Multi-stage replay with Crosscut

Jim Chow, Dominic Lucchetti, Tal Garfinkel, Geoffrey Lefebvre, Ryan Gardner, Joshua Mason, Sam Small
VMware

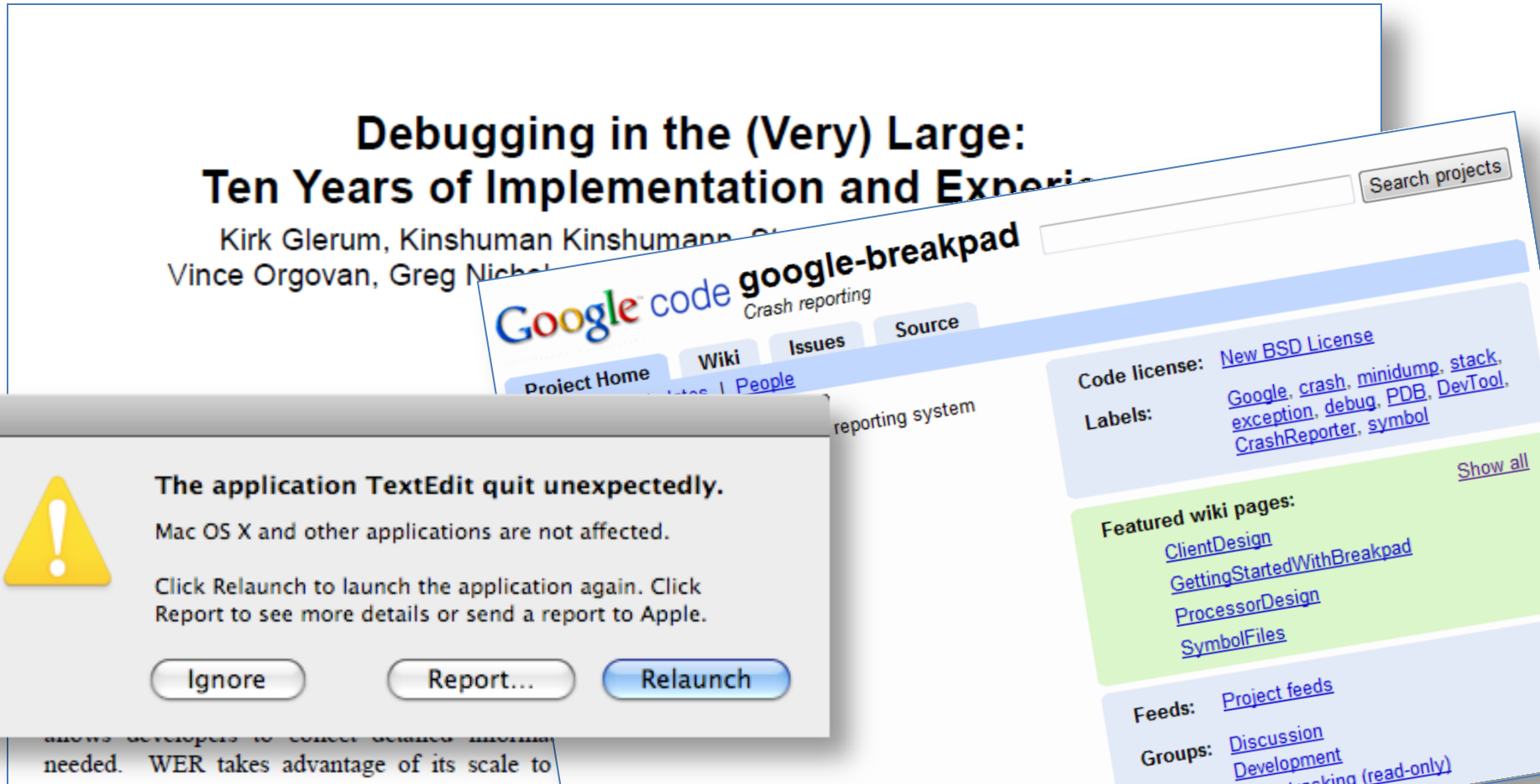
Peter M. Chen
University of Michigan

Analyzing with records

- Detailed recordings of program execution
  - Program output, logs
  - syslogd
  - Ad-hoc records (“printf” debugging)
  - Backtraces
  - Core dumps
- Useful for analyzing programs
  - Correctness, performance, security

Debugging programs with records

- So useful, now commonplace to send records back to the developers:

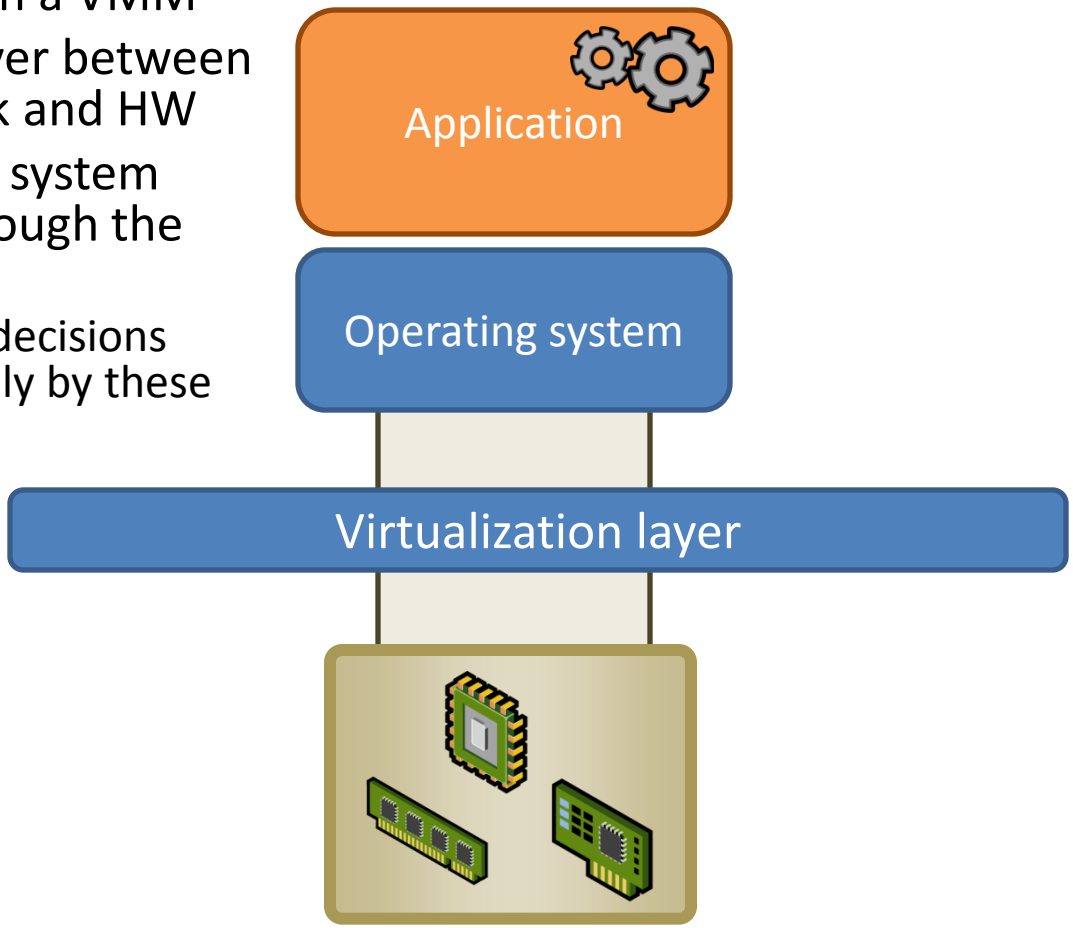


Debugging programs with records

- Despite extensive collection of records, programs still hard to debug
  - Program output, logs
  - syslogd
  - Ad-hoc records (“printf” debugging)
  - Backtraces
  - Core dumps
- Don’t know everything about a program
- Miss behavior: don’t run all the time, or over all values---must decide ***when*** or ***what*** to record (balancing act)

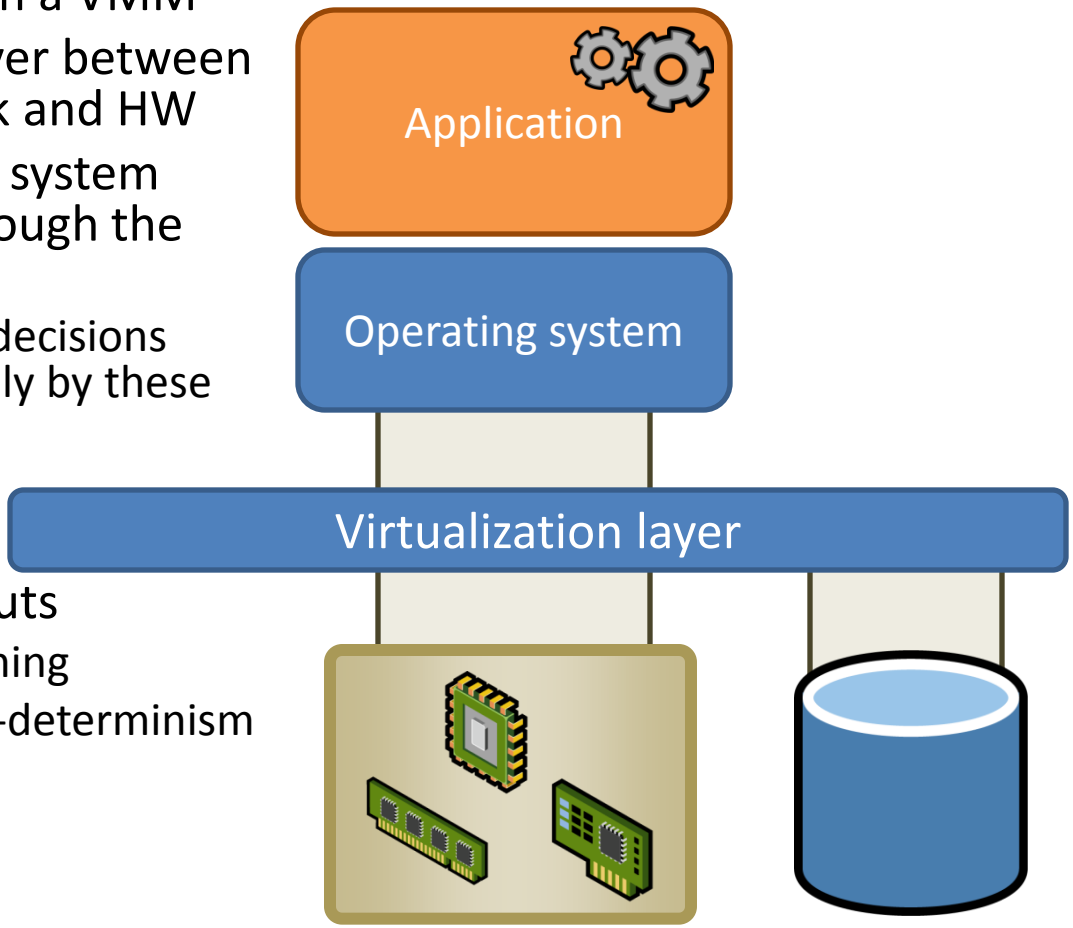
Instead: record everything, all the time

- Easy to do with a VMM
- VMM: thin layer between software stack and HW
- All inputs into system must pass through the VMM
  - All possible decisions governed only by these inputs



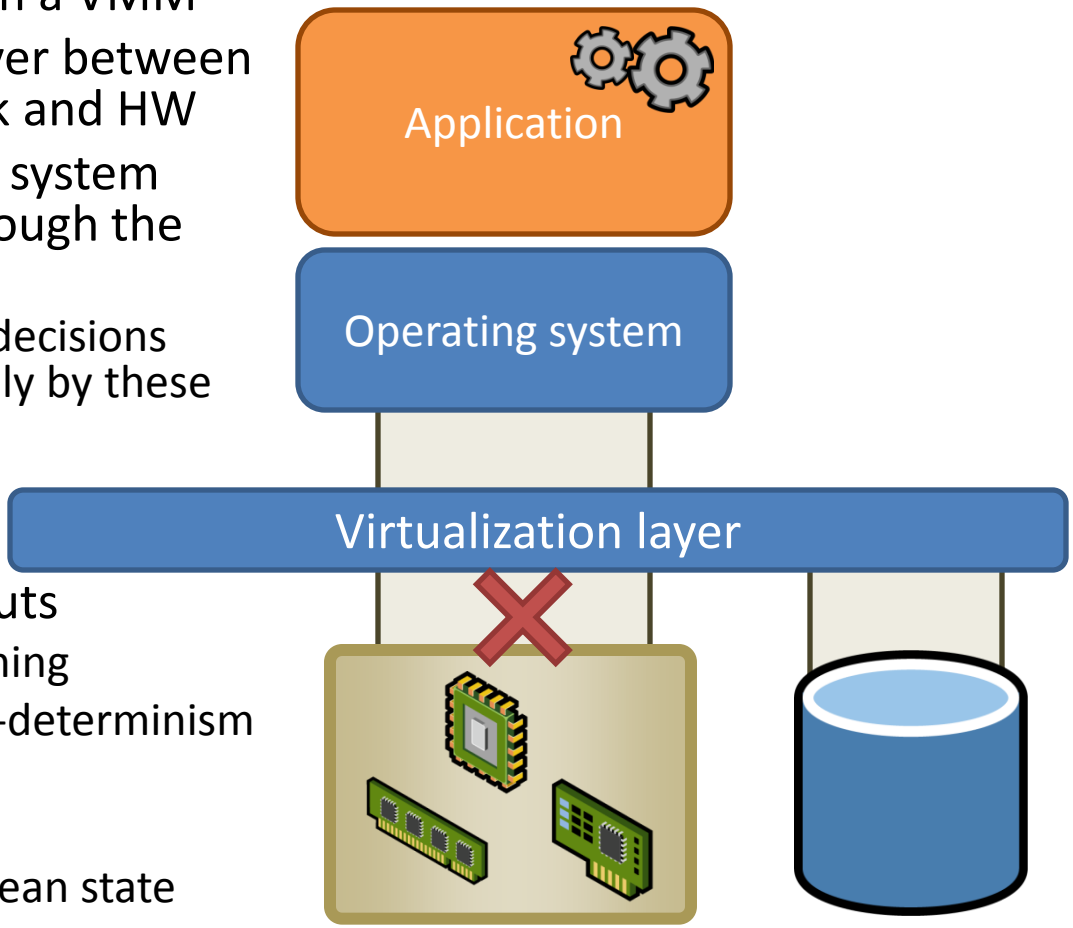
Alternative: VM record/replay

- Easy to do with a VMM
- VMM: thin layer between software stack and HW
- All inputs into system must pass through the VMM
  - All possible decisions governed only by these inputs
- If we save inputs
  - and their timing
  - have all non-determinism we need



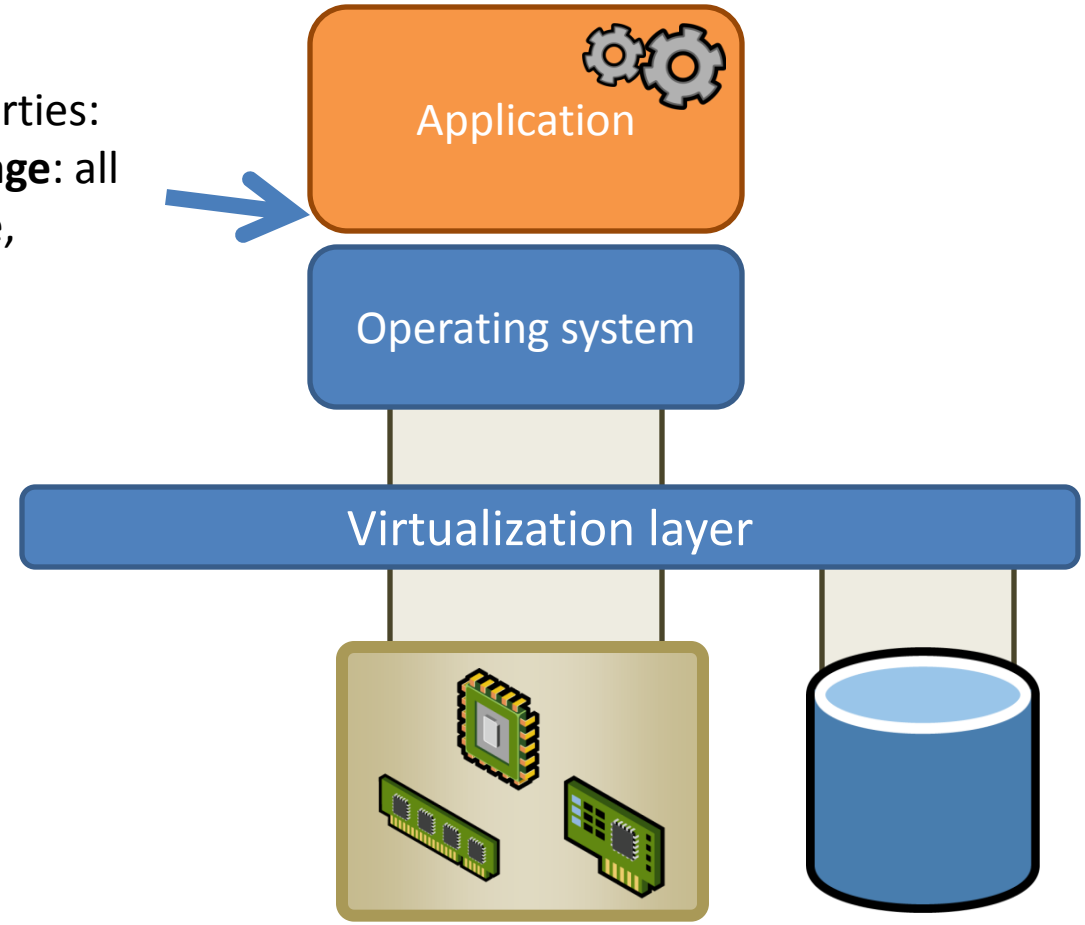
Alternative: VM record/replay

- Easy to do with a VMM
- VMM: thin layer between software stack and HW
- All inputs into system must pass through the VMM
  - All possible decisions governed only by these inputs
- If we save inputs
  - and their timing
  - have all non-determinism we need
- To replay:
  - Start from clean state



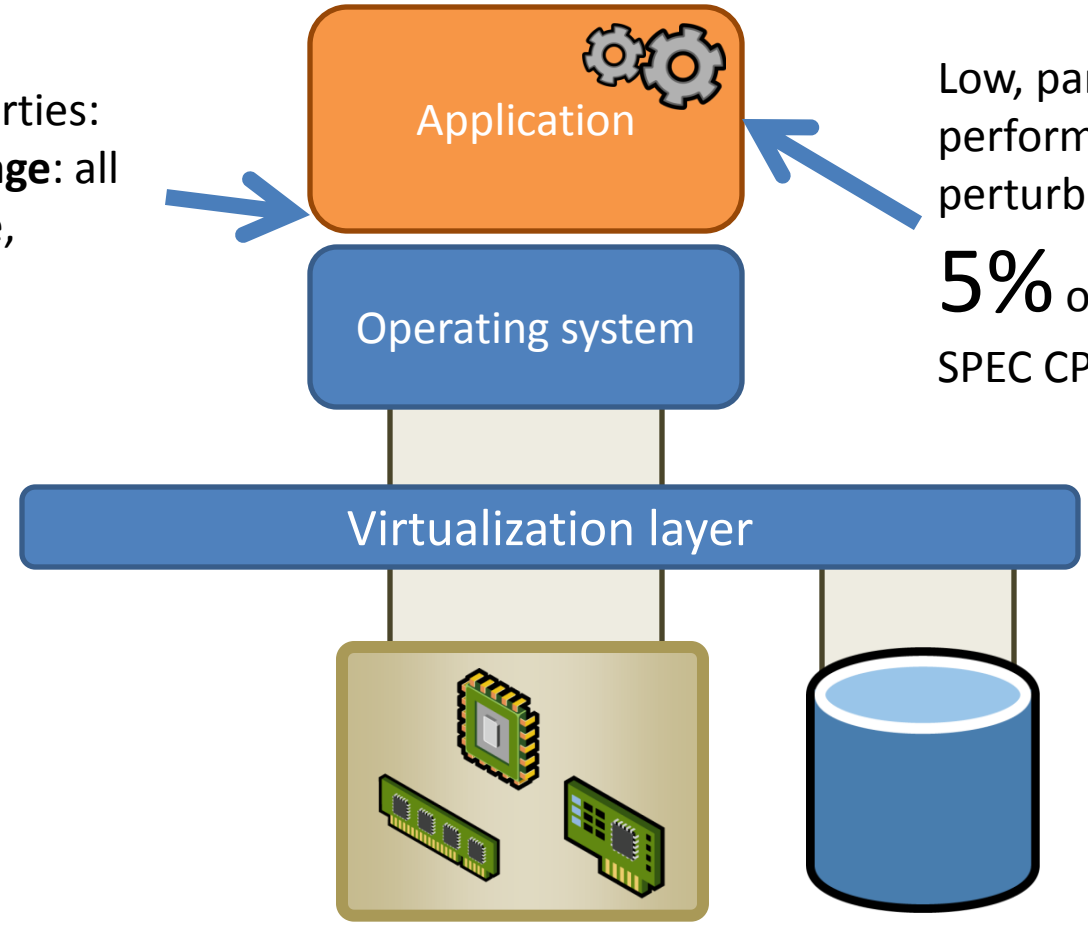
Alternative: VM record/replay

Some nice properties:
Complete **coverage**: all data, all the time, app/OS agnostic



Alternative: VM record/replay

Some nice properties:
Complete **coverage**: all data, all the time, app/OS agnostic



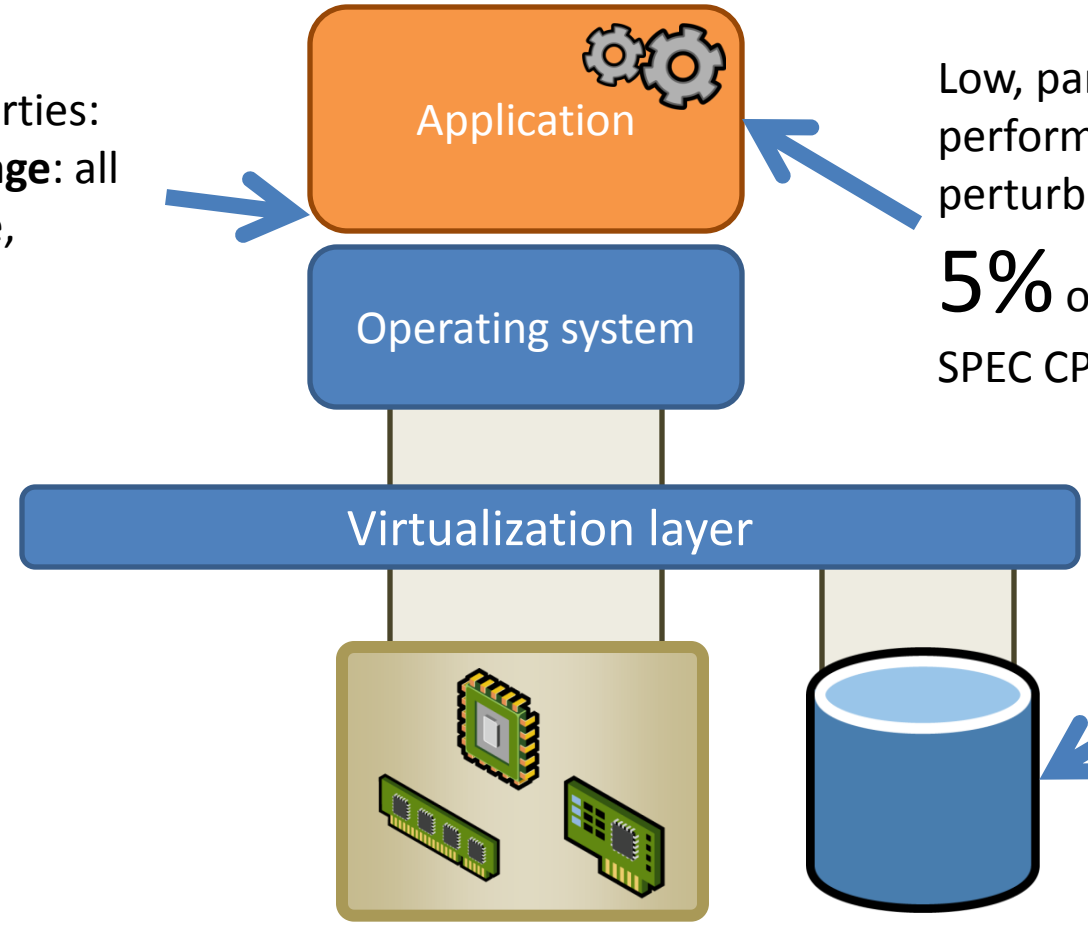
Low, paradoxical performance perturbation:

5% overhead

SPEC CPU2005

Alternative: VM record/replay

Some nice properties:
Complete **coverage**: all data, all the time, app/OS agnostic



Low, paradoxical performance perturbation:

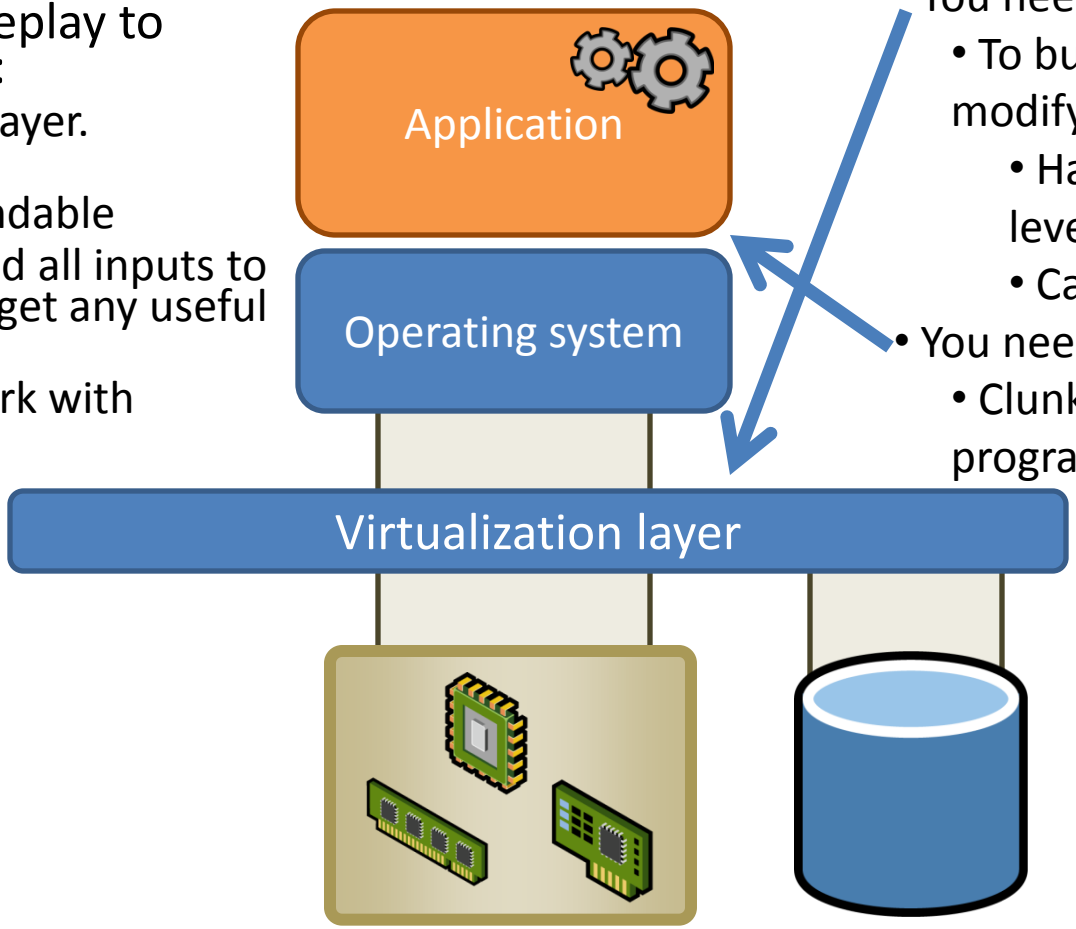
5% overhead

SPEC CPU2005

Low **bandwidth** requirements: network input + epsilon (KB/s)

Alternative: VM record/replay

- But have to replay to reclaim state:
  - Need a replayer.
    - Input not understandable
  - Need to feed all inputs to replayer to get any useful output.
    - Won't work with subset.



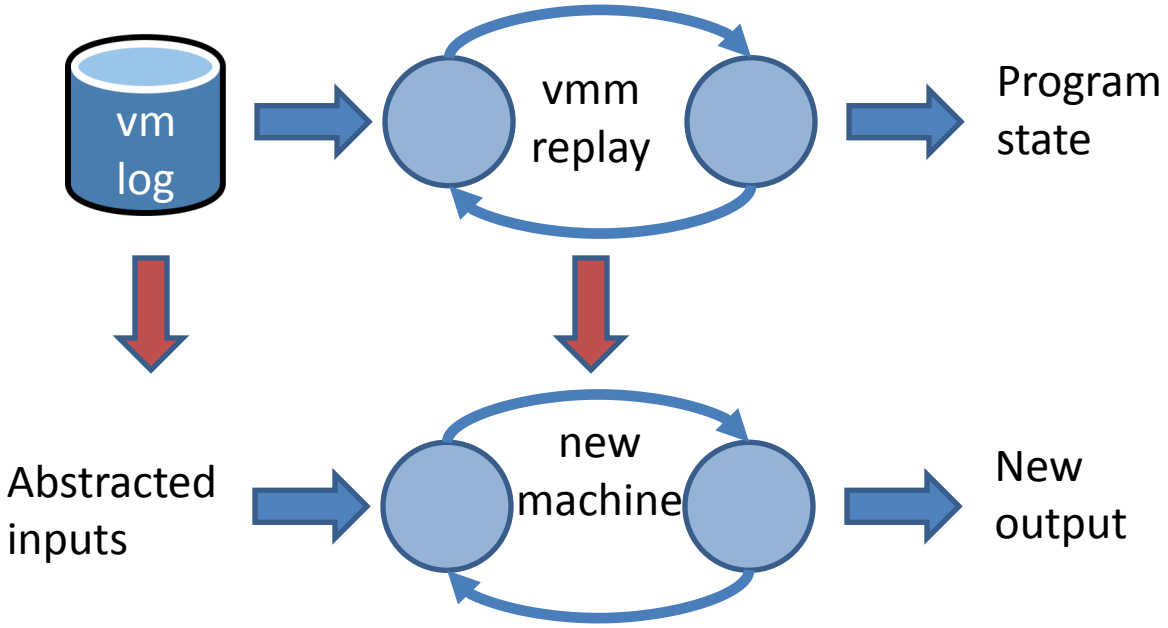
Again:

- You need a VMM
  - To build tools, must modify VMM
    - Hard to do: not user-level
    - Can be slow
- You need a VM
  - Clunky: to debug one program, you need all programs, data in VM.

Goal: replay with discretion

- VM recordings are great.
  - Provide great coverage.
- But we want to replay with discretion:
  - Don't require/expose all inputs (no VM).
  - Don't require same abstractions (no VMM).
  - Don't sacrifice ***coverage*** for discretion.
- How are we going to do this?

VM replay is a state machine



- Unhappy one size fits all
- Convert inputs to a new machine
  - Represents some computation in original

Generate abstractions

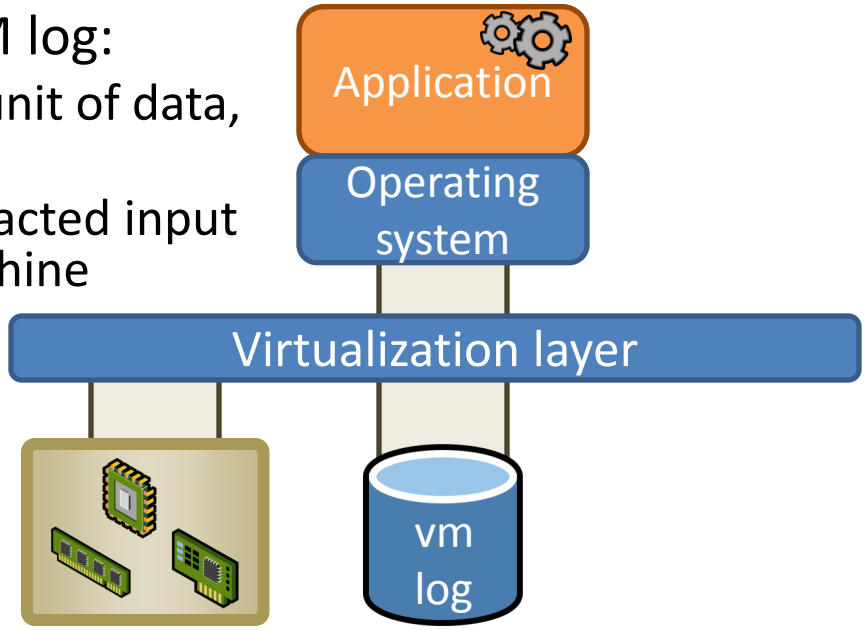
- Know we can generate new machine for any abstract state, computation in the log:
  - Program output, logs
  - syslogd
  - Ad-hoc records (“printf” debugging)
  - Backtraces
  - Core dumps

- ***VM recordings subsume all of the above.***
  - Any data we need can be generated.

Fixing replay problems with slices

In other words:

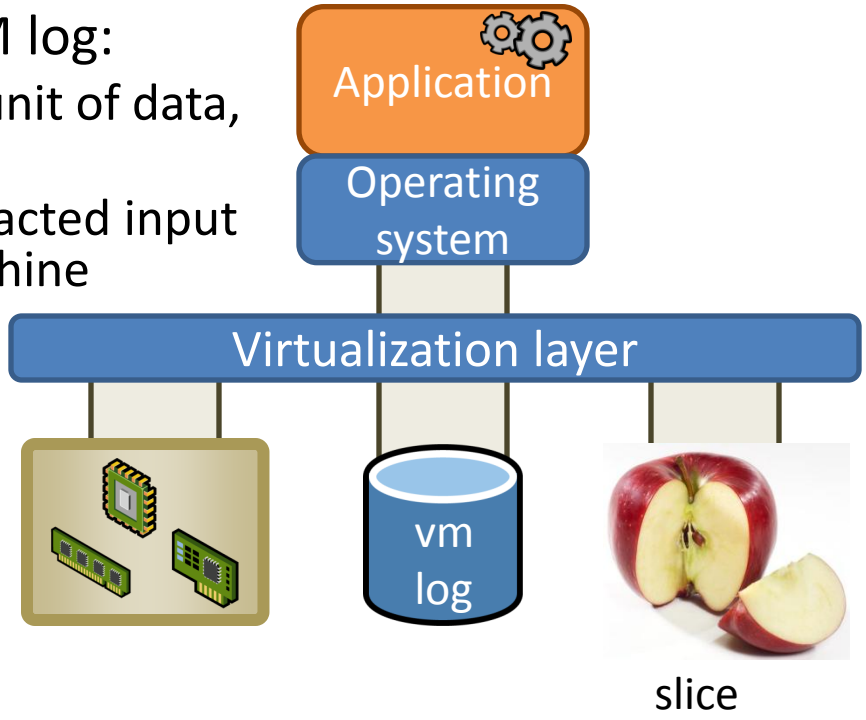
- Instead of VM log:
  - Generate a unit of data, slice
  - Slice is abstracted input for new machine



Fixing replay problems with slices

In other words:

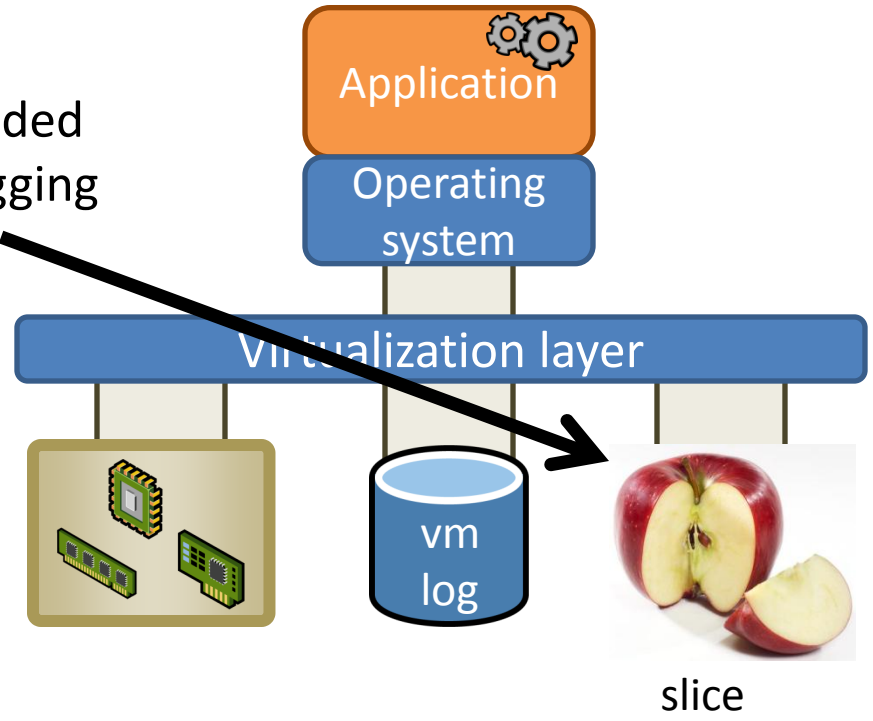
- Instead of VM log:
  - Generate a unit of data, slice
  - Slice is abstracted input for new machine



Fixing replay problems with slices

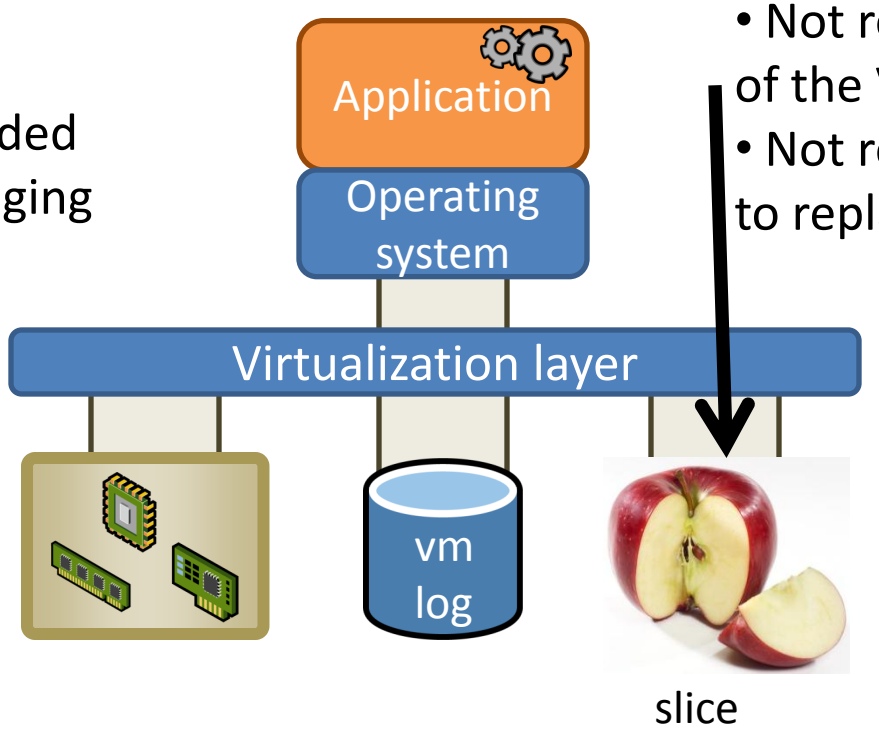
A slice will:

• Retain useful information needed for replay debugging or analysis



Fixing replay problems with slices

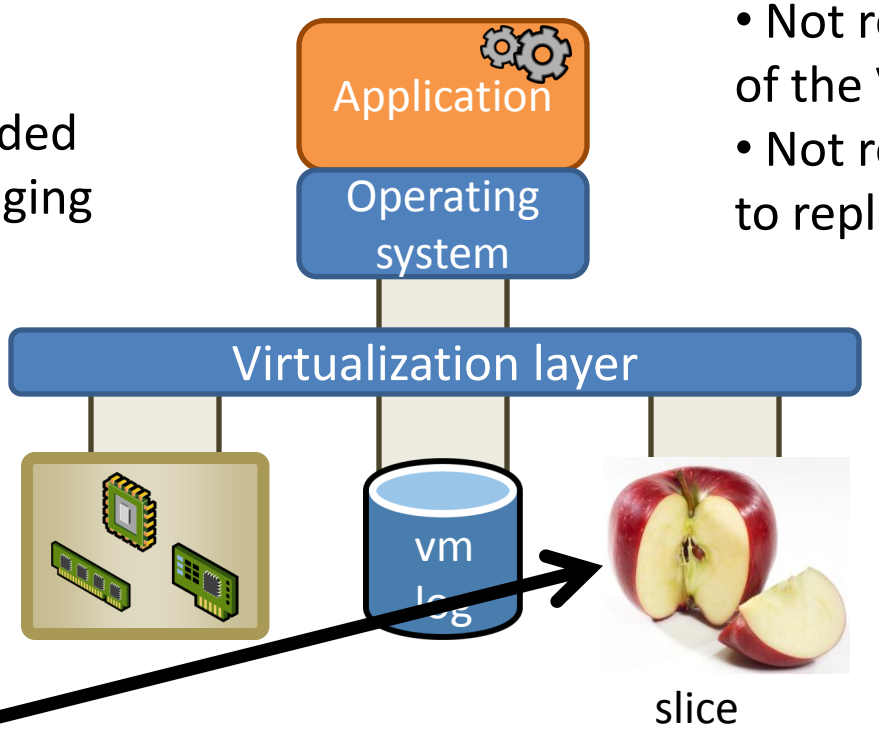
A slice will:
• Retain useful information needed for replay debugging or analysis



And it will:
• Not require a copy of the VM
• Not require a VMM to replay it

Fixing replay problems with slices

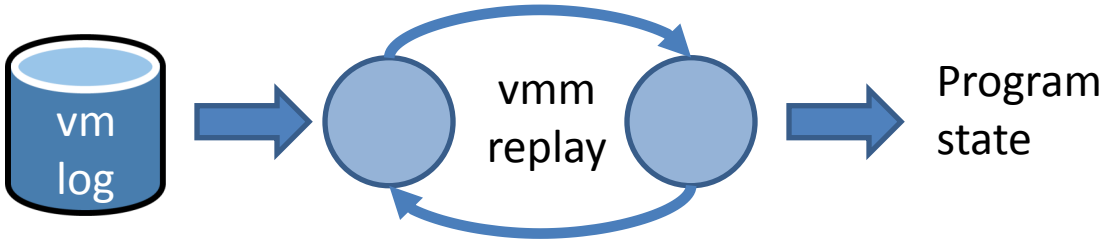
A slice will:
• Retain useful information needed for replay debugging or analysis



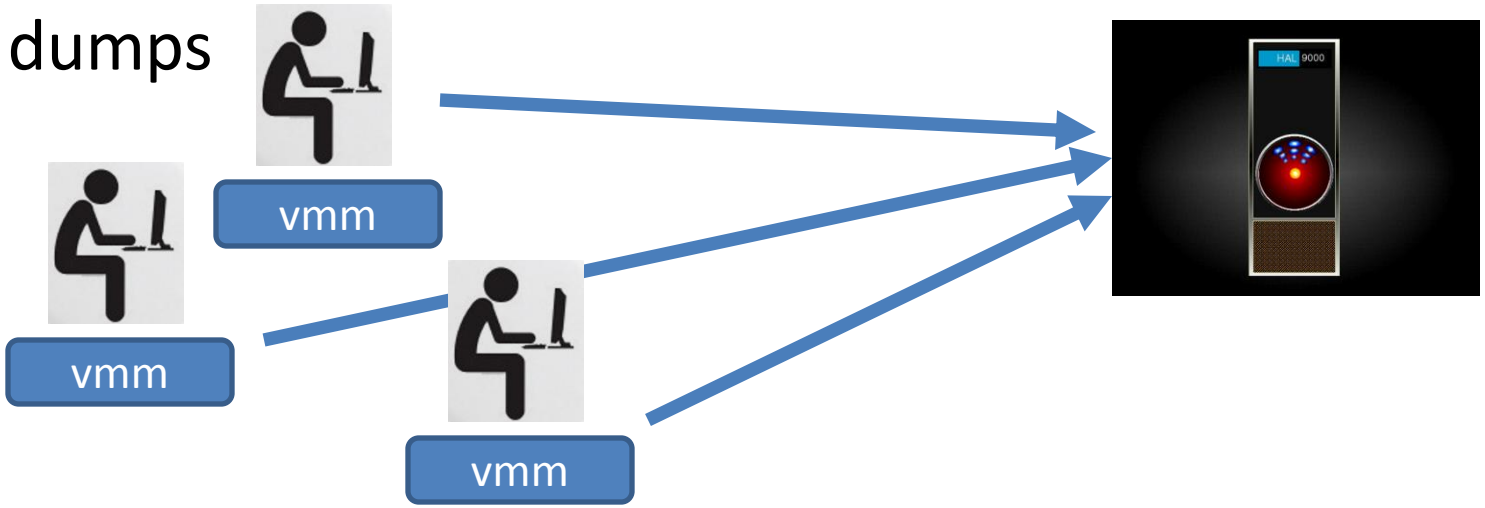
And it will:
• Not require a copy of the VM
• Not require a VMM to replay it

A slice is ***any*** higher-level recording destined for a higher-level state machine.

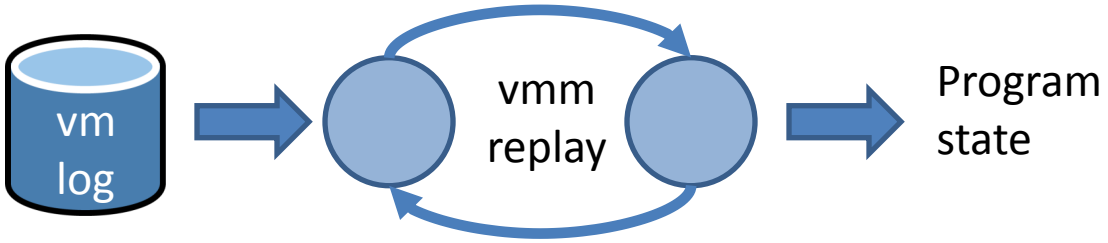
What are some useful state machines?



- Motivator:
  - Replay debugging for Dr. Watson-type crash dumps

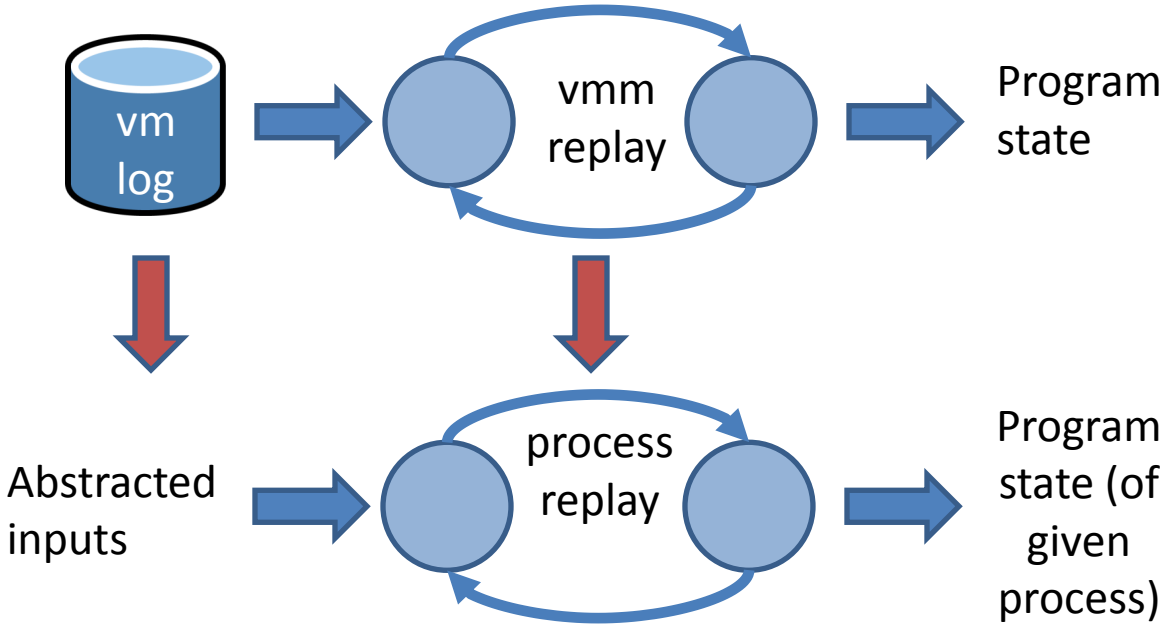


This machine is weird



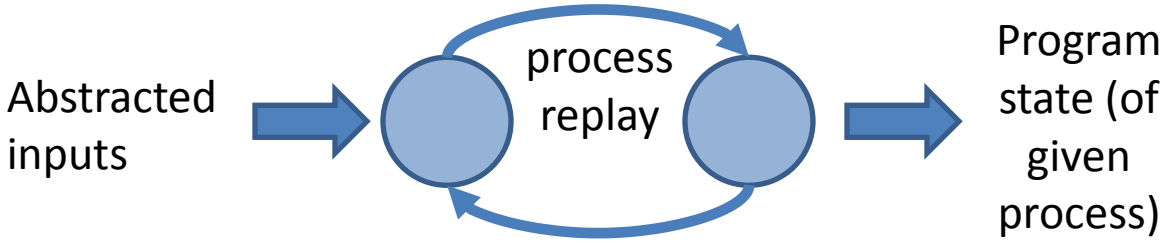
- Motivator:
  - Replay for Dr. Watson-type crash dumps
  - Requires whole VM
    - Fine within an organization
    - Silly otherwise

A better machine



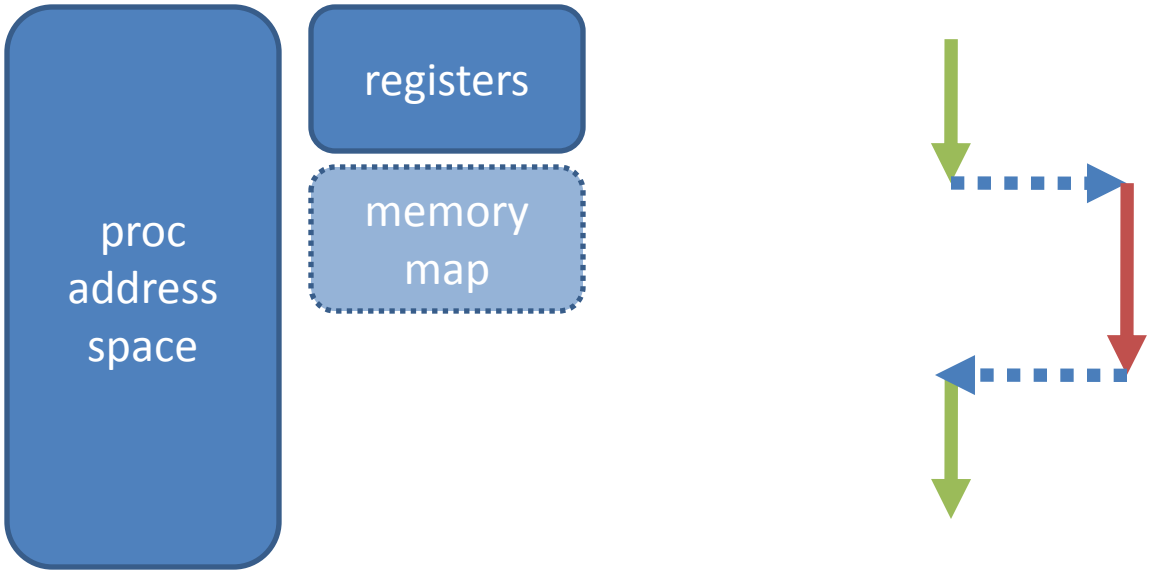
- Generate inputs for new abstract machine
  - Replays just a process
- Given inputs, cannot generate state for other processes
  - Better than original machine

How to represent process state



- Retain benefits of original system:
  - Record all input to a process
    - Including timing, races, shared memory accesses (*)
      - (*) at least for VMs that are virtual uniprocessors.
  - Agnostic to application, OS

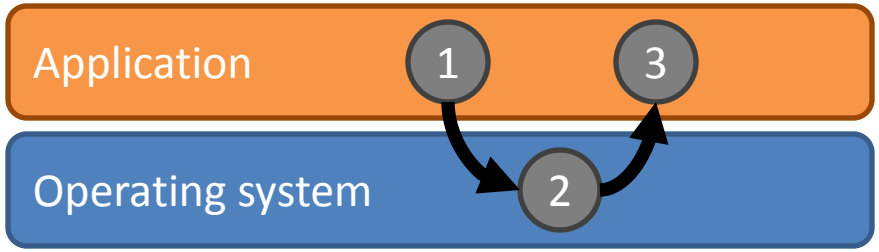
Choose a representation independent of OS



- Represented with HW state.
  - Address space, registers, memory map, no OS state.
- Given representation, runs deterministic
  - Until needs input: syscall, signals, CPU counters, etc.
  - Input's only effect: modify represented state
  - Continually supply this state.

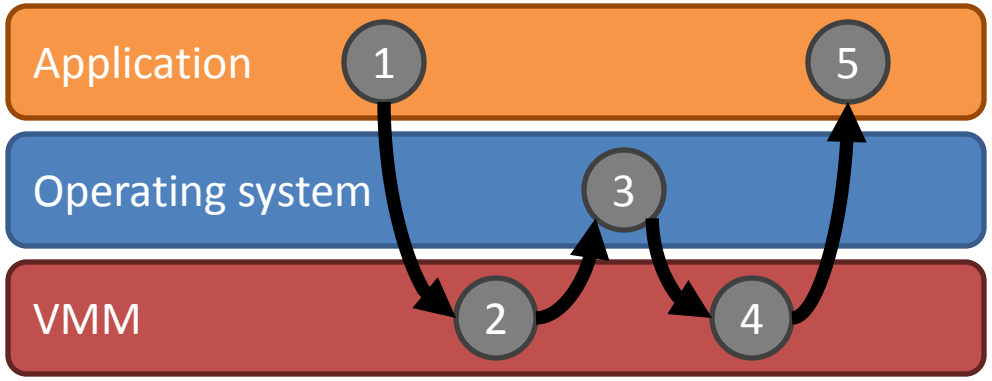
Figure out where state comes from

Normal system calls, traps, interrupts



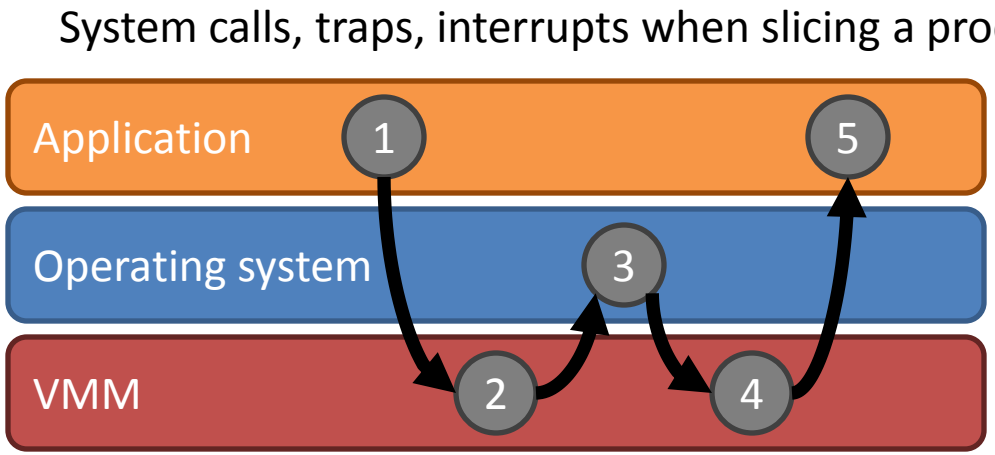
- Only comes from 3 places
- Modified VMM
  - Hook sites of introduction
  - Control flow into/out of process

System calls, traps, interrupts when slicing a process



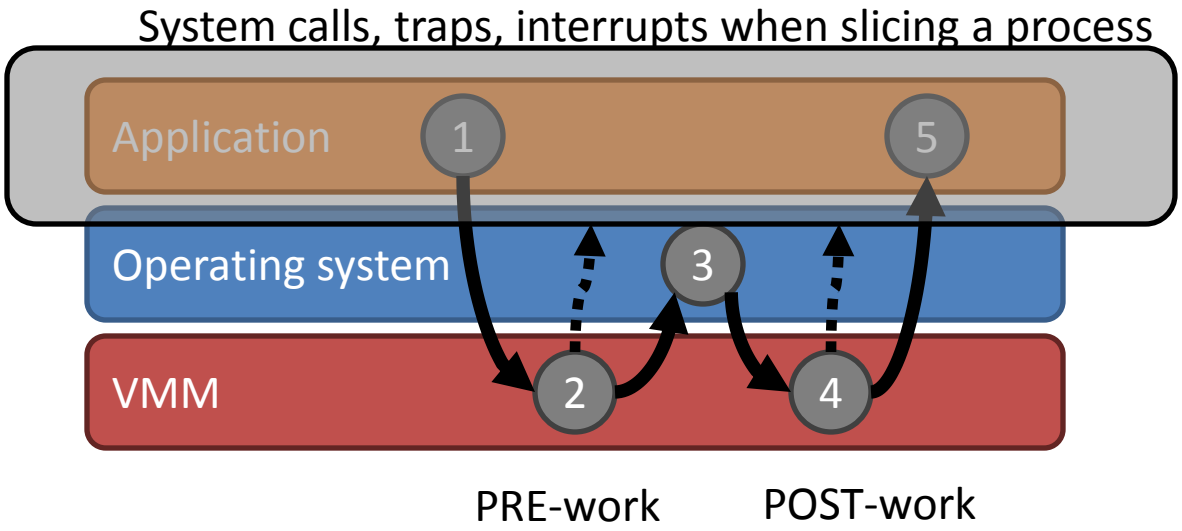
Out flow In flow

Collect input without OS help



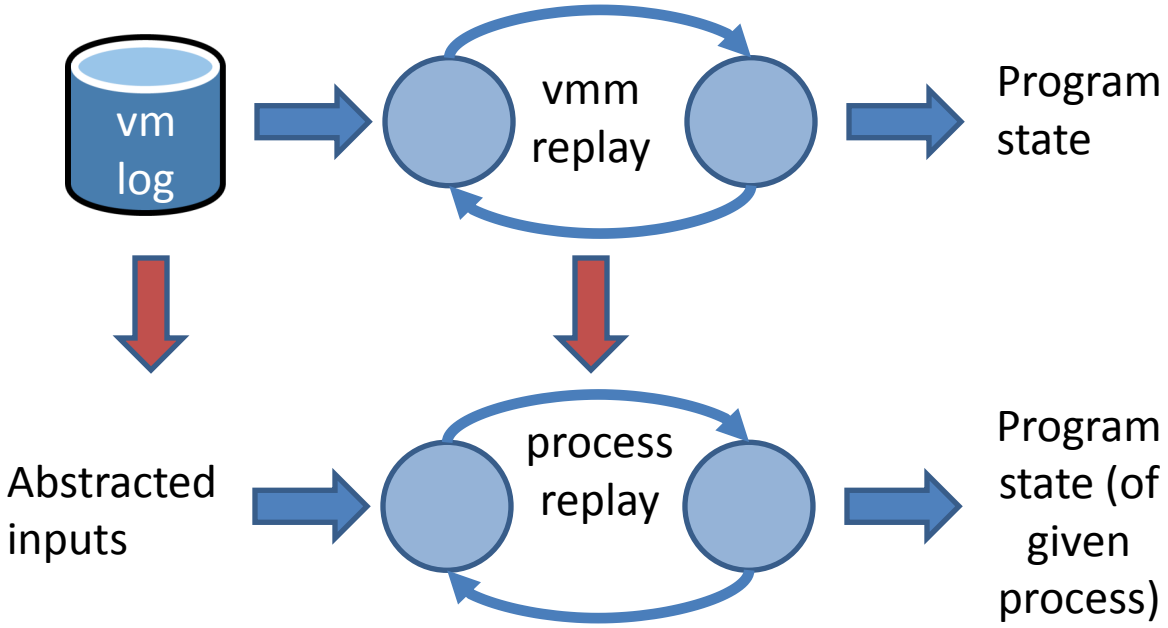
- OS injects state (directly on indirectly)
  - Do it with MMU: agnostic to OS.
  - Notice modifications to sliced process's address space when it's not running

How to detect writes



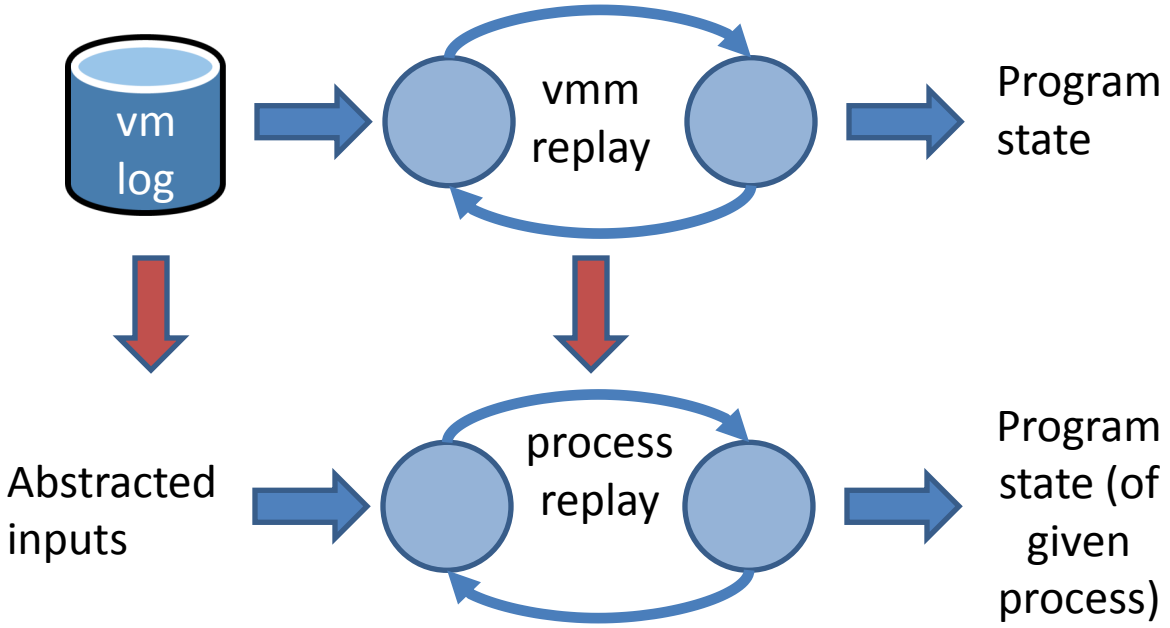
- OS injects state (directly on indirectly)
  - Do it with MMU: agnostic to OS.
  - Notice modifications to sliced process's address space when it's not running

A better machine



- Slices are standalone recordings:
  - Fully capable
  - Discrete
  - Not specific to OS/VMM
    - Why not replay at user-level?

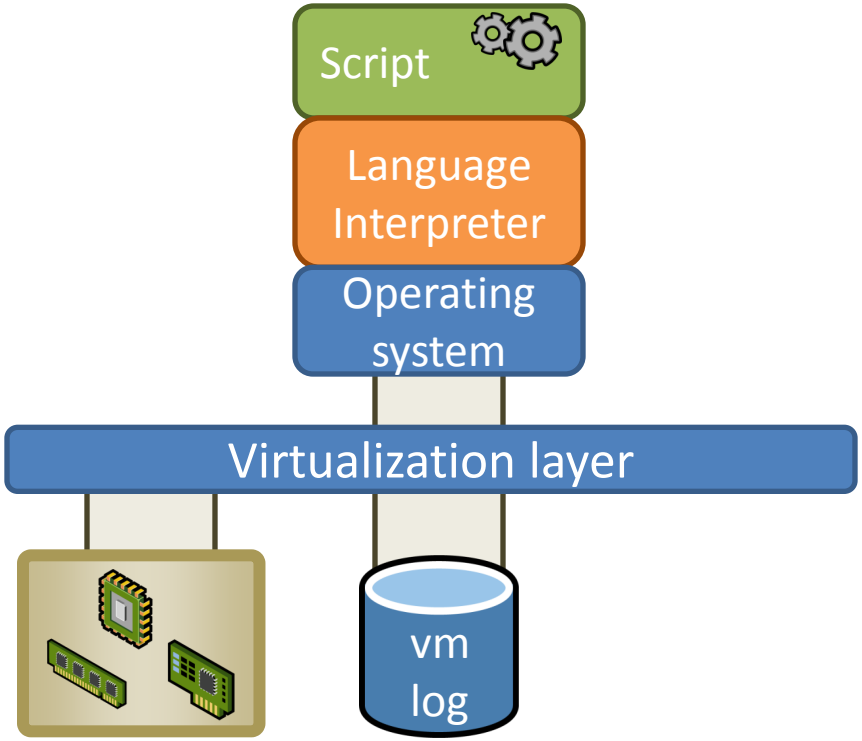
High level logs are useful



- High level log: any user-level tool can be a replayer.
- User-level a big thing:
  - Lots of user-level tools for analyzing “live” programs.
  - Crosscut supports running slices in valgrind, Omniscient debugger, Chronicle. Standard tools, gdb and visual studio. High level log: Even Windows proc on valgrind.

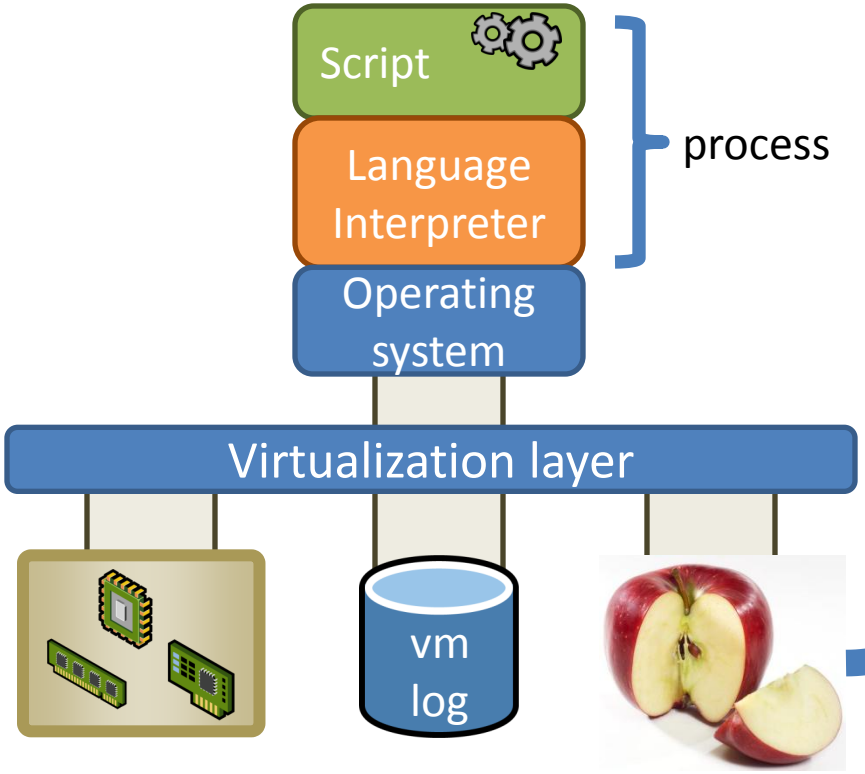
Beyond processes

- Processes not only abstraction
  - Sometimes not useful at all.



Beyond processes

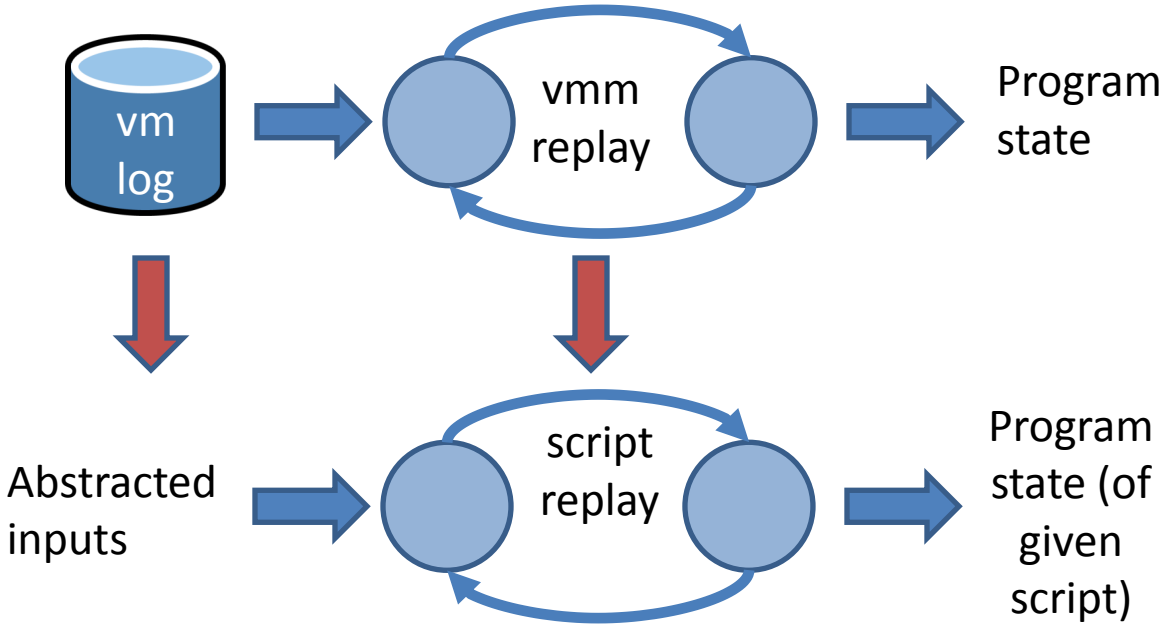
- Processes not only abstraction
  - Sometimes not useful at all.



Language Debugger

  - Debugging the interpreter, not the script (cannot change interpreter behavior)

We can solve this with yet another better machine



- Goal: create abstraction of script execution.
  - Avoid details of underlying runtime.

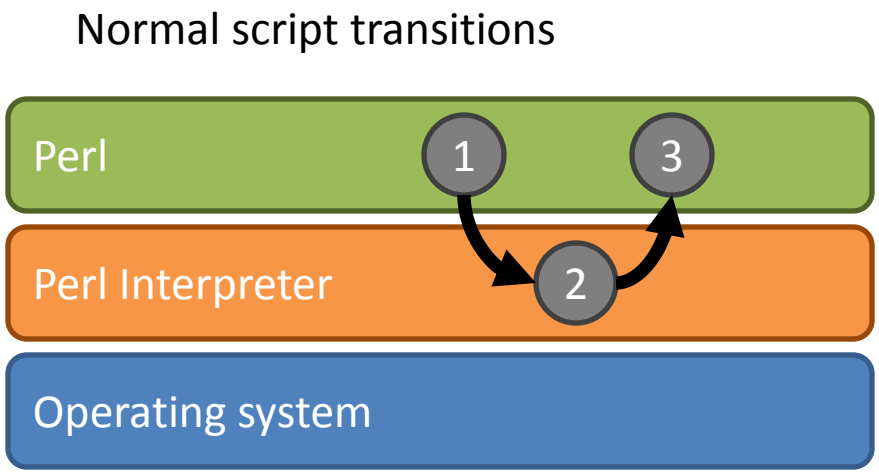
Recording a script generically is not possible

- Recording a script generically is not possible.
  - Requires intimate knowledge of the interpreter.
- Crosscut provides an API:
  - Given to guest software to create their own inputs to their own machines.
  - Guest doesn't really need an API just to create slices
    - What's wrong with *write()*?
  - Purpose:
    - Avoid overhead in the guest for creating the slice. How?
    - Do regular VM recording
      - Defer slicing to if/when it's needed.
      - Because ex-post-facto, original recording fast
      - Can be expensive---off the critical path.

What does the API do?

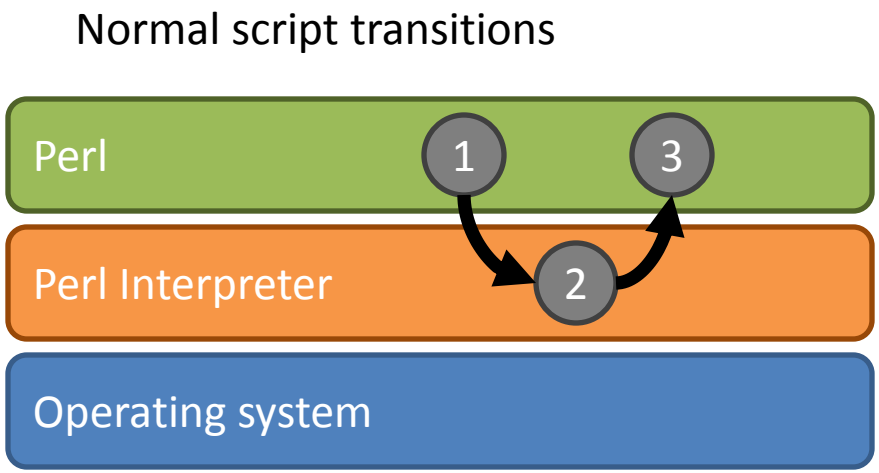
- Guest has code it wants to run.
- API provides notification to VMM of:
  - work (guest code) we'd like to do
  - … at a location we want to do it
  - On replay, VMM executes the guest code in sandbox.
- Notification mechanism must be fast:
  - It is running during original recording.
  - Standard signalling mechanism: instruction to trigger faults
    - Triggering faults in original recording too slow
      - Regular hypercall mechanisms out: port I/O, #UD
    - Silent/fast during recording: memory references, MMU

How to use API to slice a script



- What inputs do we want to save?
  - How to represent them?
- Modified Perl
  - Make deterministic recording of a script

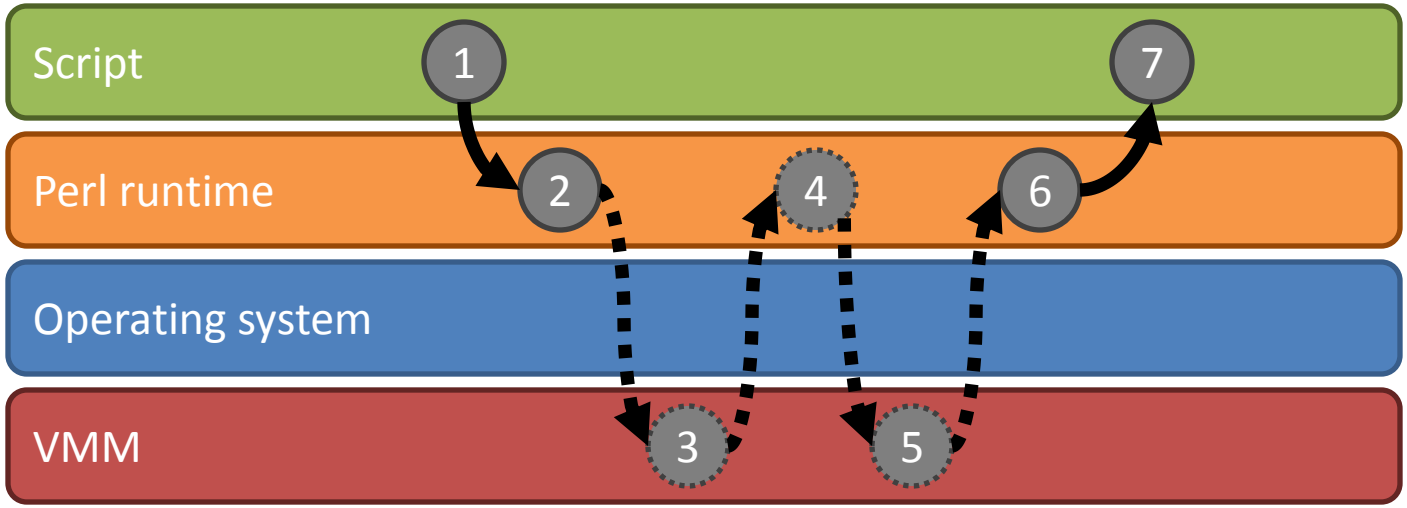
What inputs do we want to save?



- Simplistic example: system calls.
- Should be sufficient
  - Calls into Perl runtime will result in calls to the system. If not, they are deterministic.
  - Should be able to replay calls to runtime from system call inputs.

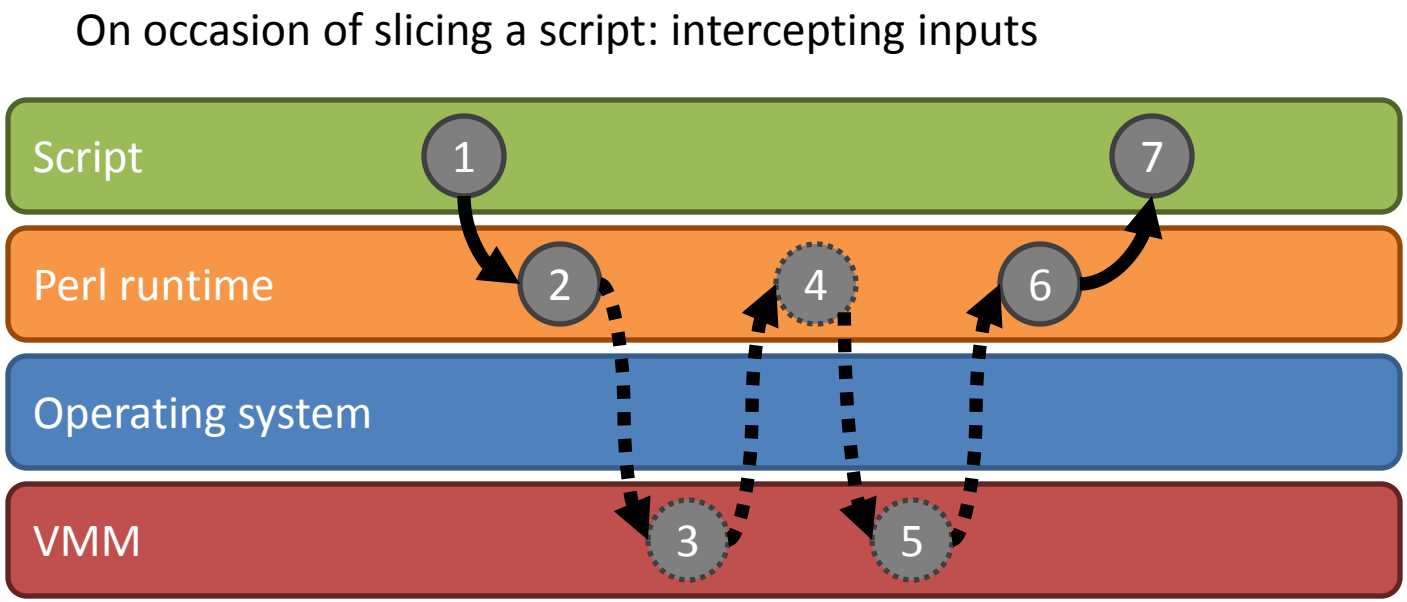
How to use API to save syscalls

On occasion of slicing a script: intercepting inputs



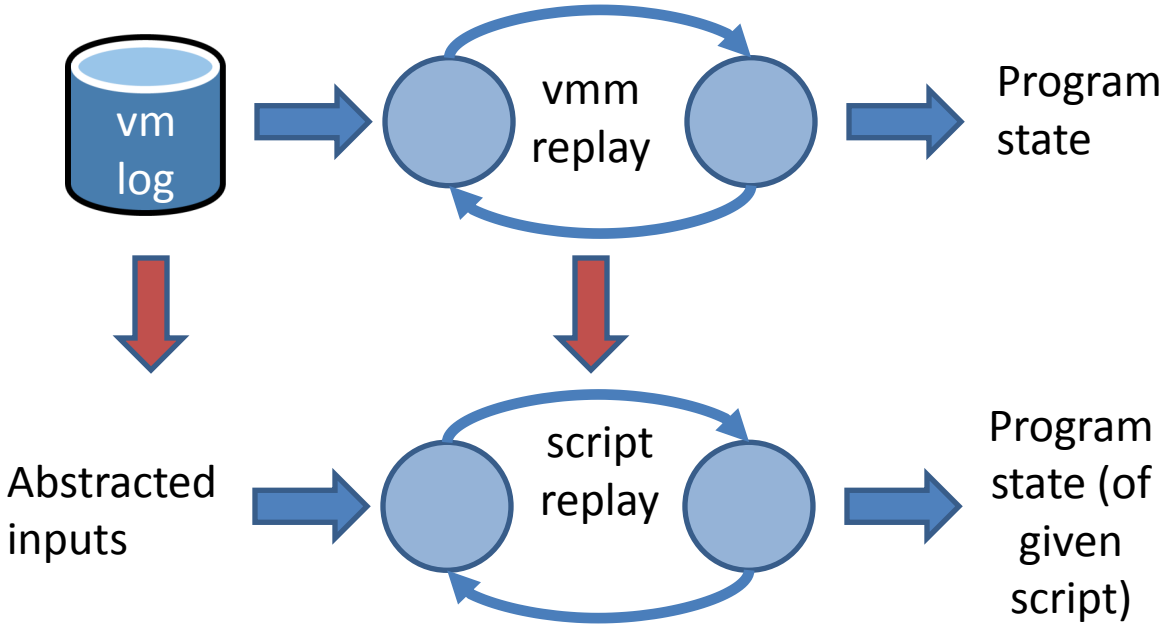
- Modified Perl runtime:
  - Record system call inputs (deferred in sandbox).
- Isn't this a process replay log?
- The difference: not all system calls belong to script.
  - Interpreter initiates some on its own behalf.
  - Don't save those: want interpreter's behavior capable of change

Want the interpreter to run free



- When replaying, interpreter runs freely
  - It can change it's behavior, because it's live.
  - When script requests input, fed from log
    - Behaves deterministically

What can you do with Perl log?



- Created a new machine: Perl interpreter + replay mechanism
- Internal Perl facilities can be used to debug the script: Perl debugger can set breakpoints, inspect variables.
- A better machine: let Perl interpreter do debugging, more natural than stapling Perl introspection into a VMM.

Goal: record program state

- VM recordings are great.
  - Provide great coverage.
- But we want to replay with discretion:
  - Don’t require VM.
  - Don’t require VMM.
  - Don’t sacrifice ***coverage*** for discretion.
- Obtain discretion with slices.
  - Abstracts replay requirements.
  - Doesn’t sacrifice coverage.

fin.