

A Particular Bug Trap: Execution Replay Using Virtual Machines

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ABSTRACT

Execution-replay (ER) is well known in the literature but has been restricted to special system architectures for many years. Improved hardware resources and the maturity of virtual machine technology promise to make ER useful for a broader range of development projects.

This paper describes an approach to create a practical, generic ER infrastructure for desktop PC systems using virtual machine technology. In the created VM environment arbitrary application programs will run and be replayed unmodified, neither instrumentation nor recompilation are required.

KEYWORDS: AADEBUG2003; execution replay; VM; virtual machine; user mode linux; x86; PowerPC

1 Introduction

The concept of execution replay (ER) has been known in literature for many years [Hus02]. Its first step is to bring the system into a well-defined and reproducible initial state. During the following system execution all non-deterministic events (stimuli to the system) like interrupts, user input, moments of scheduling etc. are recorded. This allows to re-run the program identically in particular for debugging purposes.

As the replay re-executes each single instruction, there is the opportunity to analyse its behaviour in all details and single step through it. This is in stark contrast to conventional logging mechanisms (printf) that only record a small subset of the program's execution. One of the biggest advantages of ER is that all timing-dependencies are recorded during the execution phase. Therefore it is possible to debug time-critical, multi-threaded code in non-real-time.

Despite the simple principle, implementations of ER pose substantial problems and until now were only available for specialized areas e.g. for message passing system [RBdK00]. By creating a deterministic, replay-able virtual machine environment, it will be possible to use execution replay for a broad range of development projects. By using a VM emulating a complete personal computer, the development of all software for this system can benefit from execution replay.

The rest of this paper is organized as follows: options to implement ER in generic (personal) computer systems are discussed in Section 2. Concluding that virtual machines offer many advantages, a particular example, the User-Mode-Linux (UML) virtual machine is introduced in Section 3. Section 4 explains how the UML VM can be adapted to ER and gives some consideration to relevant

In M. Ronsse, K. De Bosschere (eds), proceedings of the Fifth International Workshop on Automated Debugging (AADE-BUG 2003), September 2003, Ghent. CComputer Research Repository (<http://www.acm.org/corr/>), cs.SE/yymnnn; whole proceedings: cs.SE/0309027.

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hardware support in current microprocessor architectures. The paper is concluded by an outlook on promising directions for further research.

2 Environments for Execution Replay

For implementing execution replay, a *system* or *subsystem* to be recorded must be chosen. This can be a complete computer, an operating system process or a module of a program. In all cases the boundary of the system has to be defined precisely because all data going into the system needs to be recorded in the execution phase. During the replay this data is used to stimulate the system identically.

For practical reasons it is difficult to record all input that a personal computer receives: it would be necessary to attach hardware probes which leads to problems with timing inaccuracies, signal noise etc. Also parts of this system are not deterministic: for example the exact timing of harddisk accesses cannot be reproduced in a replay.

Alternatively one may record the inputs to a subsystem like the CPU and the memory system. In 1991 this was shown to work using specialized custom hardware in [BG91]. However, the approach does not seem applicable for modern PC systems, because the relevant signals can hardly be accessed at the main boards and — if possible at all — the hardware will be expensive.

In contrast the software domain avoids many of these problems. A natural system to record is an OS process, because this is a unit of processing, that is (mostly) independent from other processes. All data going into the process like command line arguments and file input need to be recorded. But also interactions with the OS like signals and system calls need to be kept track of. Unfortunately this interface is quite complicated for real-world operating systems. Also for parallel programs, interactions with other user or system processes need to be recorded (including shared memory accesses). Major adaptations to the operating system would be necessary for this. Due to this it would be hard to guarantee a faithful replay.

Another implementation option is to design an operating system with execution replay in mind like the Asterix kernel [TPS]. This operating system records all input to the machine (e.g. at the driver level) and records scheduling events. However, it is tailored for embedded systems and not compatible with standard operating systems.

The solution proposed in this paper is a hybrid between the conceptual simplicity of recording a complete machine and the beauty of the software world: a deterministic, replay-able virtual machine executing a standard operating system.

3 Introducing the User-Mode-Linux VM

A virtual machine has favourable properties for execution replay. It has a relatively simple structure, at least compared to an operating system. As it is pure software it does not suffer from problems of the physical domain. And last but not least it can be adapted to operate deterministically.

As a basis for further research and to illustrate the principle, the open-source User-Mode-Linux VM [Dik] by Jeff Dike was chosen. Due to its special virtualization approach, UML may only execute Linux programs. However, there are other virtual machines like [VMw] emulating a complete personal computer at the register-transfer level. These VMs can boot native operating systems like Linux or Windows from the original installation CDs and prove that this approach to ER is generally applicable.

The virtualization scheme used by UML is to port the Linux operating system to a virtual UML architecture. Inside this virtual machine there is a Linux *guest* kernel that executes regular, unmodified Linux binaries. When such a binary executes a privileged instruction like I/O or a system call, this access is detected by the host kernel and redirected to special handler routines in the UML binary. Also interrupts and exceptions generated in the UML are trapped and executed in user mode. Therefore all UML code executes in user mode (hence the name) and no modifications to the host

kernel are necessary. The resources of the *host* operating system are only accessed through (virtual) hardware drivers. For example virtual harddisks are mapped to files of the host system, the keyboard is mapped to the host keyboard etc. Also network devices are supported so that a UML can access local and remote networks.

4 Creating a Deterministic VM

Currently UML does not support execution replay. Therefore it is the goal of the author to enhance it to deterministically execute, replay and debug arbitrary software. The key to this is to record all stimuli and their respective timing.

Input stimuli to the VM are either delivered via interrupts or via virtual device drivers. Interrupts for the VM are implemented through signals created by the host OS. Like interrupts, signals are asynchronous to the program flow of the guest processes. Therefore during the execution phase the moments when they occur need to be recorded. The simplest and most accurate measure for this is the number of instructions executed until the moment when an interrupt occurs.

In principle executed instructions can be counted in software by instrumenting branch instructions and calculating the number of executed instructions from the current program counter (PC). However, this requires modifications to all executable code (kernel and applications) which is an obstacle for regular usage. Hardware instruction counters solve this problem by counting the executed (retired) instructions transparently in the background.²

A number of CPU implementations including Intel Pentium III, Pentium IV, AMD Athlon, Itanium, and PowerPC comprise configurable counters for counting *retired* instructions. Surprisingly these counters are far from accurate. For the x86 architectures the processor documentation states a number of cases where they count incorrectly. In theory this can be compensated for, but tests by the author established that there more inaccuracies that render the counters unusable. For the Itanium no tests could be performed but the processor documentation does not give any guarantees about correct counter values either.

Besides the x86 implementations the Motorola PowerPC MPC7441 was evaluated. Tests with an Apple eMac confirmed its counters to be accurate. A minor exception are interrupts which make the counter overcount: at each switch to and from the interrupt handler, the instruction counter is incremented erroneously by one. As this behaviour is deterministic, it can be compensated for by subtracting the number of switches to/from supervisor mode (this event can also be counted in hardware).

Interesting features of the MPC are to configure the counters to only increment in user and/or supervisor mode and only count instructions executed by a specially marked process. This way it is possible to only count instructions executed by the UML virtual machine. When the VM accesses services of the host OS, these requests are performed in kernel mode (after a system call) and the instructions are not counted. This is essential because the host operating system gives no guarantees that it will execute the same number of instructions during the replay. Similarly any paging operation performed by the host OS are performed in kernel mode and thus transparent to the instruction counter of the UML.

During the replay the so-called performance monitor interrupt is used. It creates (physical) interrupts after a pre-recorded number of executed instructions. By diverting these interrupts to special replay handlers in the UML, its interrupts and signals can be replayed.

Besides recording the moment of interrupts, also input from external devices needs to be stored and replayed. For UML this done is in a straightforward manner by extending the (virtual) device drivers. The attractiveness of using a VM for execution replay is mostly due to the fact, that this driver interface is small and well-defined.

²In [TH00] Thane and Hansson introduce another software approach measuring elapsed physical time with a defined resolution and inserting breakpoint instructions into the object code. This is much simpler than instrumenting branches, but there are (rare) cases where the approach fails to generate a correct replay.

The described setup allows to record and reproduce the virtual machine's behaviour, including its applications. In order to debug an application a modified debugger is needed, that attaches to a process *within* the UML VM. Normally a debugger is supported by the operating system to attach to a process. In this case the *guest* OS cannot possibly be aware of the debugger, as it merely replays a recorded instruction sequence. Thus the debugger (executing in the host OS) must be aware of the structure and memory layout of the guest OS in order to read the stacks, register contents, set breakpoints and single step through the code etc. It is intended to adapt `gdb` or a kernel debugger (`kgdb`) for this purpose.

5 Outlook

To be generically applicable, the overhead in the execution phase must be small enough to execute the program with sufficient speed. Many application programs — in particular GUI driven software — have very moderate performance requirements and run satisfactorily on low-end machines. Therefore the author assumes that a high-end machine will have enough (processor) resources to record the input stimuli in the background without slowing down the program too much. If this assumption holds, the chosen approach will allow to apply the ER concept to nearly all areas of software development — without modifications to the program or system.

As this paper illustrates, the base technology for making ER a reality is available today: a generic virtual machine environment and software or hardware instruction counters. It is the aim of the author to combine these technologies for further research in this area and to prove its viability.

In the long run, improved hardware instruction counters may allow simplified implementations in more architectures. Also special hardware extensions dedicated solely to execution replay are conceivable. These may include support for virtual machines (as known from mainframe systems like the IBM S390) or automatically record data read from peripheral registers or save time stamps for interrupts. By careful design, such hardware extensions might even perform all recording stealthily in the background and thus eliminate the so-called probe effect. This would allow to apply ER to all software executing on such a machine.

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