Time-Travel in Closed Distributed Systems

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Motivation and Goals

- Distributed systems are complex:
  - Non-deterministic
  - Asynchronous
  - Long-running
  - Intricate component interaction
- We need a tool to analyze and debug long-running distributed systems
- Our Goal: Time-travel a network of thousands of virtual machines spread across multiple physical machines in the Emulab testbed environment

What's New?

- Existing solutions employ only deterministic time-travel and operate on:
  - A single VM [King et al., USENIX05] or
  - Multiple VMs on one physical machine [Ho et al., GRID04] or
  - Specific user applications across physical machines [Geels et al., USENIX06]
- Our work differs in the following ways:
  - It is designed to be a practical system that time-travels multi-node experiments in "Emulab Classic"
  - We emphasize system scalability. Some design decisions towards this end include:
    - VMs distributed across physical machines
    - "Closed world" assumption
    - Relaxed determinism
    - Cooperative replay
  - We allow state mutations during replay by non-determinism

Emulab – The "Closed World"

- Experiments in Emulab Classic are typically "closed" - nodes within an experiment tend to communicate only with each other
- "Closed world" assumption helps improve scalability and enables exploring relaxed determinism
- Emulab's reliable, low-latency network fabric for control plane helps simplify the overall system by bounding clock skews to microsecond range [Veitch et al., IMC04]
- Emulab automation makes it easy to setup large-scale experiments

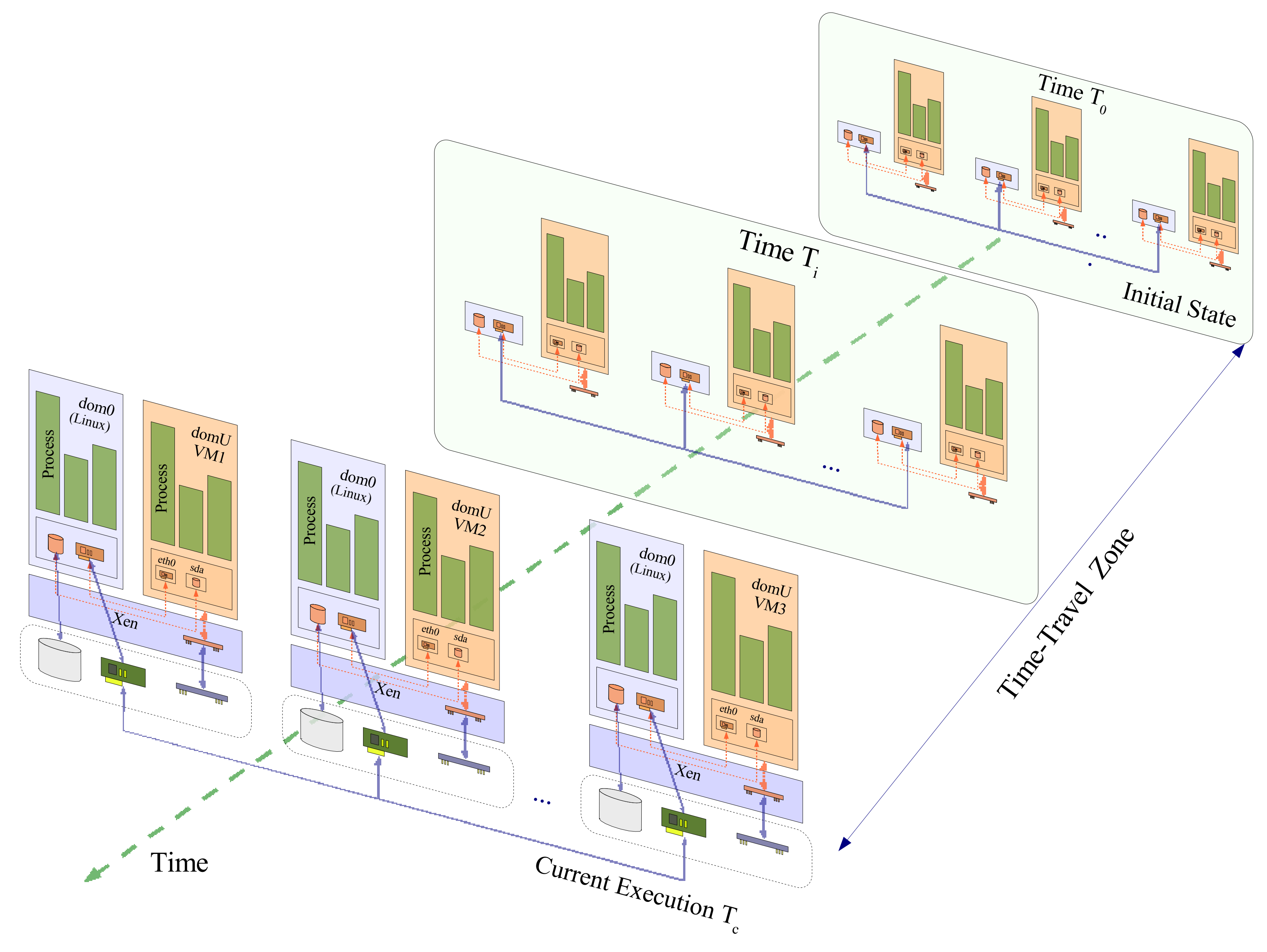
Why Relax Determinism?

- Mutating debugging operations are incompatible with deterministic replay
- Non-deterministic time-travel reduces logging overhead
- Some applications may not need determinism for debugging

Implementation

- Uses existing Xen VMM technology
- Implements both non-deterministic and deterministic time-travel in an attempt to compare them
- Logs sources of non-determinism during original execution
  - Timer Interrupts, Disk I/O, Network I/O, Physical Time
- Employs cooperative logging
  - Obviates logging of packet contents
- Takes periodic consistent distributed checkpoints for efficient time-travel
  - Tag all network packets with checkpoint "epoch-id"
- Replay
  - Deterministic: uses branch counters
  - Non-deterministic: uses VM virtual time

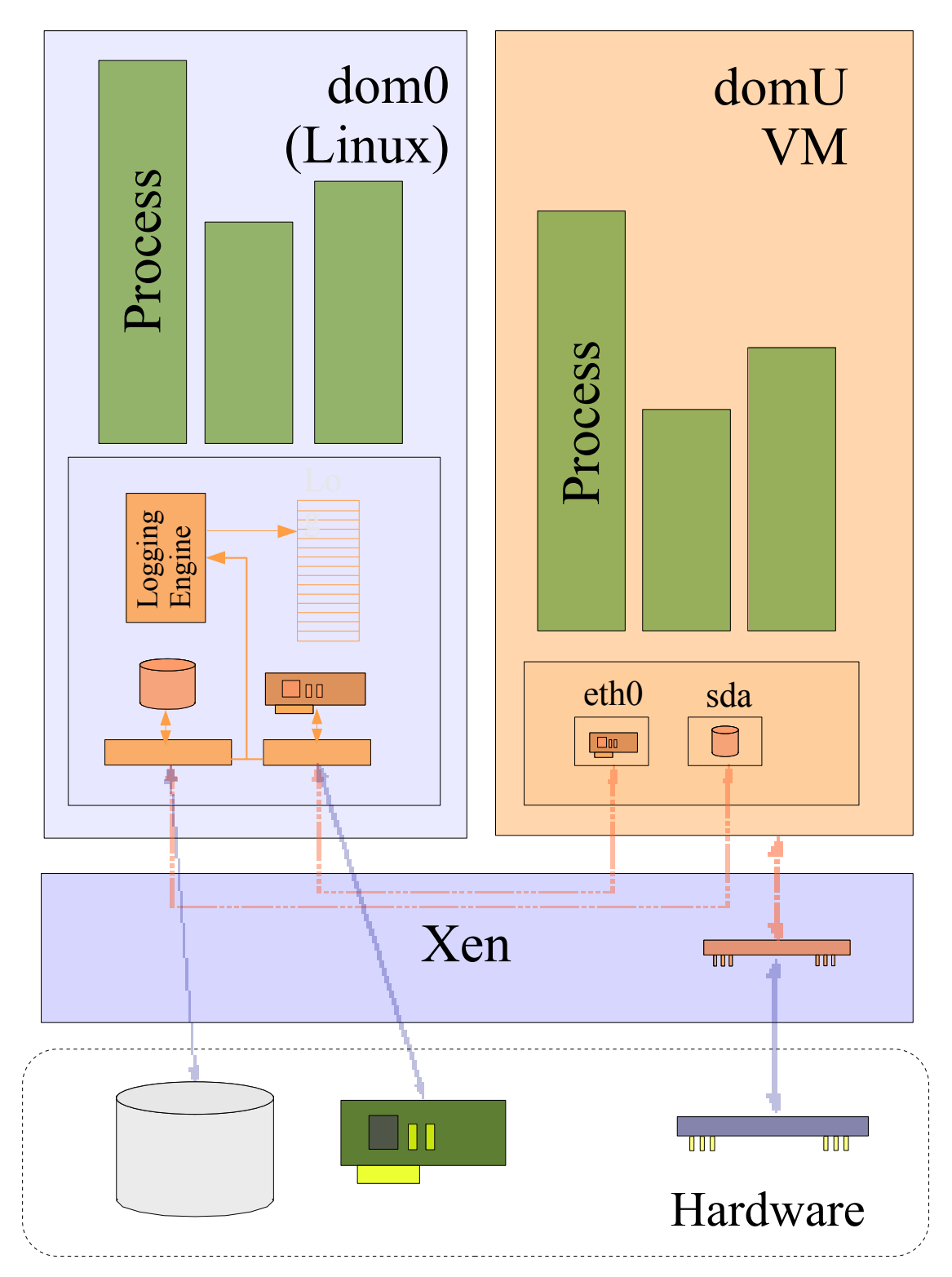
Time-Travel in Action



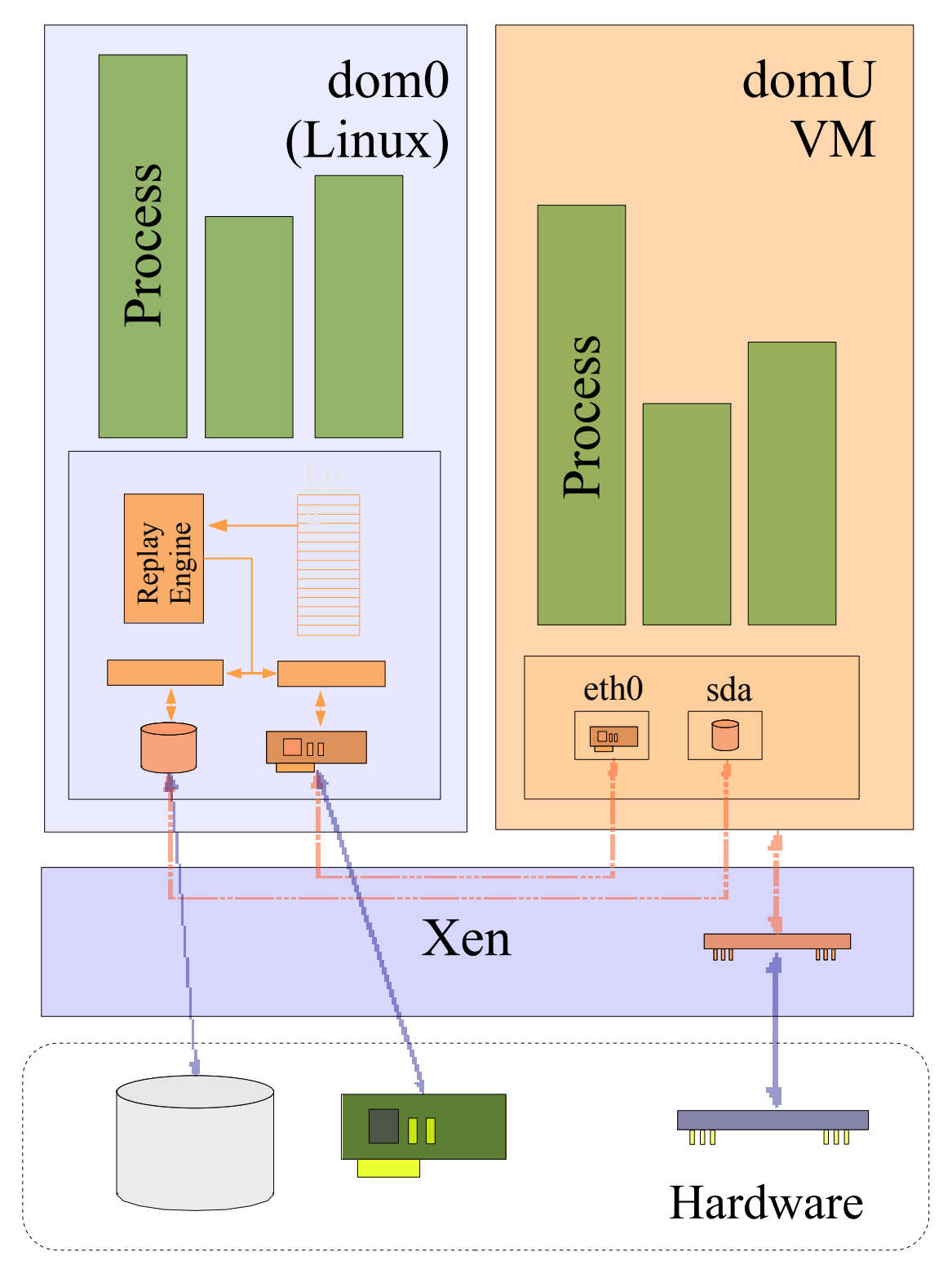
Virtual Machines VM1, VM2 and VM3 constitute the time-travel system. These are "user-domains" (domU) that run on top of the Xen Virtual Machine Monitor. Xen, with assistance from an administrative domain (dom0), virtualizes CPU, memory, and physical devices (disk and network) to the domUs.

The figure above illustrates the state of the time-travel system at three points in time: current execution (T_c), initial state (T_o) and at an arbitrary point (T_i) in the execution history. The system can be time-traveled to any point in the interval (T_o, T_c].

Basic Time-Travel



Logging
During original execution, log disk and network interactions of the time-traveling domU. Logging happens in dom0, where the physical device drivers reside.



Replay
During time-travel run of the domU, replay the contents of the log to recreate domU's disk and network interactions.

Current Status, Future Work, and Conclusions

- Prototype non-deterministic time-travel is working
  - LVM for disk checkpointing
  - Xen mechanisms for memory checkpointing
- Future work:
  - Implementing deterministic time-travel
  - Making disk checkpointing efficient by leveraging versioning filesystem research work, like Ventana [Pfaff et al., NSDI06] and Parallax [Warfield et al., HOTOS05]
  - Making memory checkpointing efficient by implementing CoW memory
  - Evaluating determinstic vs. non-deterministic time-travel
- Research questions:
  - Is non-deterministic replay useful for many applications?
  - Does non-deterministic replay have performance advantages?
  - What is the overhead of time-traveling a network of virtual machines?