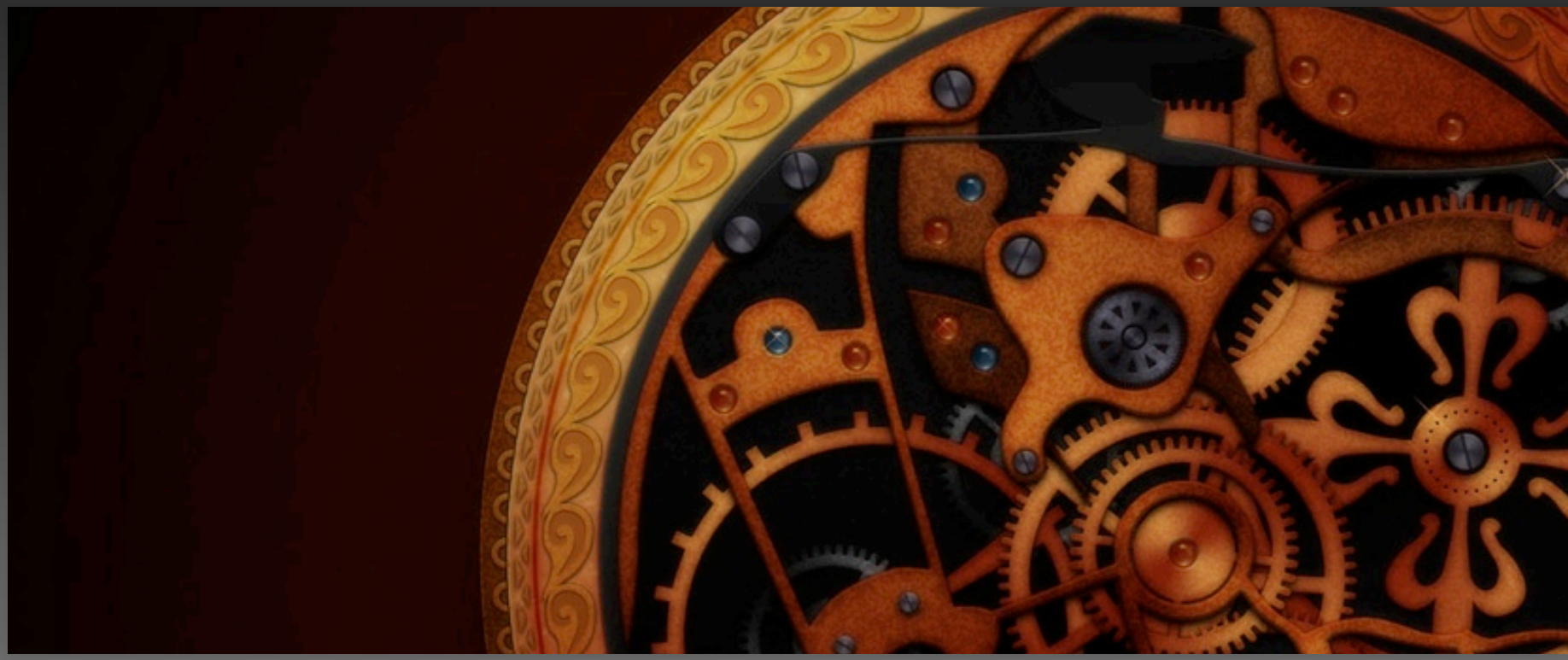

Capo:
A Software-Hardware Interface for Practical Deterministic Multiprocessor Replay

Pablo Montesinos, Matthew Hicks, Samuel T. King and Josep Torrellas

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Motivation: Time Travel

- Allows us to visit and recreate past states and events in computer
- Wide range of uses:
  - Debugging
  - Security
- Enabled by using Deterministic Replay of Execution

How Deterministic Replay Works

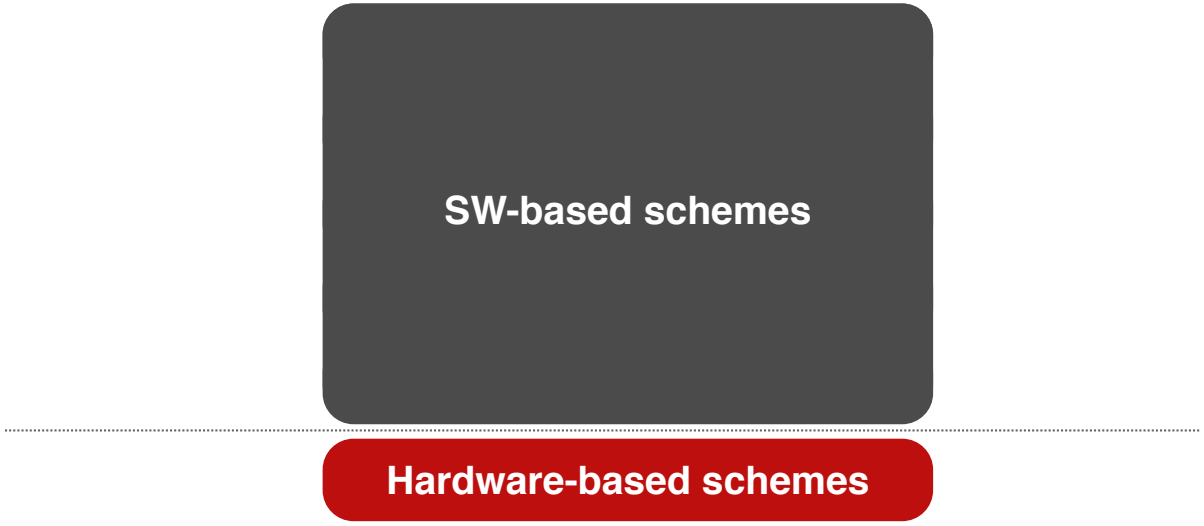
- Phase I: **Initial Execution** (a.k.a **Recording**)

- Phase II: **Replay**

SW-Based Deterministic Replay

- \+ Flexible, integrate well with rest of SW stack
- − Very **slow** or non-applicable to **multiprocessor** execution:
  - − Software is slow at capturing memory access interleaving

HW-Based Deterministic Replay of Multiprocessors



- \+ HW can record interleaving of shared-memory accesses effectively:
  - \+ Small Memory Access Interleaving Log
  - \+ Little overhead
- − Limitation: integration with SW stack is poor

Limitations of HW-Based Replay of Multiprocessors

- Past proposals focused only on HW primitive for recording and replaying
  - How does it integrate with the SW stack?
- Ca
  - P
  - R
- Ca e
  ma

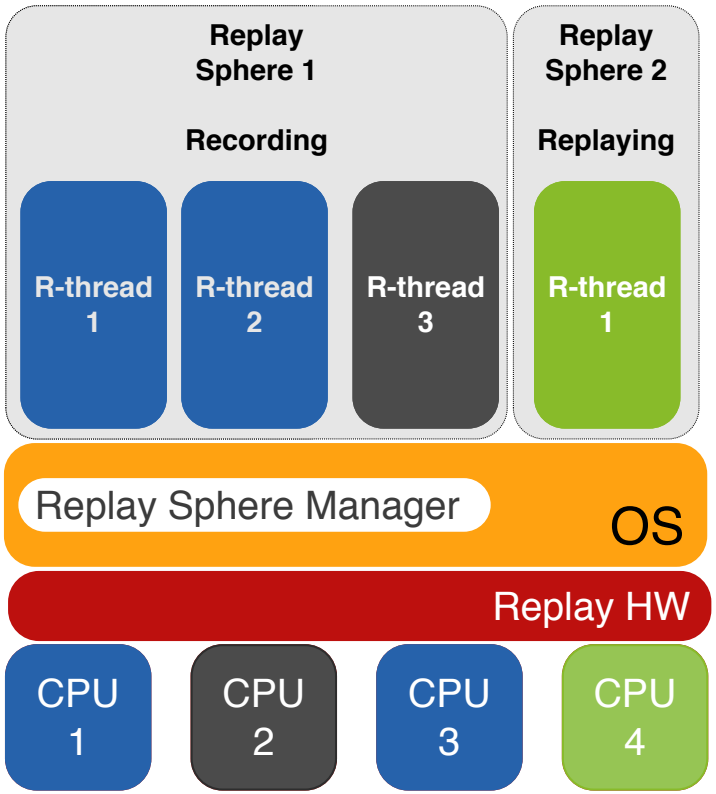
We must adapt HW-based replay systems and carefully integrate them with SW in order to make HW-based replay practical

Capo Contributions

- **SW-HW interface** for practical HW-assisted deterministic replay
  - Works with any HW-based replay system
- **Replay Sphere:** new abstraction
  - Isolates SW that is being recorded (replayed) from the rest
  - Separates the responsibilities of the HW and the SW components
- **CapoOne:** Linux-based prototype

Replay Sphere: Isolating Processes

- **Replay Sphere:** Set of threads recorded and replayed as a unit and their address space
  - Only user-mode threads run inside spheres
  - Threads inside a sphere: R-threads
- Replay spheres and processes:
  - R-threads that share memory must run within same sphere
  - Many processes can run within the same sphere



Replay Sphere: Separating Responsibilities

- HW:
  - Records memory access interleaving of R-threads running within same sphere
  - Produces per-sphere **Memory Access Interleaving Log**
  - Enforces same memory access interleaving during replay

- SW (Replay Sphere Manager):
  - Logs the other sources of non-determinism that affect the sphere
  - Produces per-sphere **Input Log**
    - Includes system call return values, signals, data copied into the sphere...
  - Injects data from log into sphere during replay

Other Replay Sphere Manager Responsibilities

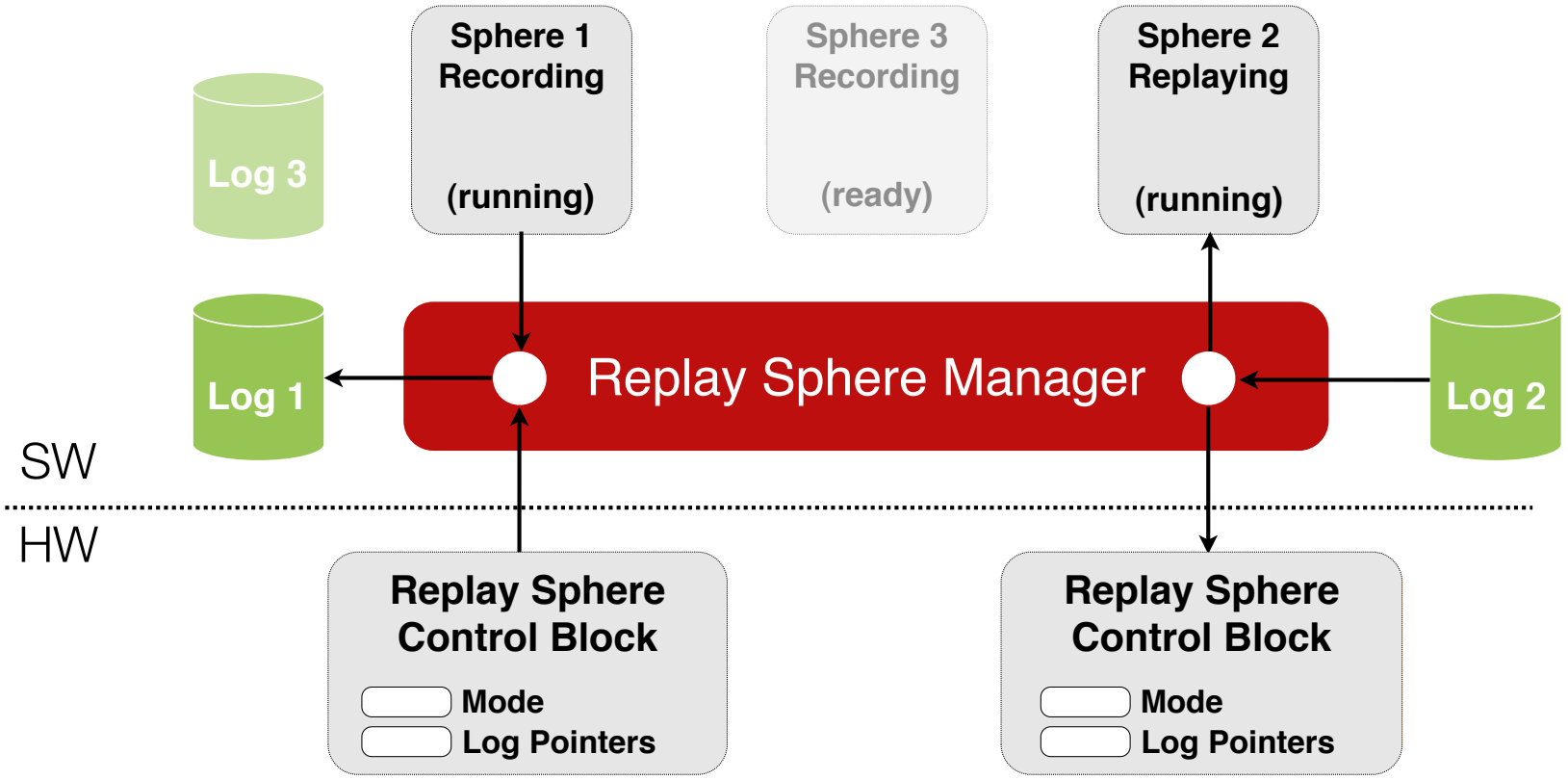
- Assign the same virtual memory addresses during recording/replay
- Assign the same IDs to R-threads during recording/replay
- Manage Memory Access Interleaving Log and Input Log
- Manage replay HW resources

Capo's HW Interface

- Works with any HW-based replay system
- **Per-processor** R-Thread Control Block:
  - Sphere ID register
  - R-Thread ID register
- **Per-sphere** Replay Sphere Control Block:
  - Mode register: specifies whether the sphere is recording or replaying
  - Log pointers: insert to / remove from Memory Access Interleaving Log

Virtualizing the Replay HW

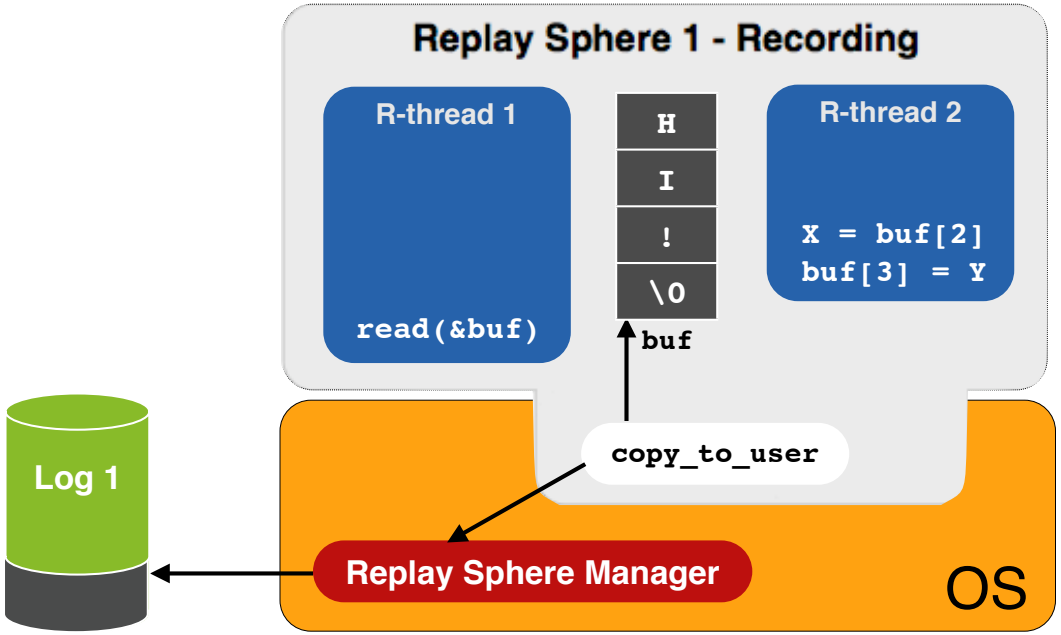
- Replay sphere manager schedules spheres into hardware contexts



Three Key Challenges

1. Ensuring deterministic interleaving when OS copies data into a sphere
2. Using fewer processors during replay than were used during recording
3. Emulating vs. re-executing system calls

OS Copies Data into Spheres



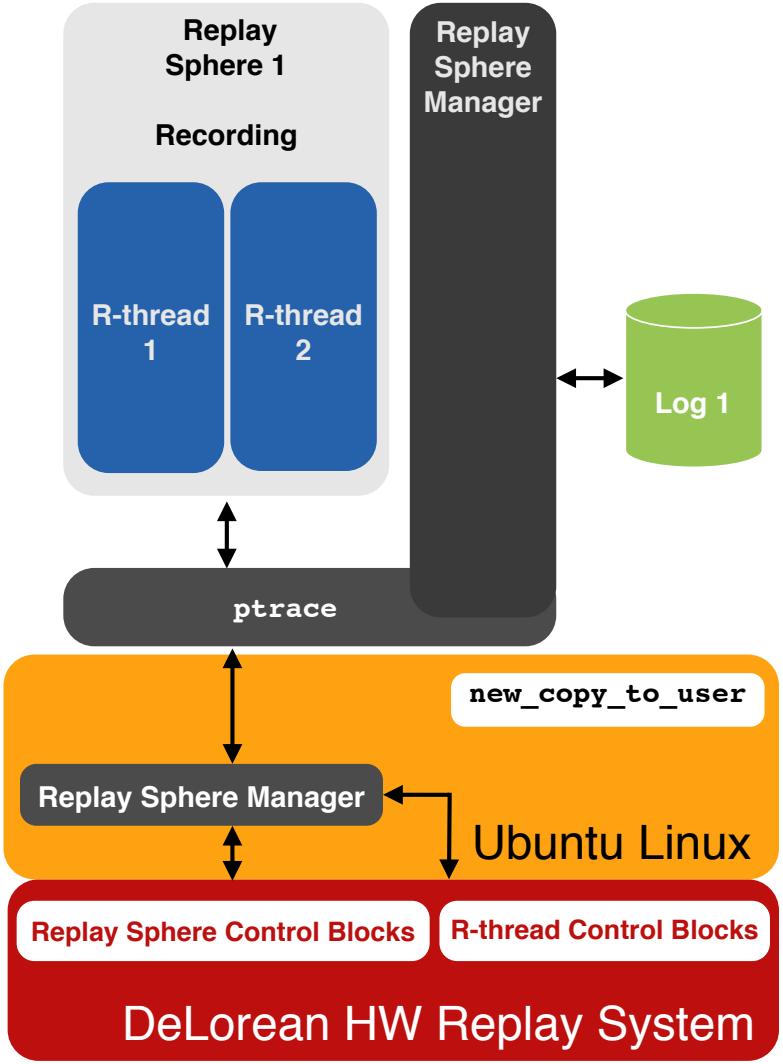
- Problem: interleaving between OS copies and R-threads not recorded
- Solution: insert `copy_to_user` into sphere:
  - HW can log memory access interleaving
  - `copy_to_user` exits sphere once copy is over

Replaying with a Lower Processor Count

- Problem: R-thread that should replay next log entry not scheduled in CPU
- Solution 1: HW detects problem and raises interrupt
  - Efficient, but it requires additional HW and SW support
- Solution 2: SW inspects Interleaving Log and tries to prevent problem
  - Not trivial, requires changes to OS scheduler
- Solution 3: Do nothing, simply wait for OS to schedule R-thread
  - Simple, but can hurt performance

CapoOne: First Capo Implementation

- Simulated replay HW:
  - DeLorean HW system [Montesinos ISCA'08]
  - Augmented with Capo's HW interface
- Modified 2.6.24 Linux kernel
  - Supports replay spheres, R-threads
  - New, deterministic `copy_to_user`
- Split Replay Sphere Manager:
  - User-level component based on ptrace
  - Kernel-level component schedules spheres and R-threads



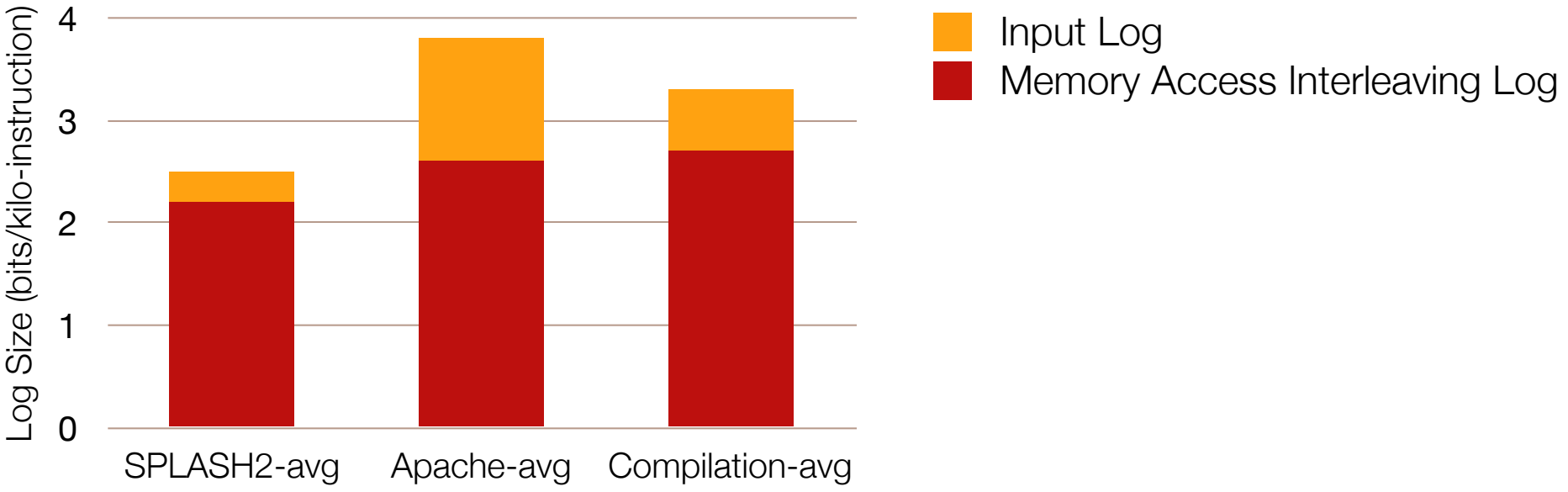
Also in the Paper

- CapoOne implementation details
- Lessons learned during CapoOne's development
- Emulating vs. Re-Executing System calls
- Using Capo with different HW-Based replay systems

CapoOne Evaluation Setup

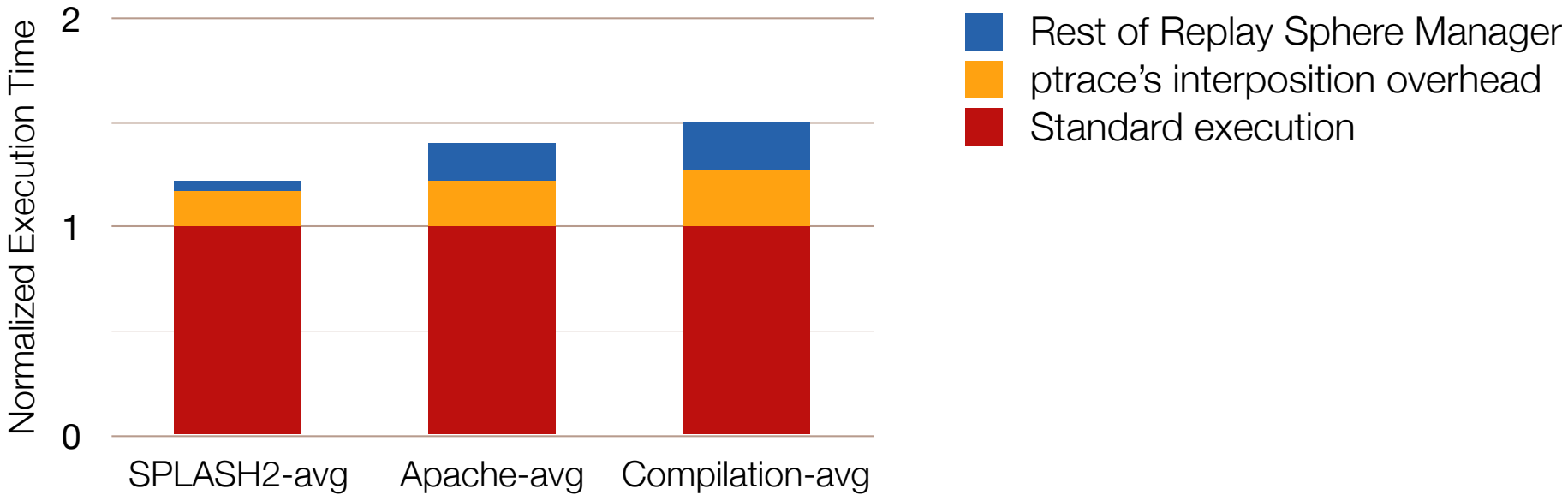
- Two HW configurations
  - Simulated DeLorean HW replay system (SIMICS): 4 x86 processors
  - Real hardware: 4-Core x86 Intel processor without DeLorean HW
- SW: Ubuntu 7.10 with Replay Sphere Manager
  - Modified 2.6.24 Kernel
- Benchmarks:
  - Scientific Benchmarks: SPLASH-2
  - System benchmarks: Apache, Compilation

Overall Log Size



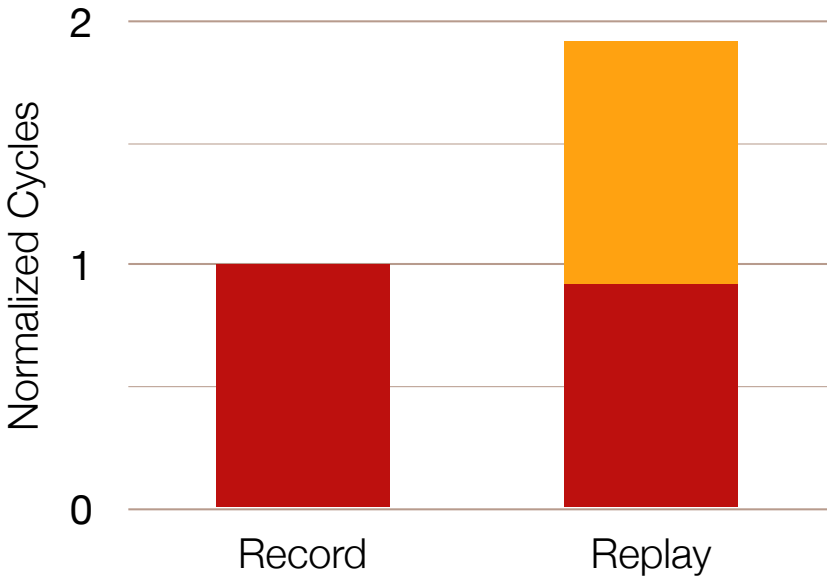
- Memory Access Interleaving Log takes most of the space
- Small overall log: 3.17 bits/kilo-instruction

Recording Performance



- Moderate overhead: 21% for SPLASH2 and 41% average for system apps
  - Minimal timing distortion for debugging concurrency defects

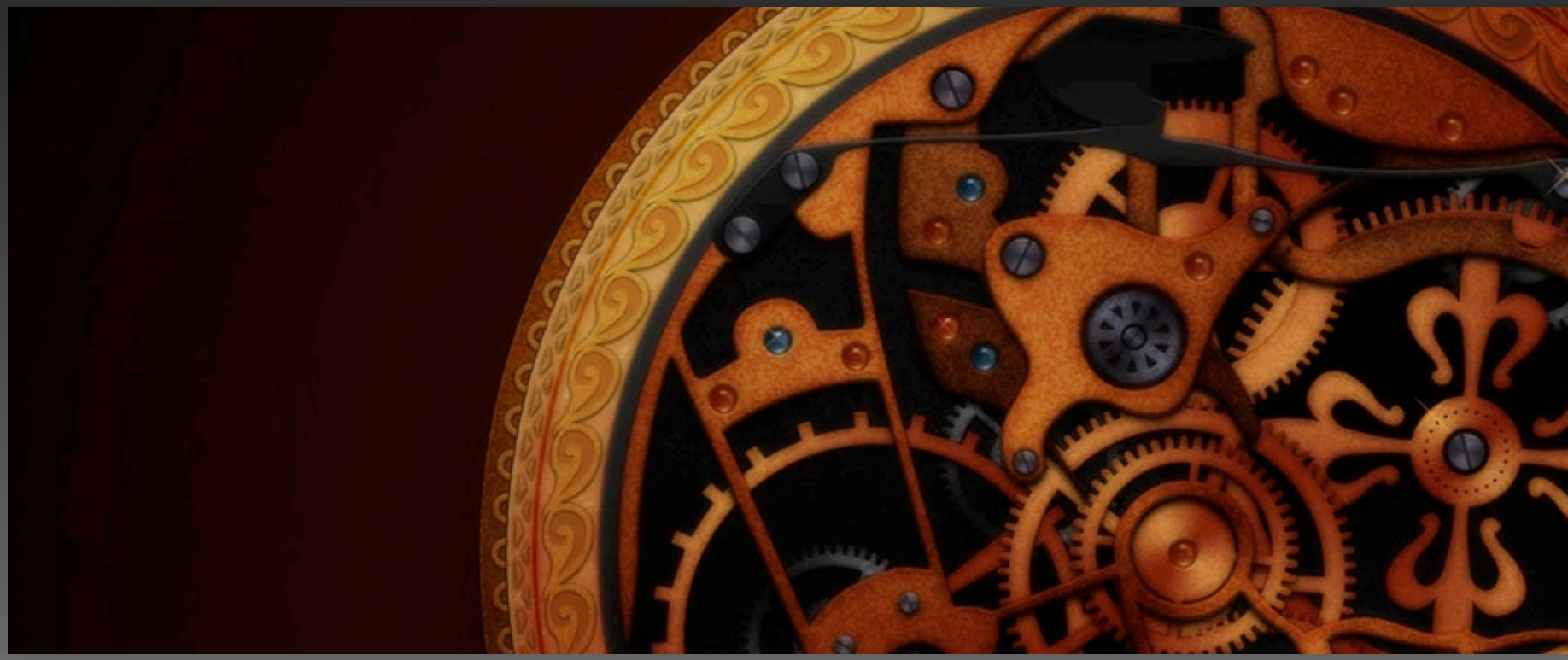
Replay Performance: SPLASH-2



- Emulating system calls reduces cycles during replay
- Replay takes only 80% more cycles
  - R-Threads must wait for their turn to commit

Conclusions

- Capo enables practical replay of execution for systems with replay HW
  - The Replay Sphere is a powerful abstraction
  - Enable mixing recording, replay and standard execution
- CapoOne: first Capo prototype
  - Working system
  - Good performance (21-41% recording overhead, 80% replay overhead)
  - Good for debugging concurrency defects



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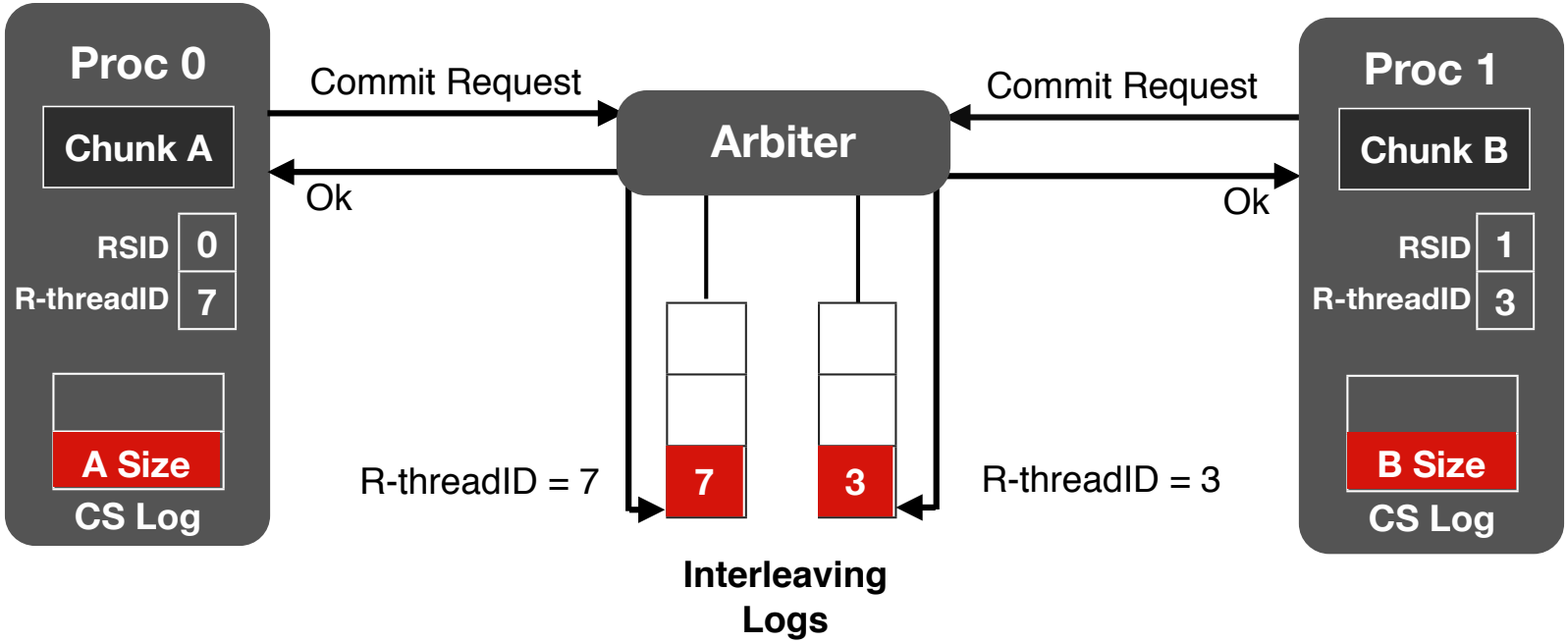
CapoOne: Basic HW Operation

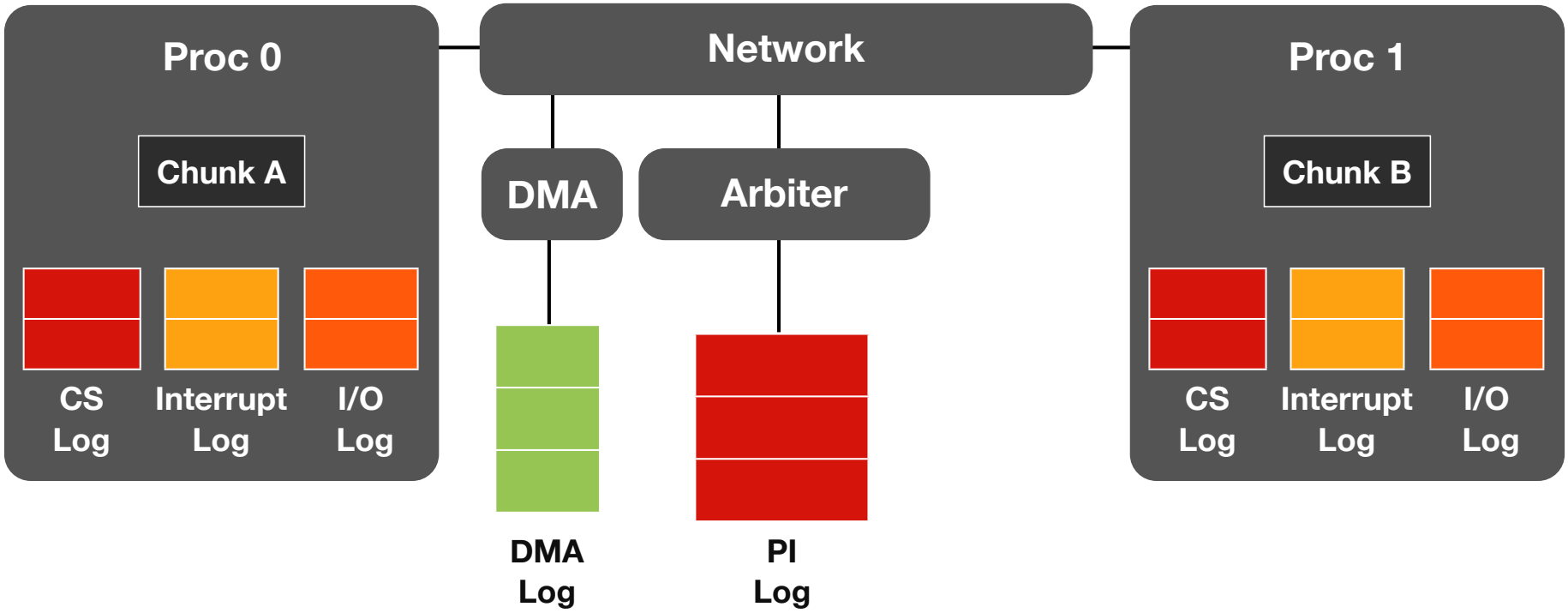


- Two new per-processor registers: RSID, R-threadID
- Arbiter now supports concurrent spheres
  - Manages an Interleaving Log for each of them

Today's Agenda: Towards the Perfect Replay System

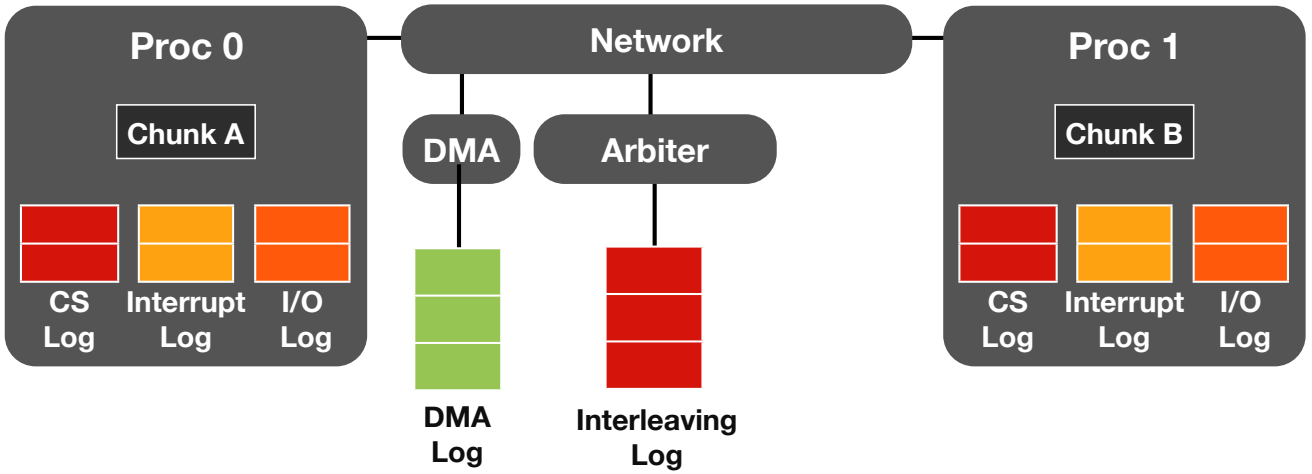
- **DeLorean:** New hardware replay engine
  - Very efficient multiprocessor support
  - Vastly improved log requirements
- **Capo:** New SW-HW interface for replay
  - Makes HW-based replay systems practical
- Evaluation
- Future work

Overall DeLorean System



- Interrupt, I/O and DMA logs are common to other HW-based schemes

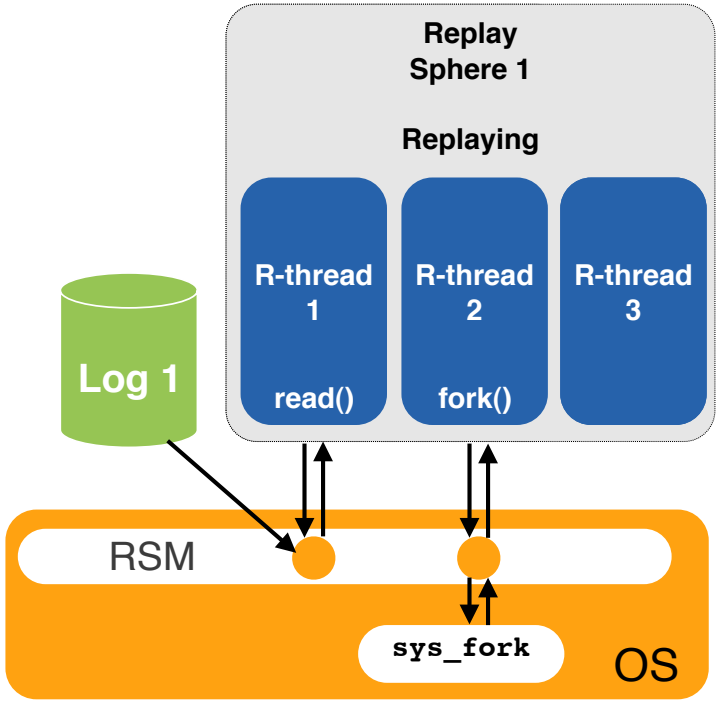
CapoOne: HW Implementation



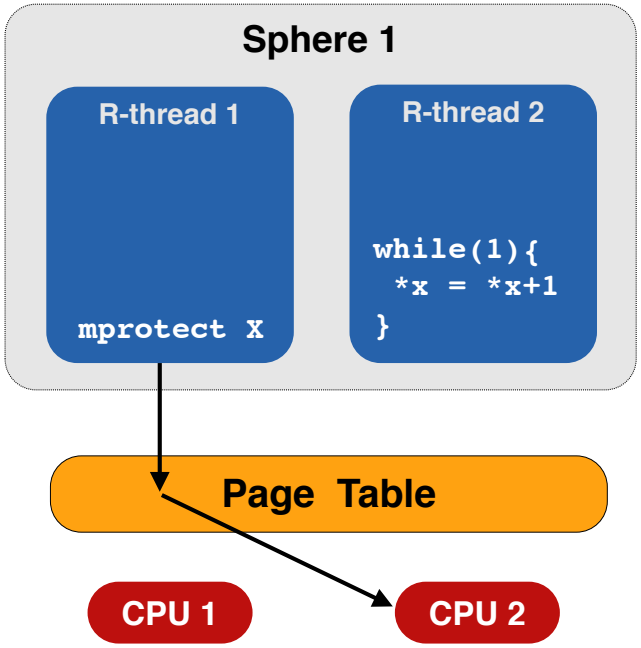
- No need for DeLorean's Interrupt Log, DMA Log nor I/O Log
  - PI Log becomes the per-sphere Interleaving Log
  - CS Log becomes a per-R-thread Log
- Chunks only have instructions from one application (or the kernel)

Emulating vs Re-Executing System Calls

- During replay, the RSM emulates most system calls:
  - RSM injects return values from Sphere Input Log, squashes outputs
- Some have to be re-executed
  - Thread management (`clone`)
  - Address space modification (`mprotect`)



Implicit Dependencies



- R-thread changes mapping or protection of address space, and another R-thread uses this changed address space
- RSM can express these dependencies to hardware so these interactions can be recorded