Record and Replay

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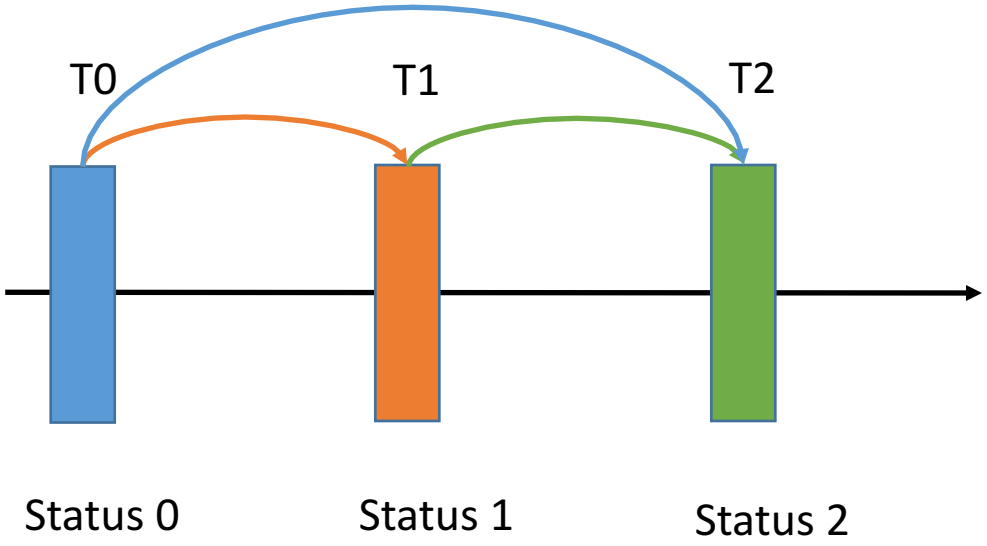
Agenda

- Introduction
- Challenges
- Solutions
- QEMU record & replay
- Cicada?

Introduction

- It allows capturing the execution of a running system for later replay
- Good for bug analysis
- Good for malware analysis
- Good for post-attack analysis
- Etc.



Challenges

- Modern CPUs are not deterministic
  - Out-of-order execution
  - Previous status based speculate algorithm
  - Unpredictable Cache miss
  - So, choose a probe checkpoint
  - Depends on Interrupt to flush its pipe line
  - Memory-chunk based
- Accurate time scale
  - Higher resolution than instruction execution
  - Interrupt based time-keeping is not suitable for Record & Replay.
  - Hardware performance counter (e.g., instructions count)
- Non-deterministic event record
  - Interrupt
  - Context-switch
  - Race conditions
  - Etc. ……

Solutions: Single process based record & Replay

- A example: Jockey: A user-space library for record-replay debugging
- it intercepts system calls and rewrites all CPU offending instructions
  - To intercept system call
  - To rewrites CPU instructions, e.g., rdtsc
    1. Fetch text section by reading ELF header
    2. Scan text section and rewrite the inst.
- Advantage: it is simple enough
- Disadvantage
  - Single application only
  - Event based rather than inst. based

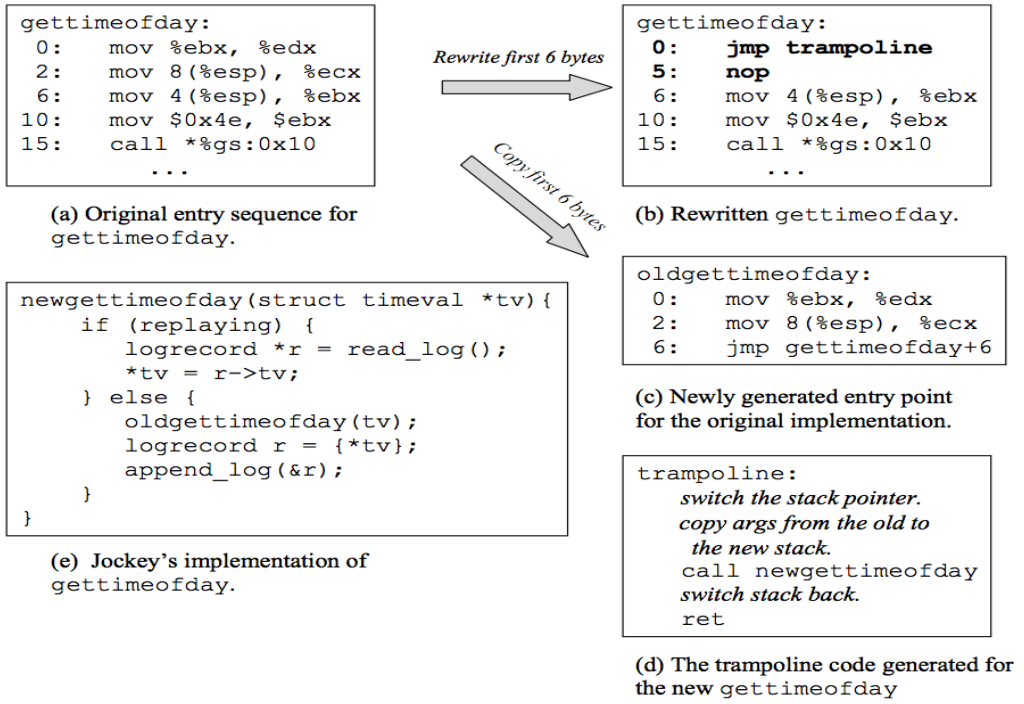


Figure 4: *Recording and replaying* `gettimeofday`.

Solutions: Single process based record & Replay (Cont.)

- The methods to solve the challenges

Challenge	The way to solve
Non-deterministic CPU	Memory barrier can be applied in the handler
Time scale	Event based
Non-deterministic event record	None is recorded

Solutions: multi-threaded process based Record & Replay

- A example: Flashback: A Lightweight Extension for Rollback and Deterministic Replay for Software Debugging
- Make checkpoints for the whole process status where it can be replayed later
- Record memory status – by forking a new process
- Log system calls – by intercepting system calls in kernel
- Handle shared memory by forcing page-fault
- Record signals
- Advantage: multi-thread workable
- Disadvantage: require kernel change, can not record context switch (can not replay race conditions)

Solutions: multi-threaded process based Record & Replay

- The methods to solve the challenges

Challenge	The way to solve
Non-deterministic CPU	Memory barrier can be applied in the handler
Time scale	Event based
Non-deterministic event record	None is recorded

Solutions: Virtual Machine based Record & Replay

- Checkpoint system status
- Replay storage
- Log non-deterministic events
- Advantage: replay for the whole system
- Disadvantages:
  - 1) Over configure (e.g., dedicated VM images)
  - 2) Overload (e.g., log everything)

Solutions: Virtual Machine based Record & Replay (Cont.)

- The methods to solve the challenges

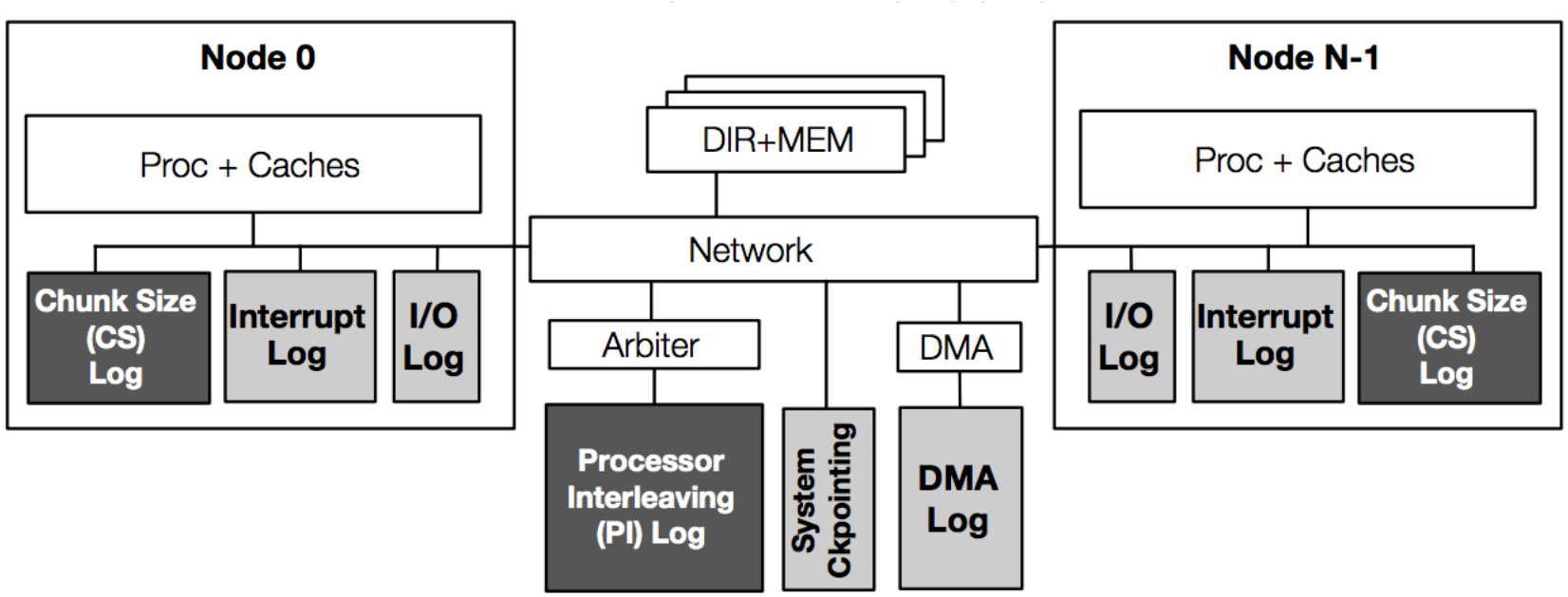
Challenge	The way to solve
Non-deterministic CPU	Based on interrupt which can flush CPU pipe lines automatically
Time scale	Instruction count (e.g, instruction-count hardware performance count)
Non-deterministic event record	Record and associate it with the executed instruction sequence

Solutions: hardware-based Record & Replay

- Log the execution chunk which is not collisional with other CPUs and associated with a sequence number and CPU ID, consequently, these chunks can be replayed.
  - Instruction & memory reorder are allowed in the chunk
  - External interrupt can truncate the chuck
- Can be based on hardware transaction memory
- Advantage: full record & replay support
- Disadvantage: expensive for dedicated hardware and no real CPU supports it so far (cicada?)

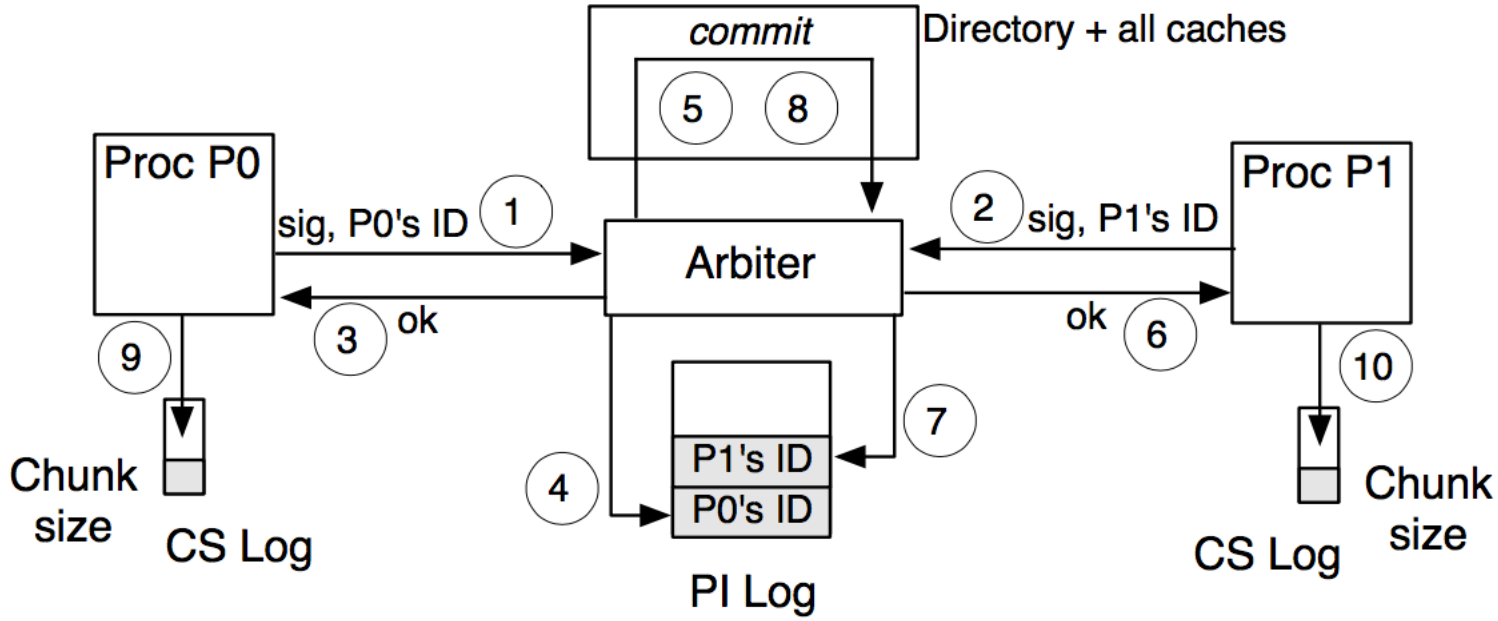
Solutions: hardware-based Record & Replay (Cont.)

- Architecture



Solutions: hardware-based Record & Replay (Cont.)

- Work flow



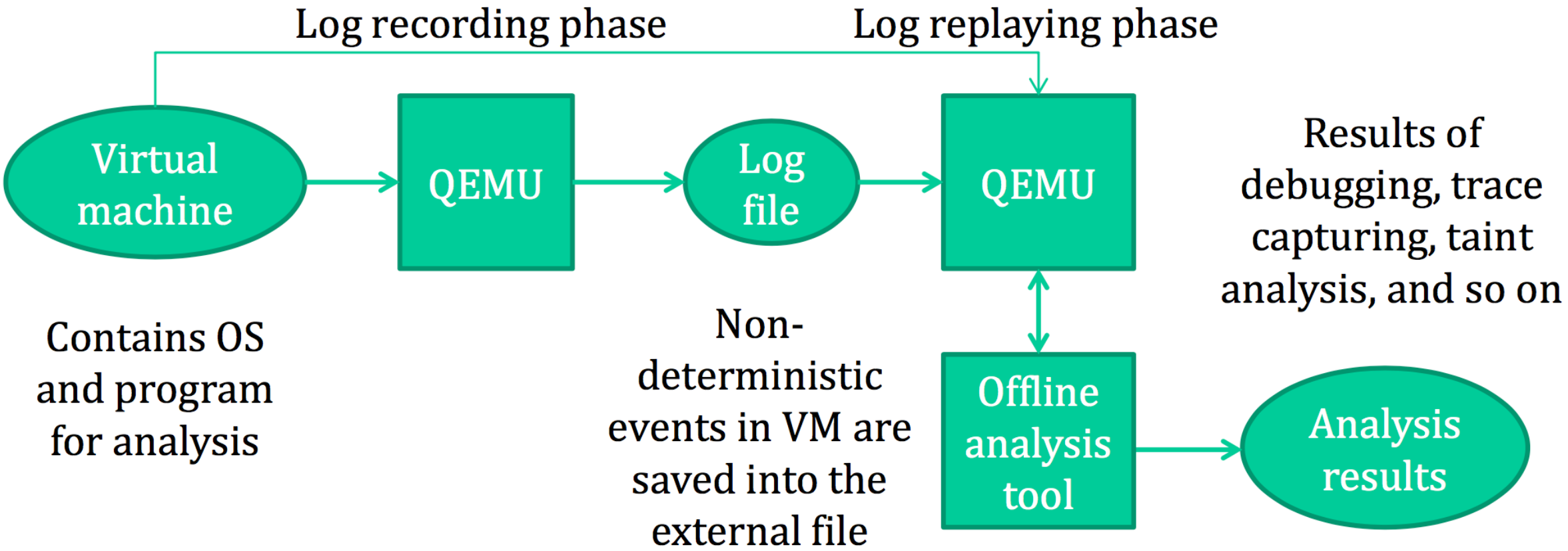
Solutions: hardware-based Record & Replay (Cont.)

- The methods to solve the challenges

Challenge	The way to solve
Non-deterministic CPU	Hardware guarantee (e.g, flush CPU pipe line at the boundary of chunk)
Time scale	Based on the chunk size which is predefined or recorded by the hardware (CS-LOG)
Non-deterministic event record	Hardware record them at the boundary of chunk

QEMU Record & Replay

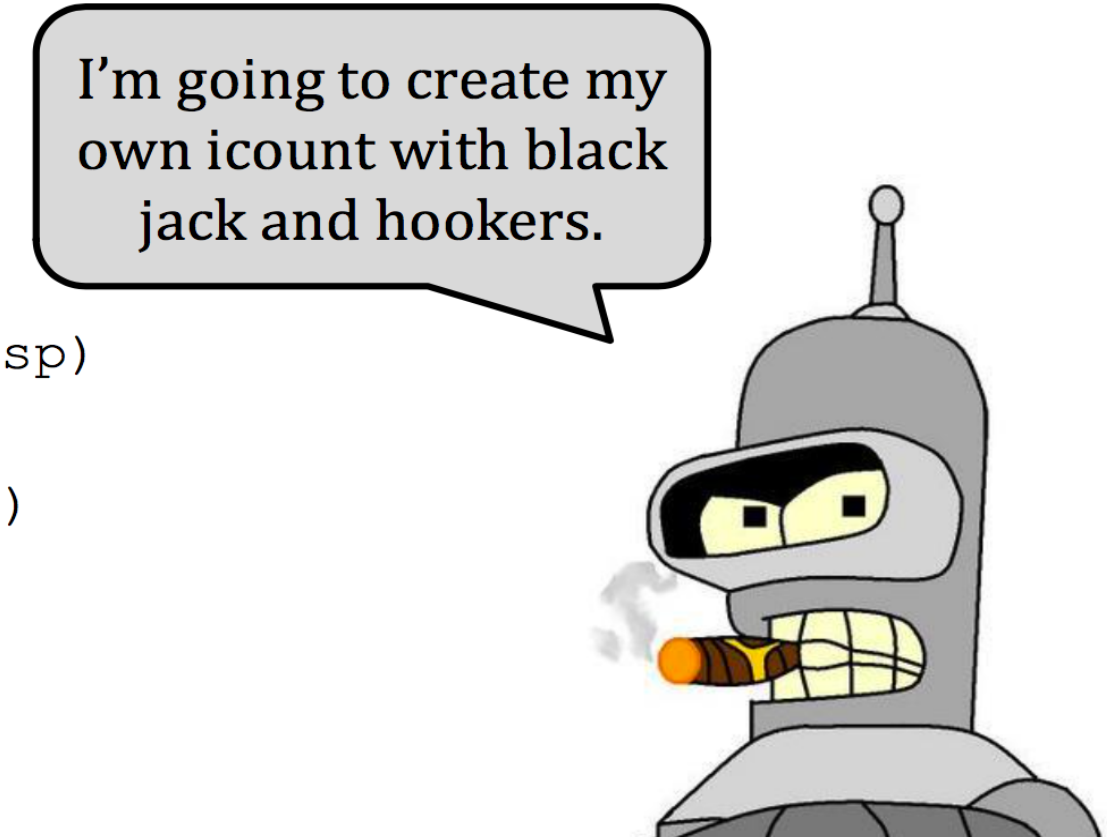
- Only works on !KVM && !Xen, e.g., no hardware-based virtualization (there has some researches for KVM based RR)



QEMU Record & Replay (Cont.)

- Use ‘icount’ (instruction count) as its time scale

```
check tcg_exit_req
000f2e0e: push   %ebx
++icount
000f2e0f: sub    $0x2c,%esp
++icount
000f2e12: movl $0xf64bc,0x4(%esp)
++icount
000f2e1a: movl   $0xf4d50,(%esp)
++icount
000f2e21: call   0xf1ca0
++icount
```



QEMU Record & Replay (Cont.)

- ‘icount’ limitations
  - Only supports single vCPU
  - Different counting for REP instructions in single step and normal modes
    - icount is not incremented for the last (ecx=0) iteration in normal mode
  - Incorrect when using breakpoints through gdb
    - icount is incremented for non-executed instruction, which located at the breakpoint address

Hmm, no memory barrier is used to avoid instruction reorder?

QEMU Record & Replay (Cont.)

- Non-deterministic events
  - Only save non-deterministic to make log file smaller
  - Clock
  - The input of from peripheral devices, e.g.
    - Networking packets
    - Mouse & keyboard input
    - Etc
- Deterministic event
  - Not logged
  - It includes
    - Memory
    - Software interrupt
    - Instruction execution

QEMU Record & Replay (Cont.)

- Checkpoint
  - Replaying of the execution of virtual machine is bound by sources of non-determinism.
- Block device replay
  - It is inserted between disk image and virtual driver controller. Therefore all disk requests may be recorded and replayed.
- Networking replay
  - Qemu puts all packets coming from the outer world into a log. In replay mode packets from the log are injected into the network device.

Cicada?

Q & A?

References

- Jockey: A user-space library for record-replay debugging (http://www.hpl.hp.com/techreports/2005/HPL-2005-46.pdf)
- Flashback: A Lightweight Extension for Rollback and Deterministic Replay for Software Debugging (https://www.usenix.org/legacy/event/usenix04/tech/general/full_papers/srinivasan/srinivasan_html/paper.html)
- Deterministic Replay of System's Execution with Multi-target QEMU Simulator for Dynamic Analysis and Reverse Debugging (https://www.computer.org/csdl/proceedings/csmr/2012/4666/00/4666a553.pdf)
- Samsara: Efficient Deterministic Replay with Hardware Virtualization Extensions (https://www.usenix.org/system/files/conference/atc16/atc16_paper-ren.pdf)
- DeLorean: Recording and Deterministically Replaying Shared-Memory Multiprocessor Execution Efficiently (http://iacoma.cs.uiuc.edu/iacoma-papers/isca08_rep.pdf)
- Deterministic Replay and Reverse Debugging for QEMU (http://www.linux-kvm.org/images/d/d0/02x06b-DeterministicReplay.pdf)