Determinating Timing Channels in Compute Clouds

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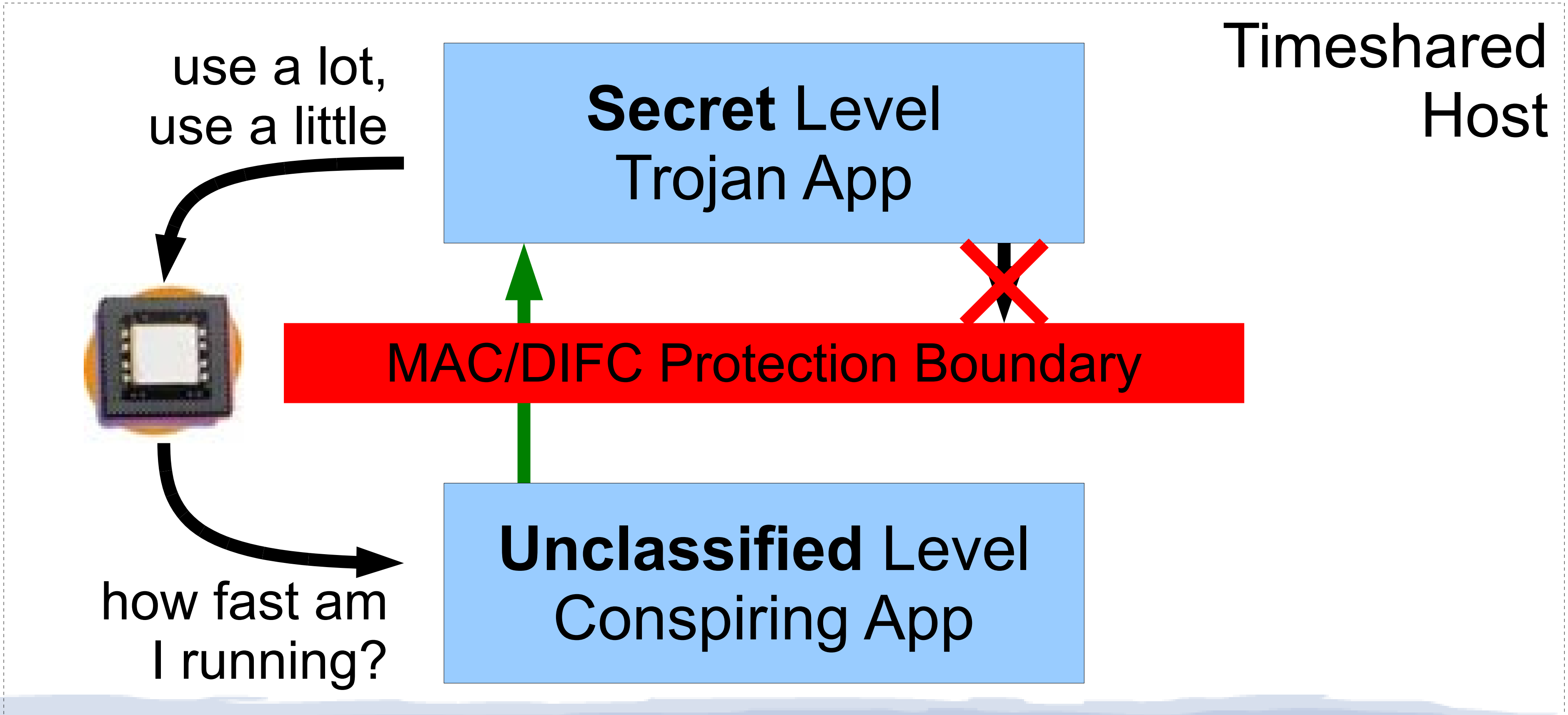
Timing Attacks

- **Cooperative attacks** – apply to:
  - Mandatory Access Control (MAC) systems [Kemmerer 83, Wray 91]
  - Decentralized Information Flow Control (DIFC) [Efstathopoulos 05, Zeldovich 06]
- **Non-cooperative attacks** – apply to:
  - Processes/VMs sharing a CPU core [Percival 05, Wang 06, Acıiçmez 07, …]
  - Including VM configurations typical of clouds [Ristenpart 09]

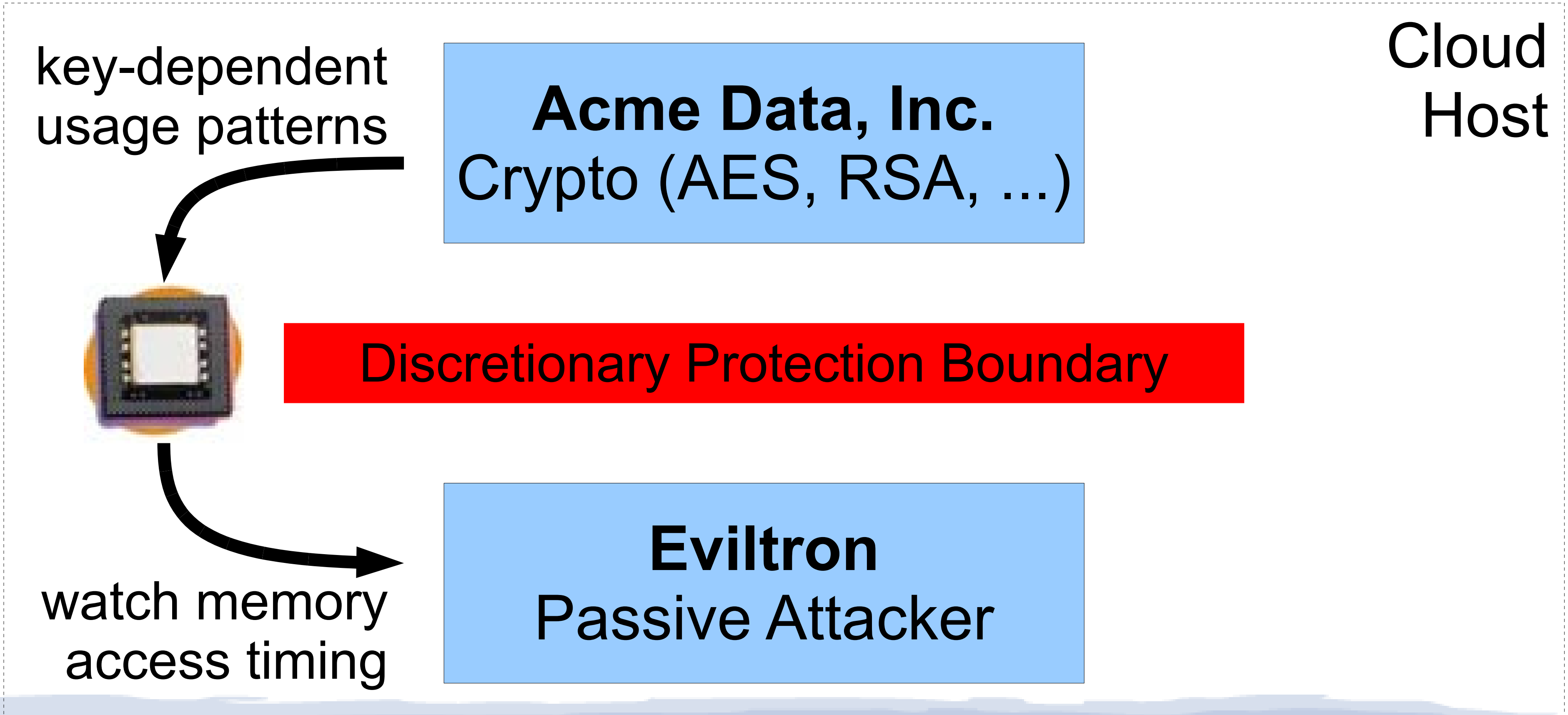
Cooperative Attacks: Example

Trojan leaks **secret** information by modulating a *timing channel* observable by **unclassified** app



Non-Cooperative Attacks: Example

Apps *unintentionally* modulate shared resources to reveal secrets when running standard code!



Cloud Host

key-dependent usage patterns

Acme Data, Inc.
Crypto (AES, RSA, ...)

Discretionary Protection Boundary

watch memory access timing

Eviltron
Passive Attacker

The Big Question

Are timing attacks practical in the cloud?

- Answer 1: *Maybe.* [Ristenpart 09]
- Answer 2: *I don't know.*

Answer is **not** the subject of this talk.

The *Other* Big Question

“Attacks never get worse;
they only get better.”
- NSA?

If timing attacks become practical in the cloud,
what can we do about them?

Talk Outline

- ✓ The Timing Channel Problem
- **Why They're Worse in the Cloud**
- A Deterministic, Timing-Hardened Cloud
- Feasible? A Bit of Evidence
    - (preliminary performance results)
- Conclusion

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:

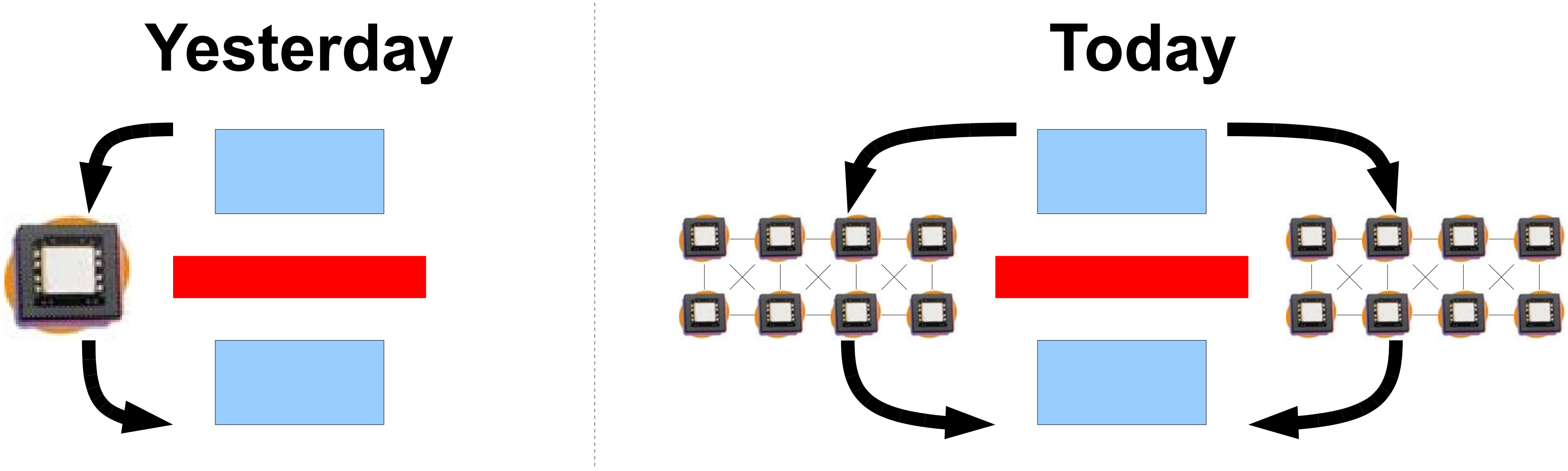
- Owner can manage all running software
- Attacker must **get code installed locally** (e.g., malware) before starting attack

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***


Yesterday

Today

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 wouldn'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!**

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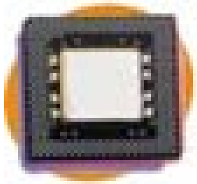
Anatomy of a Timing Channel

Two elements required: [Wray 91]

- A *resource* that can be *modulated* by the signaling process (or victim)

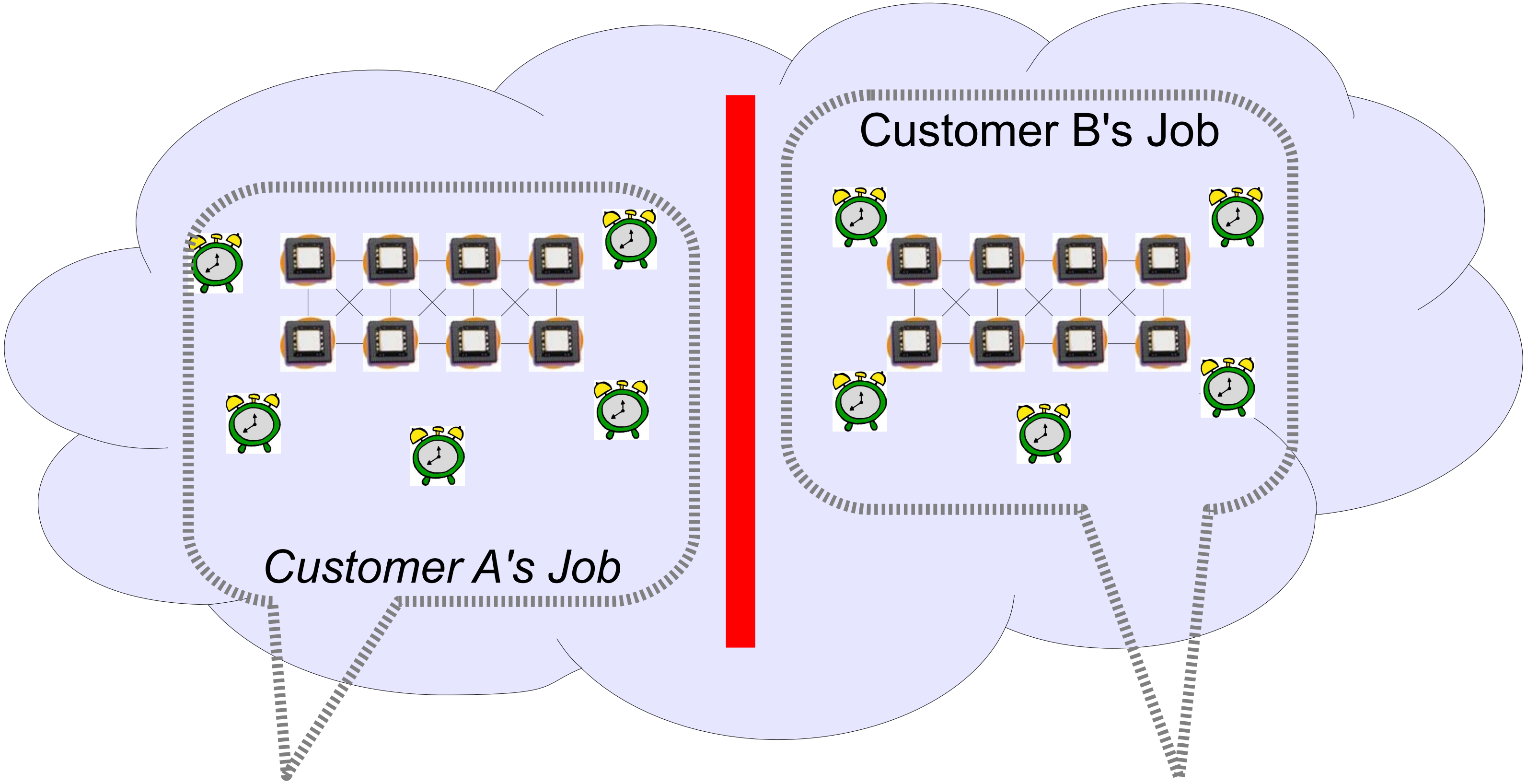


- A *reference clock* enabling the attacker to observe, extract the modulated signal

Remove either → no timing channel.

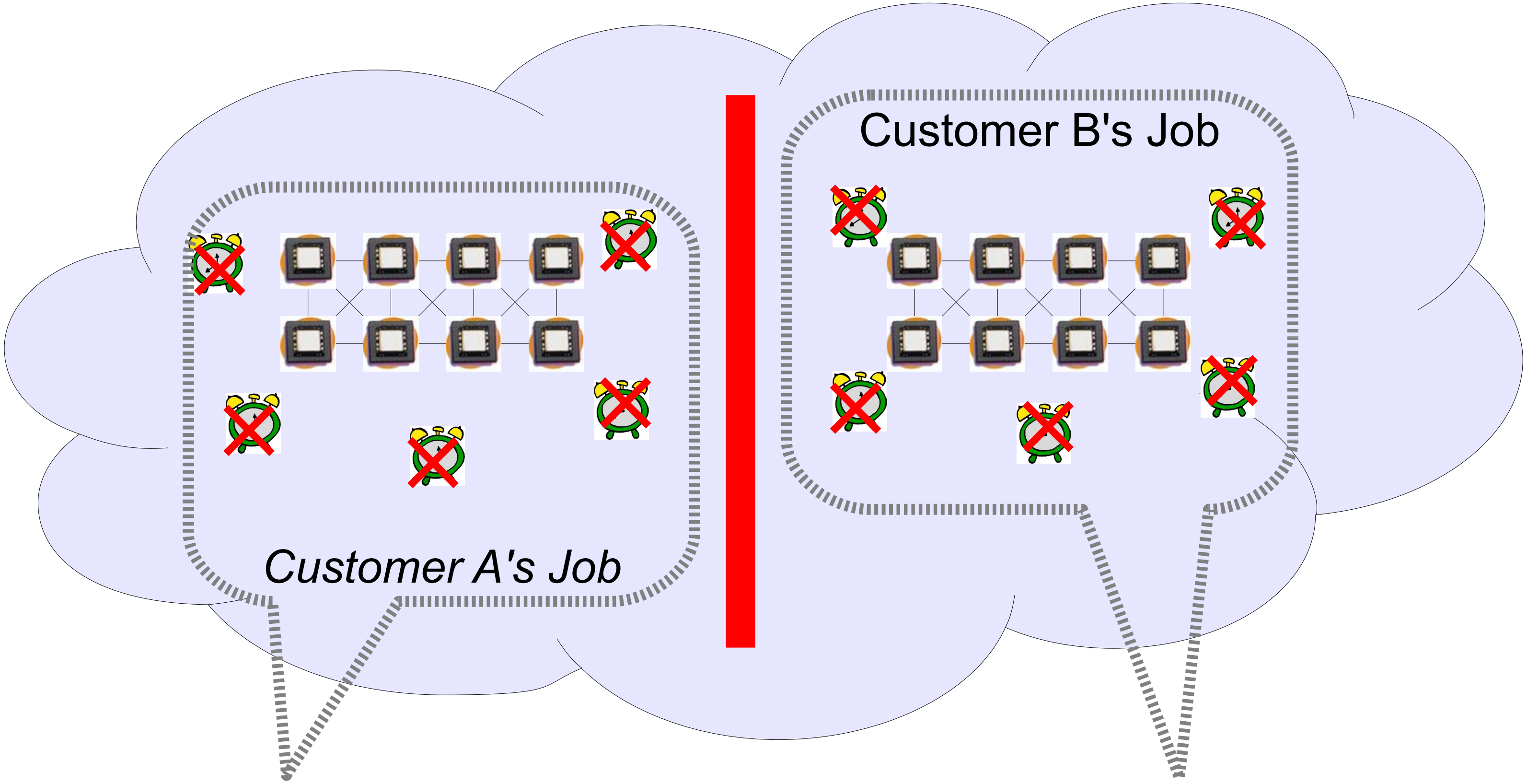
Prior Approaches

- Attempt to **eliminate modulation**
  - e.g., by partitioning hardware resources



Our Approach

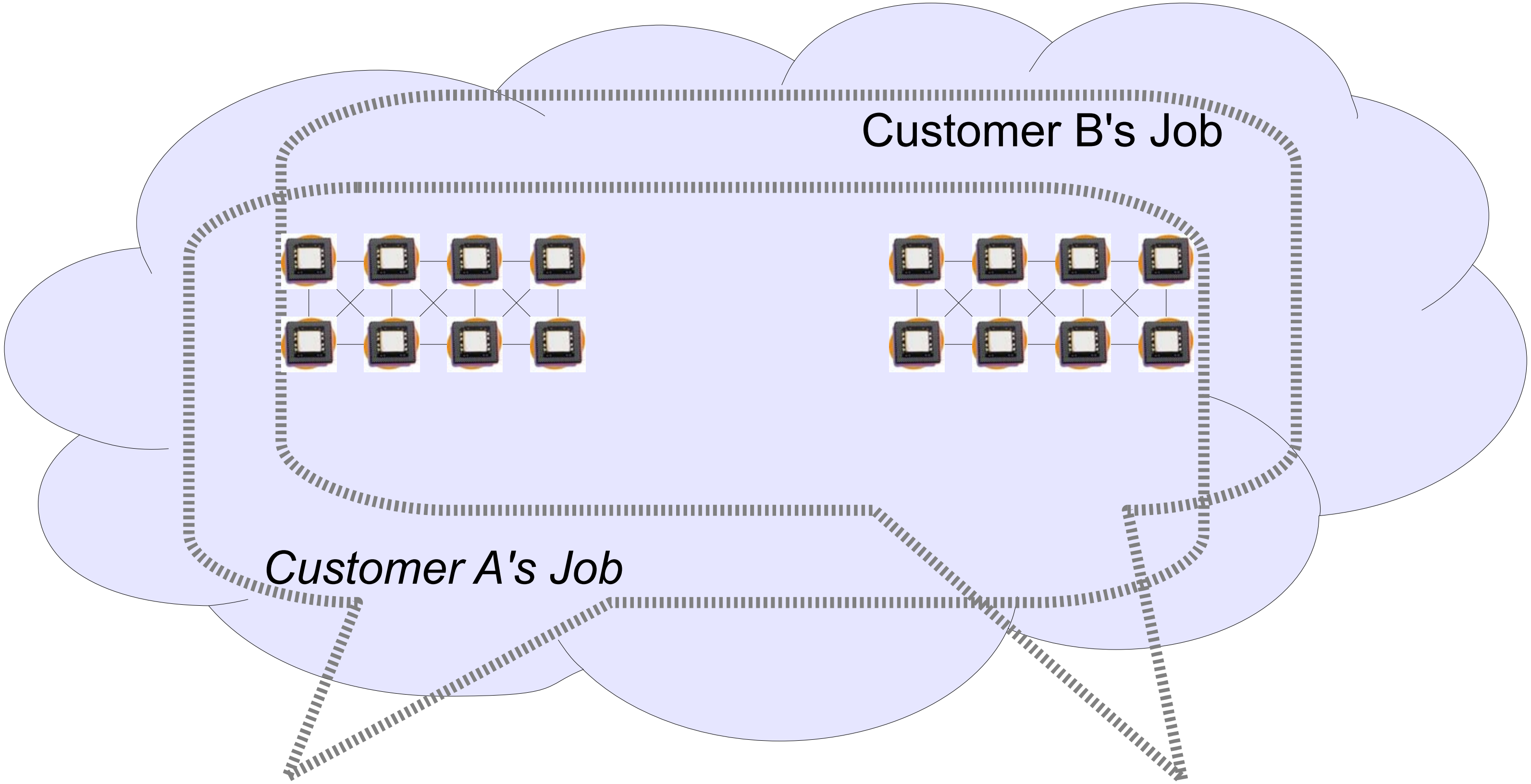
Allow modulation, **eliminate reference clocks**



Our Approach

Allow modulation, **eliminate reference clocks**

- *Dynamic statistical multiplexing allowed*



Deterministic Execution

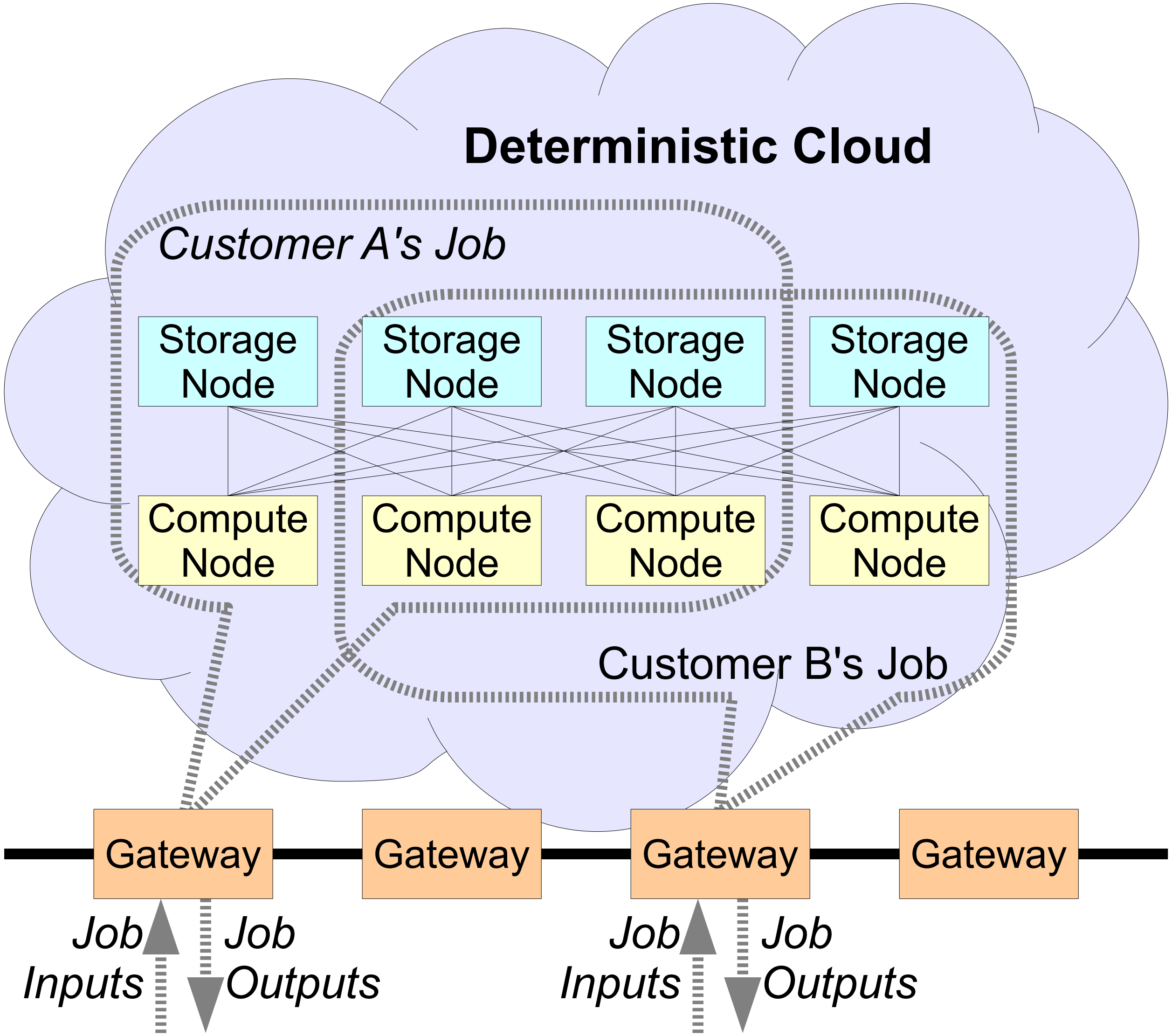
Definition:

- Given *same inputs* from external world
- Always yields *same execution flow & outputs*

What this means:

- Execution not affected by *internal* timing
- No *internal* reference clocks (only external)

A Timing-Hardened Cloud



Deterministic Cloud

Customer A's Job

Storage Node

Storage Node

Storage Node

Storage Node

Compute Node

Compute Node

Compute Node

Compute Node

Customer B's Job

Gateway

Gateway

Gateway

Gateway

Job Inputs

Job Outputs

Job Inputs

Job Outputs

What We've Accomplished

Eliminated all *internal* timing channels

- Independent of **resource** (cache, disk, …)
- Independent of **algorithm** (AES, RSA, …)

Leaves **one** aggregated timing channel

- How long did the entire job take to run?

Can **rate control** by scheduling job outputs

Eliminating Reference Clocks

Just protect hardware clocks/timers from apps.

Easy, right?

Wrong.

A Thread is a Reference Clock

```
volatile long long timer = 0;

void *timer_func(void *)
  { while (1) timer++; }

main() {
  pthread_create(&timer_thread, NULL,
                 timer_func, NULL);
  ...
  // Read the "current time"
  long long timestamp = timer;
  ...
}
```

Deterministic Parallelism

Requires **new approach to parallel execution**

- Threads *access memory* deterministically
- Threads *synchronize* deterministically
- Processes *access shared system resources* (e.g., file systems) deterministically

→ Parallelism introduces **no reference clocks**,

→ Hence **no internal timing channels**

Introducing Determinator

A Determinism-Enforcing Microkernel/Hypervisor

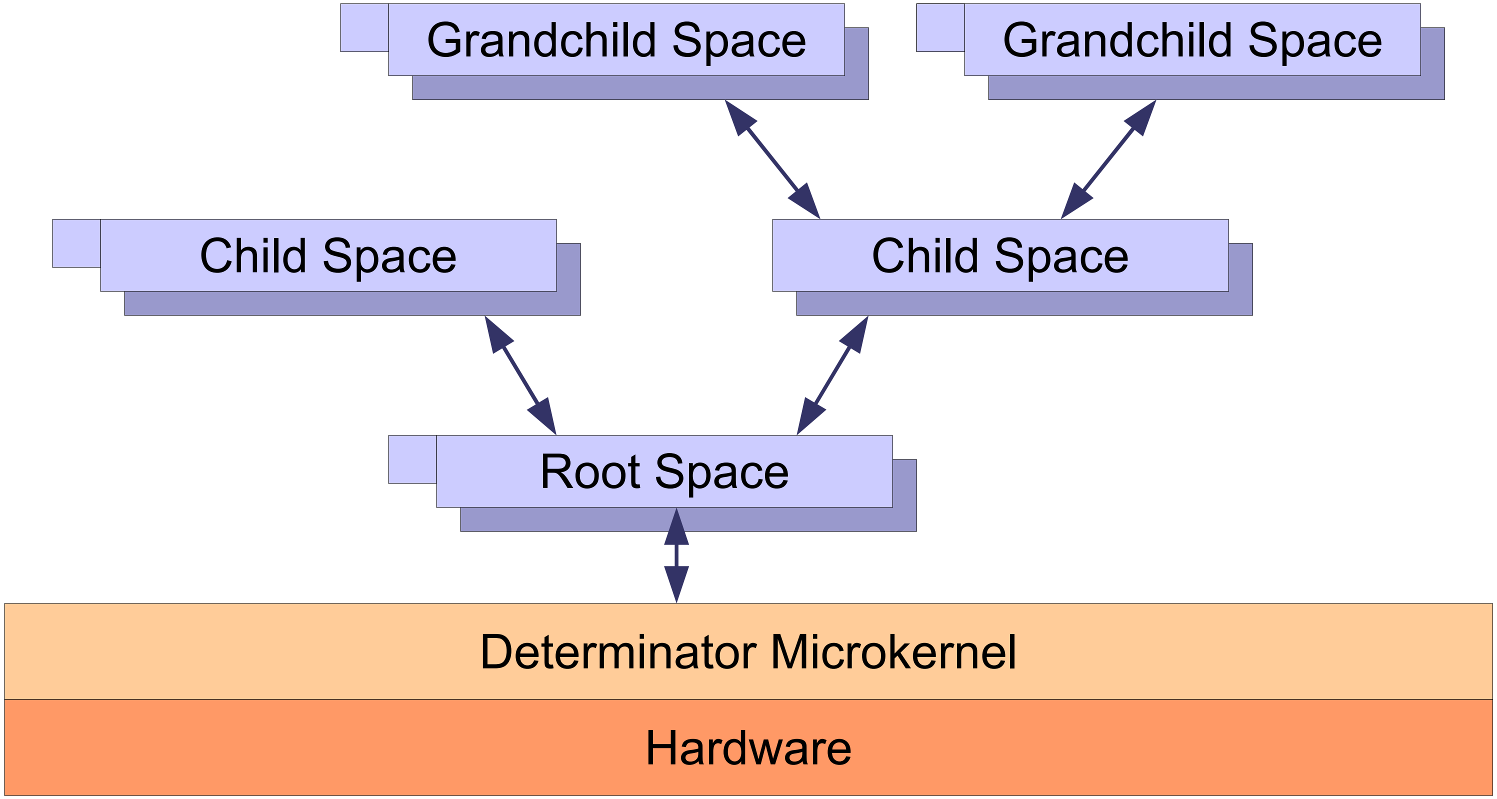
- ***“Efficient System-Enforced Parallelism”*** (Jay Lepreau Best Paper Award, OSDI 2010)
- Explores a new, *naturally deterministic* parallel application programming model

Other Approaches

- DMP/CoreDet/dOS [Bergan 2009/2010]
- Grace [Berger 2009]

Determinator Architecture

A Determinism-Enforcing Microkernel/Hypervisor



Other Benefits of Determinism

Simpler Application Development/Debugging

- No races/heisenbugs → all bugs repeatable

More efficient logging/replay

- Log only *external*, not *internal* events

State machine replication, checking, analysis

- Bit-for-bit correspondence across replicas

Are Deterministic Clouds Practical?

Determinism *could* help control timing channels, *but:*

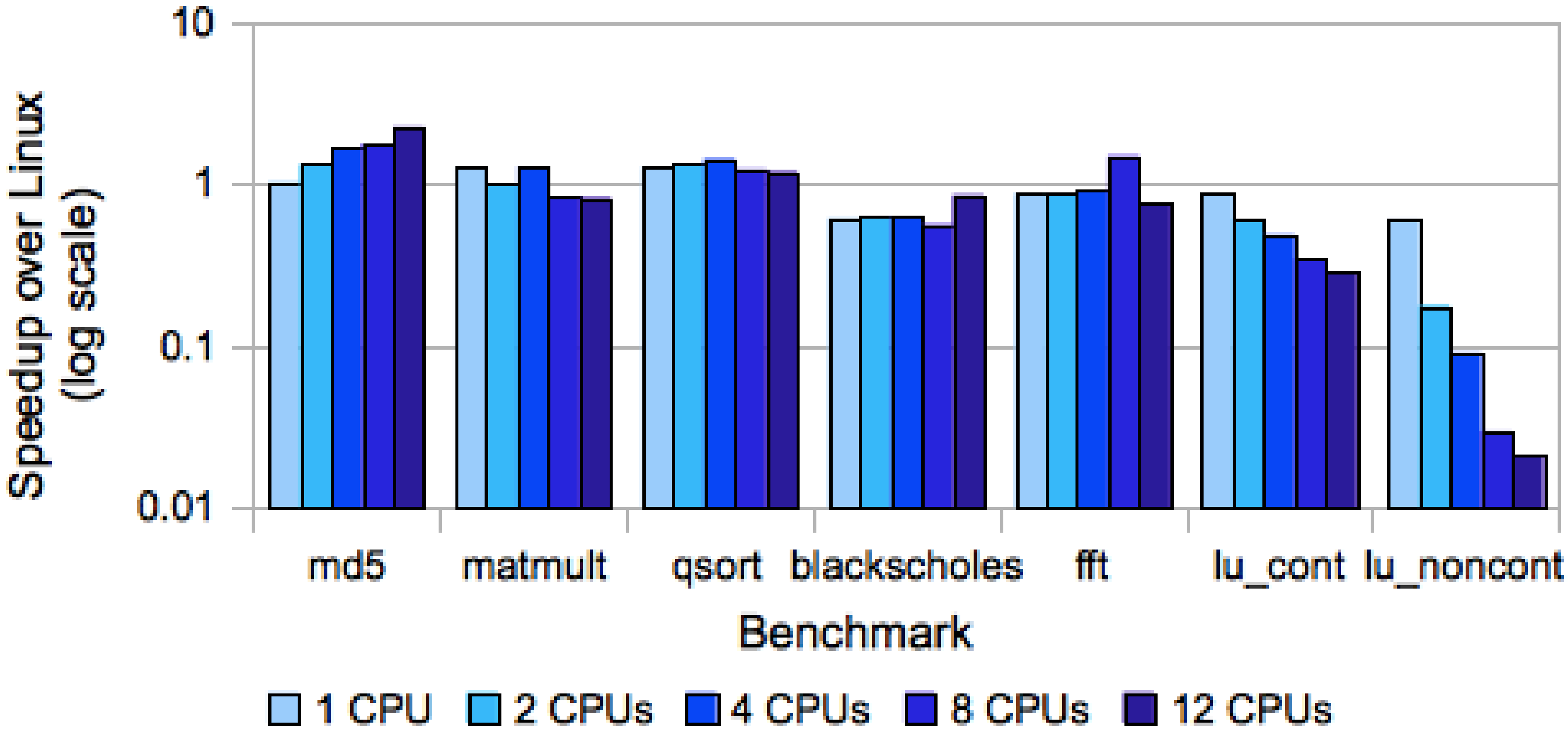
- Can it offer a **rich enough environment?**
- Can it be made **efficient enough?**

Some open issues and possible solutions...

Can It Be Efficient Enough?

Some preliminary evidence...

- (see OSDI paper for more detailed evaluation)



Creating a Rich Cloud Environment

Sometimes apps **need to tell the time**

- External nodes or gateways supply timestamps as explicit, *external* inputs

May be some forms of **“safe nondeterminism”**

- Random numbers from provider's trusted RNG

Sometimes want **application-level scheduling**

- App can fork off “scheduler process,” but use IFC to prevent it from affecting app's results

Conclusion

- Timing channels ***may*** be a serious challenge
  - Clouds create *massive untrusted co-residency*
  - Parallelism creates *pervasive timing channels*
  - Timing attacks are *unlikely to be caught*
  - Resource partitioning *defeats business model*
- Deterministic parallelism may offer a solution
  - Eliminates all *internal* timing channels
  - Performance practical at least for some apps

Further information: http://dedis.cs.yale.edu