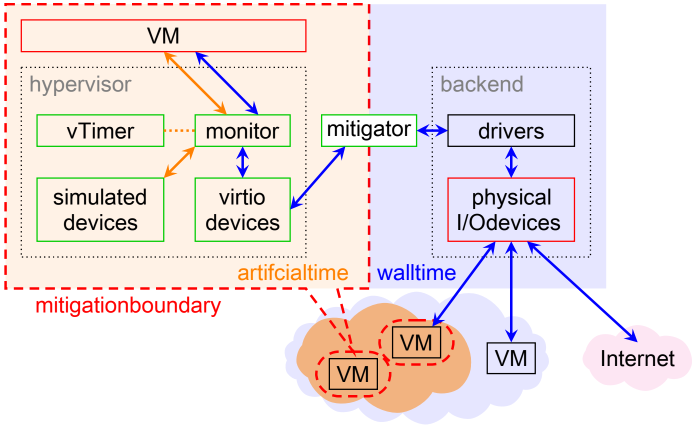


Deterland Hypervisor

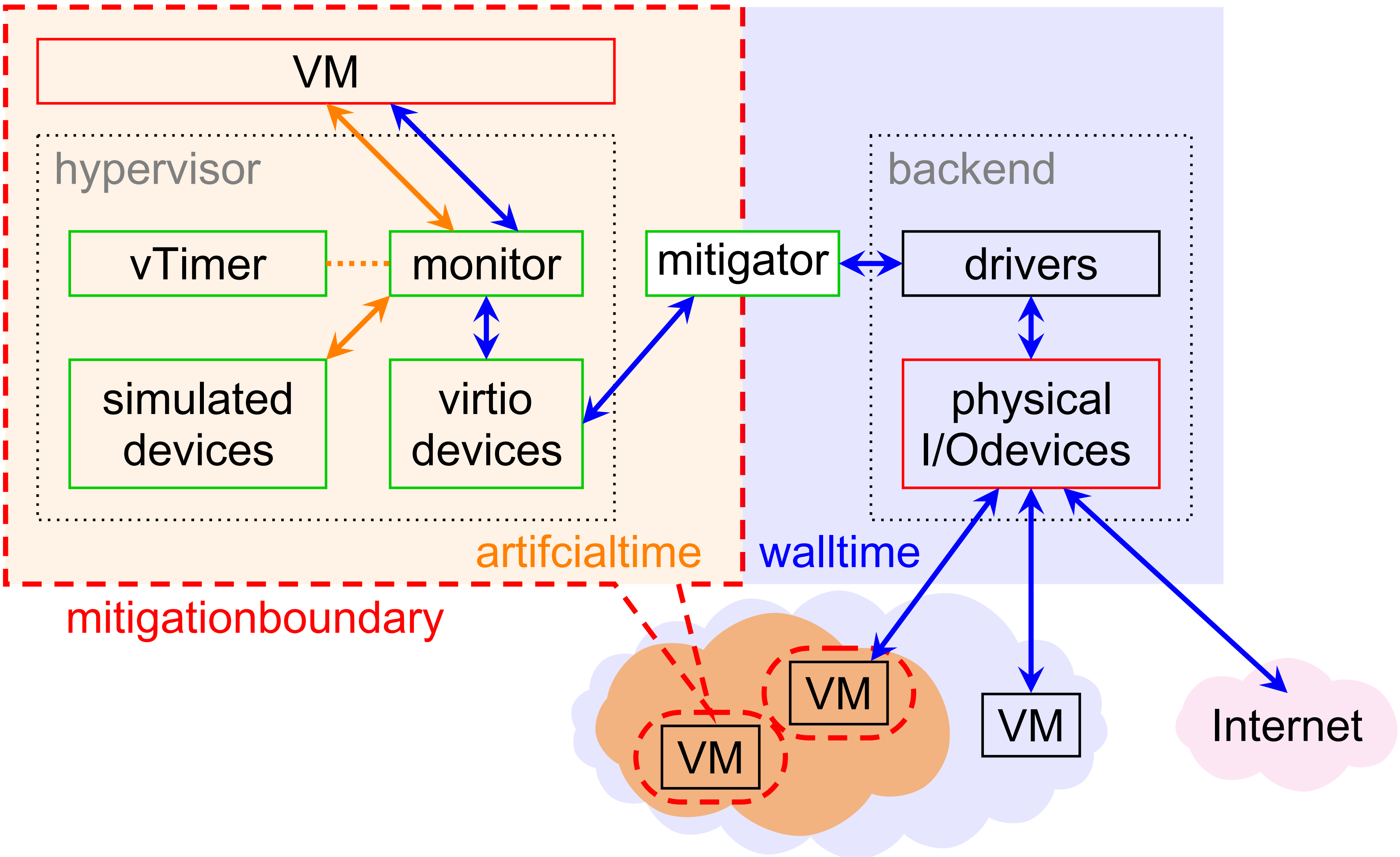
- Based on CertiKOS
  - In turn based on Determinator
- Designed to be simple, formally verifiable hypervisor
  - CertiKOS is largely verified, but Deterland isn't (yet)







Deterland Hypervisor Architecture

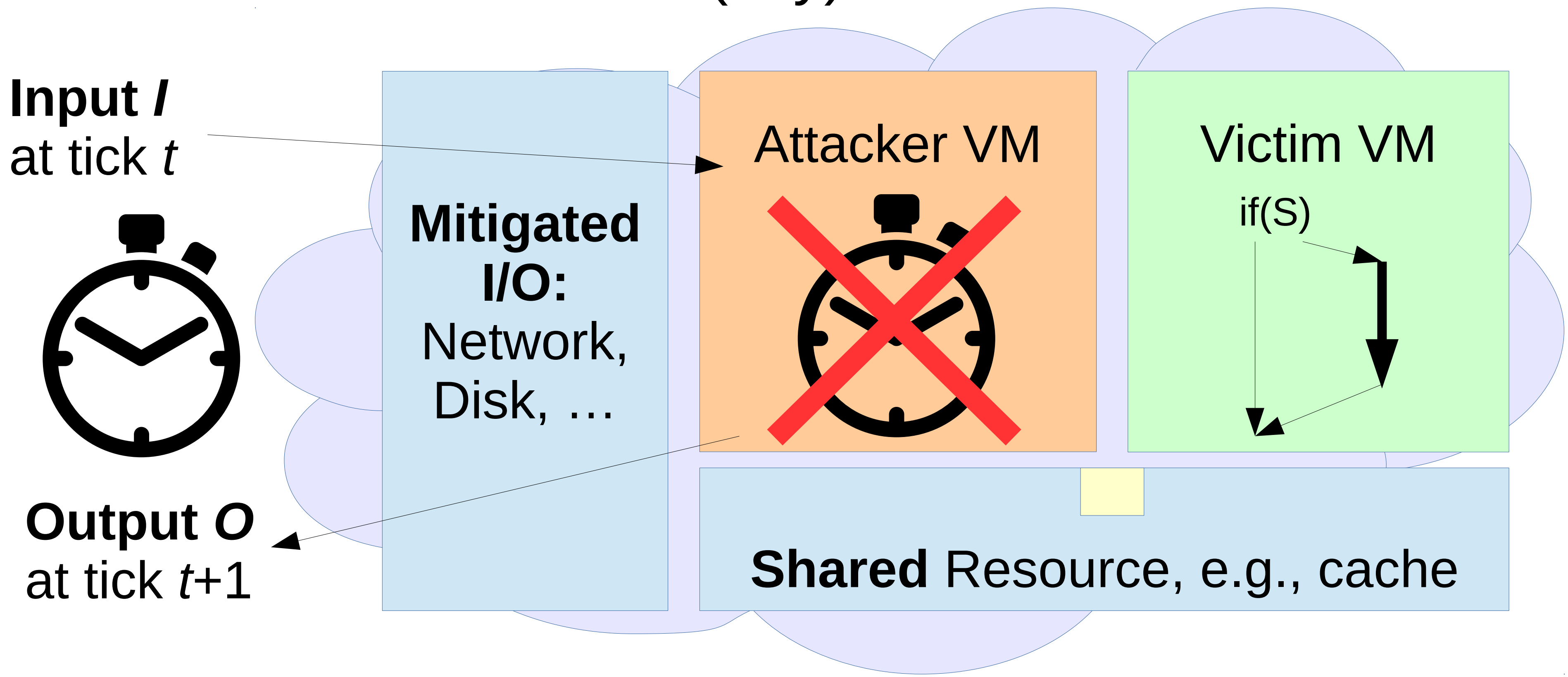


Mitigation Operation: Overview

- Start with **unrealistic** simplifying assumptions
  - Need “batch” processing jobs only (mainframe-era)
  - Can predict job's worst-case execution time
- Then relax, make more general/realistic
  - Quantize time into coarse-grained **ticks**
    - Secure deterministic execution *between ticks*
    - Inputs accepted, outputs produced only at ticks
    - Virtual CPU speed trades efficiency vs leakage risk
  - For compatibility: use **virtio** for all mitigated I/O
  - For throughput: batch virtio inputs/outputs each tick

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



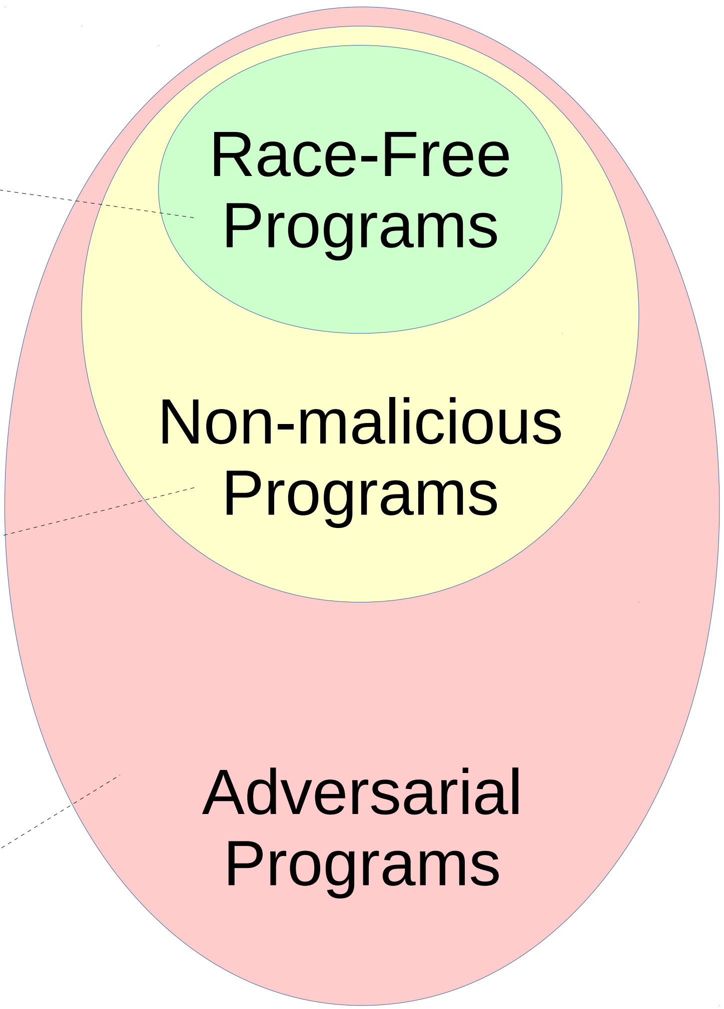
Overly-Simplified Example

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]



Deterland 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

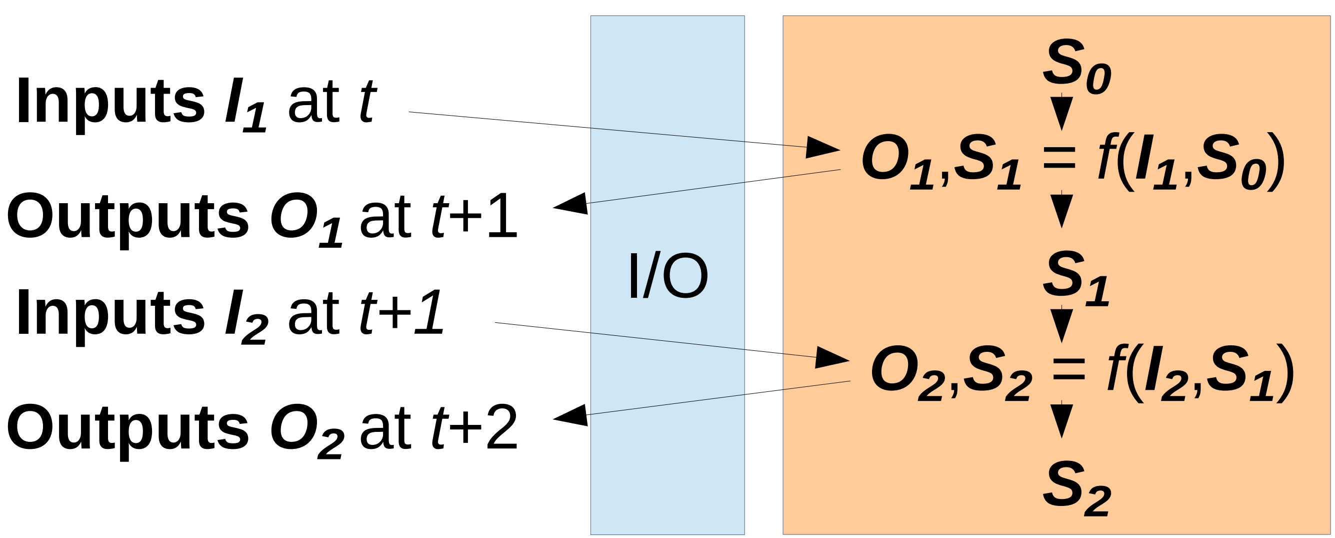
```
int bogoTime = 0

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

From Batch to Interactive

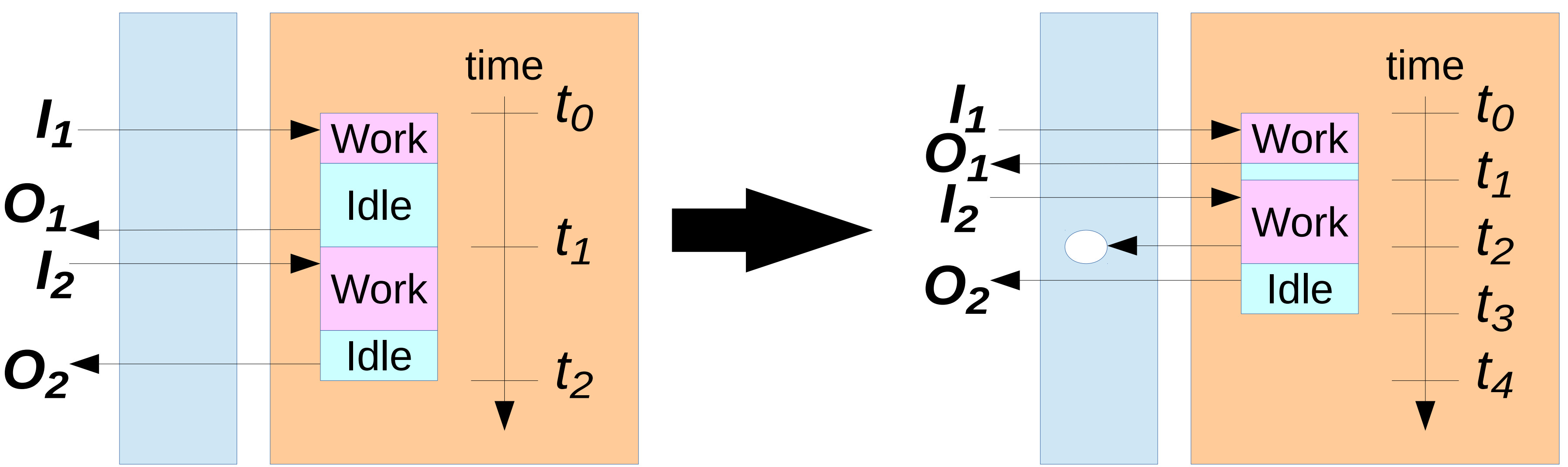
Intuition: "interactive operation" is just a series of small batch operations

- Cloud customer (e.g., attacker) can submit **one** new "batch input" per regular "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



Mitigation in Deterland Hypervisor

- Runs unmodified legacy OSes and applications
- All I/O uses standard **virtio** interface
  - Each tick, guest gets a new batch of virtio inputs, and produces a new batch of virtio outputs
  - General: mitigates **all devices** with virtio support
- Configurable **clock tick period**
  - Short better for I/O, long better for CPU efficiency
- Configurable **instructions-per-tick**
  - Fewer better for leakage, more better for efficiency

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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

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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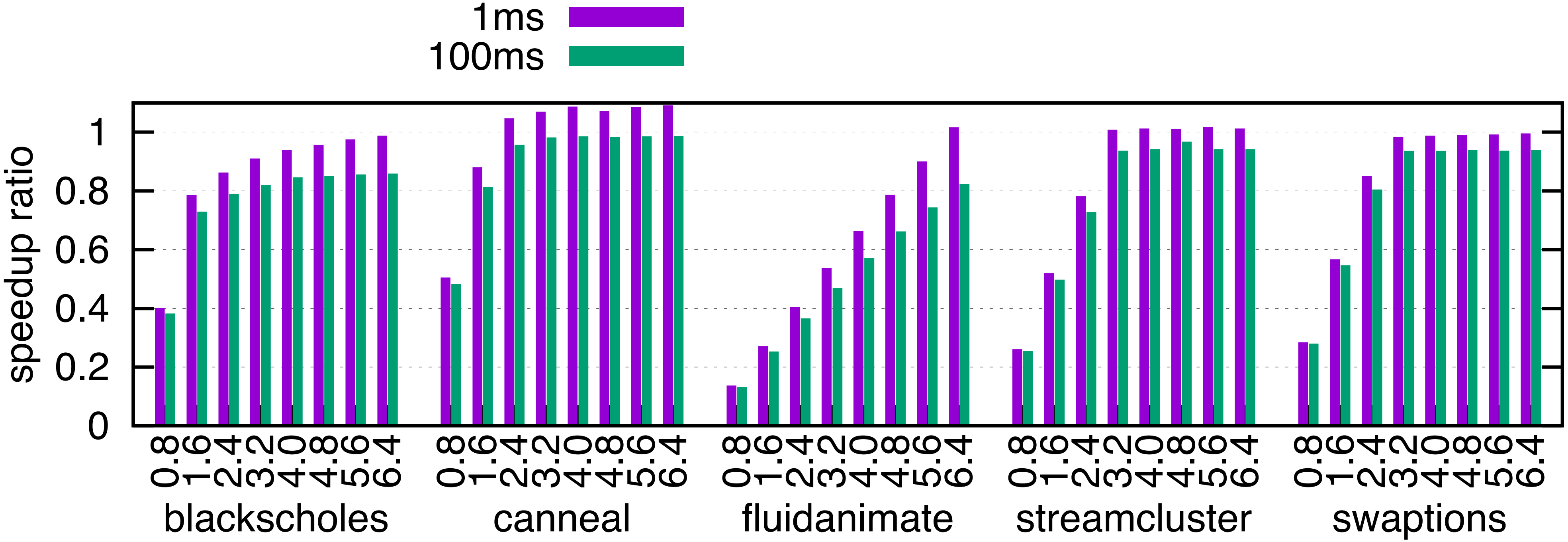
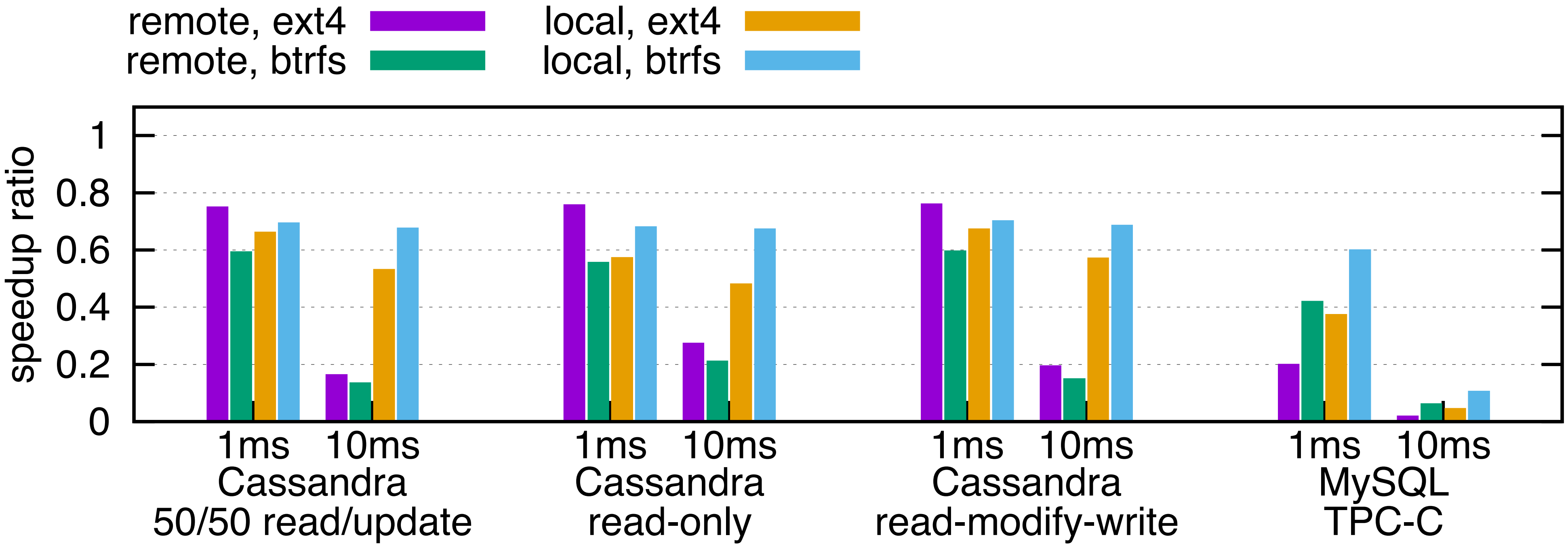
PARSEC Benchmark Results



Database Benchmark Results



Potential Future Optimizations

- Currently *all* I/O is mitigated, may be overkill:
  - *Intra-cloud, inter-guest communication:* could use deterministic messaging, avoid mitigation
  - *Intra-cloud disk access:* could offer deterministic read/write, avoid mitigation
- Mitigate at higher level of abstraction:
  - Mitigate sockets, move TCP stack out of guest VM → avoid bad mitigation effect on congestion control
  - Mitigate files, move filesystem out of guest VM → avoid bad mitigation effect on sync writes, etc.

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 proof-of-concept of 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

Details (preprint): http://arxiv.org/abs/1504.07070

Yale DeDiS group: http://dedis.cs.yale.edu