Enhanced Operating System Security Through Efficient and Fine-grained Address Space Randomization

Cristiano Giuffrida Anton Kuijsten Andrew S. Tanenbaum

Vrije Universiteit Amsterdam

21st USENIX Security Symposium

Bellevue, WA, USA
August 8-10, 2012

Kernel-level Exploitation

- Kernel-level exploitation increasingly gaining momentum.
- Many exploits available for *Windows*, *Linux*, *BSD*, *Mac OS X*, *iOS*.
- Plenty of memory error vulnerabilities to choose from.
- Plethora of internet-connected users running the same kernel version.
- Many attack opportunities for both local and remote exploits.

Existing Countermeasures

- Preserving kernel code integrity [SecVisor, NICKLE, hvmHarvard].
- Kernel hook protection [HookSafe, HookScout, Indexed hooks].
- Control-flow integrity [SBCFI].
- No comprehensive memory error protection.
- Virtualization support required, high overhead.

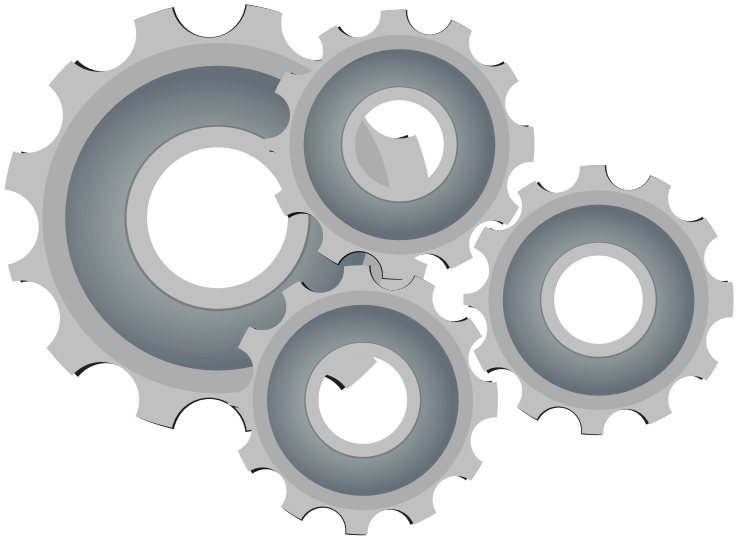
Address Space Randomization

- Well-established defense mechanism against memory error exploits.
- Application-level support in all the major operating systems.
- The operating system itself typically not randomized at all.
- Only recent *Windows* releases perform basic text randomization.
- Goal: Fine-grained ASR for operating systems.

Challenges in OS-level ASR

Instrumentation

Challenges in OS-level ASR

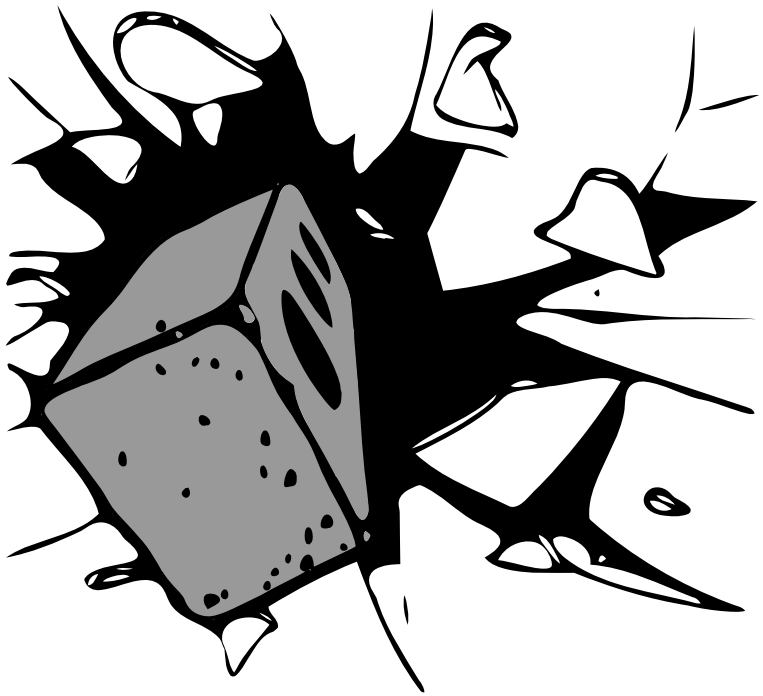


Rerandomization

Challenges in OS-level ASR

Information leakage

Challenges in OS-level ASR

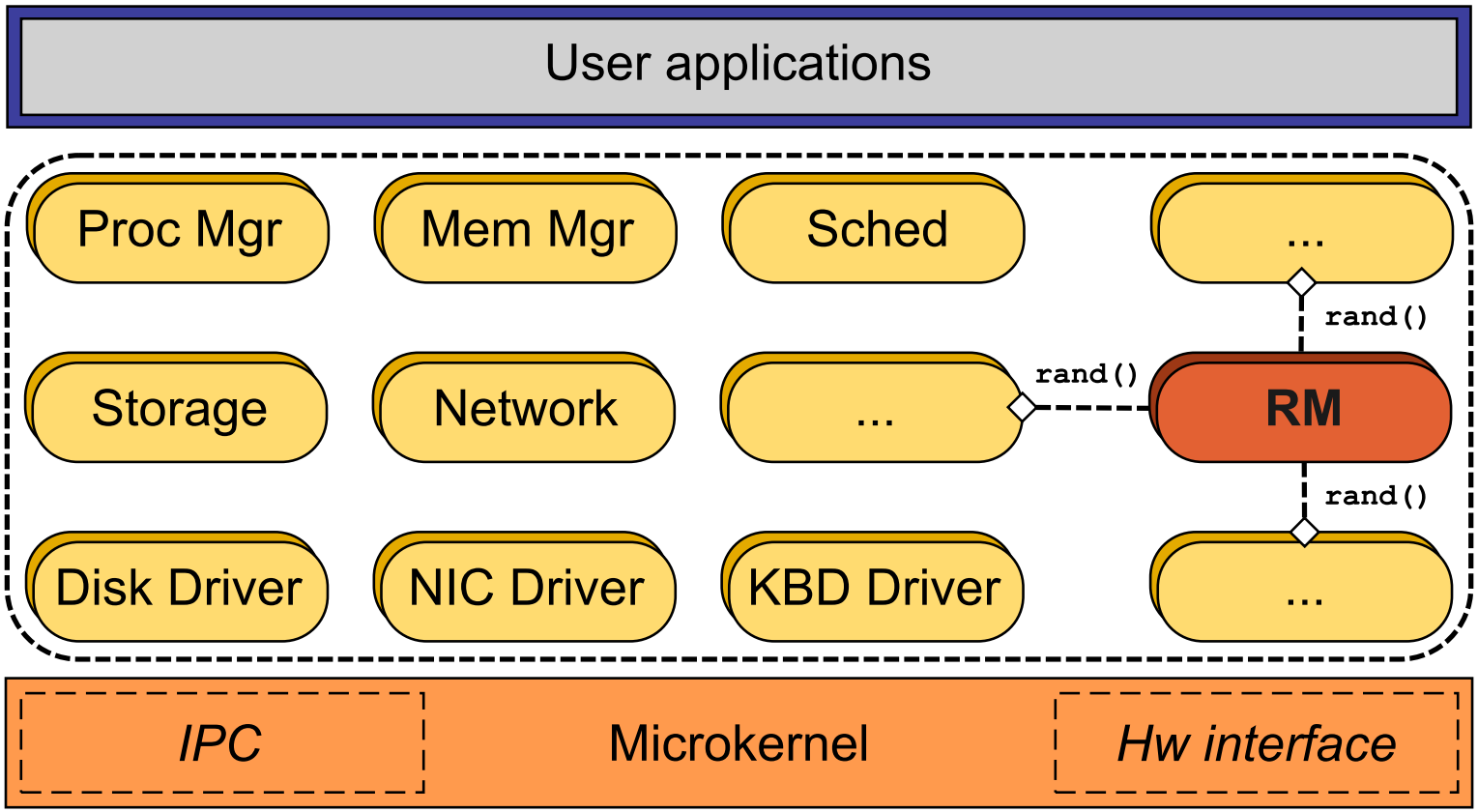


Brute forcing

A Design for OS-level ASR

- Make both **location** and **layout** of memory objects unpredictable.
- LLVM-based link-time transformations for safe and efficient ASR.
- Minimal amount of untrusted code exposed to the runtime.
- Live rerandomization to maximize unobservability of the system.
- No changes in the software distribution model.

Architecture



Code Randomization

```
0x...00 | define i32 @my_function() nounwind uwtable {
  +0x00 | entry:                                    ; original entry block
        |   %6 = call @printf(i8* getelementptr inbounds (@.str, ...))
        |   [...]
        |   ret i32 0
        | }
```

Original function (LLVM IR)

Code Randomization

```
0x...b4   define i32 @my_function() nounwind uwtable {
  +0x00   entry:                                    ; original entry block
            %6 = call @printf(i8* getelementptr inbounds (@.str, ...))
            [...]
            ret i32 0
          }
```

Randomize function location

Code Randomization

```
0x...a0 | define void @my_function_padding() nounwind uwtable { ... }

0x...b4 | define i32 @my_function() nounwind uwtable {
  +0x00 | entry:                                    ; original entry block
        |   %6 = call @printf(i8* getelementptr inbounds (@.str, ...))
        |   [...]
        |   ret i32 0
        | }
```

Add random-sized padding

Code Randomization

```
0x...a0 | define void @my_function_padding() nounwind uwtable { ... }

0x...b4 | define i32 @my_function() nounwind uwtable {
  +0x00 | entry:                                    ; new entry block
        |   br label %original_entry
        |
        | dummy:                                    ; new dummy block
        |   call void @nop()
        |   [...]
        |   br label %original_entry
        |
  +0xF8 | original_entry:                           ; original entry block
        |   %6 = call @printf(i8* getelementptr inbounds (@.str, ...))
        |   [...]
        |   ret i32 0
        | }
```

Basic block shifting

Static Data Randomization

```
0x...00 | @my_variable = global %struct.my_struct zeroinitializer
        |
        | %struct.my_struct = type {              ; original type
  +0x00 |   i32 flags,
  +0x04 |   i16 id,
  +0x08 |   %struct.my_struct *next
  +0x0C |   i8* address,
  +0x10 |   [8 x i8] string,
        | }
```

Original variable and type (LLVM IR)

Static Data Randomization

```
0x...b4 | @my_variable = global %struct.my_struct zeroinitializer

        | %struct.my_struct = type {              ; original type
  +0x00 |   i32 flags,
  +0x04 |   i16 id,
  +0x08 |   %struct.my_struct *next
  +0x0C |   i8* address,
  +0x10 |   [8 x i8] string,
        | }
```

Randomize variable location

Static Data Randomization

```
0x...a0 | @my_variable_padding = global [... x i8] zeroinitializer

0x...b4 | @my_variable = global %struct.my_struct zeroinitializer

        | %struct.my_struct = type {              ; original type
  +0x00 |   i32 flags,
  +0x04 |   i16 id,
  +0x08 |   %struct.my_struct *next
  +0x0C |   i8* address,
  +0x10 |   [8 x i8] string,
        | }
```

Add random-sized padding

Static Data Randomization

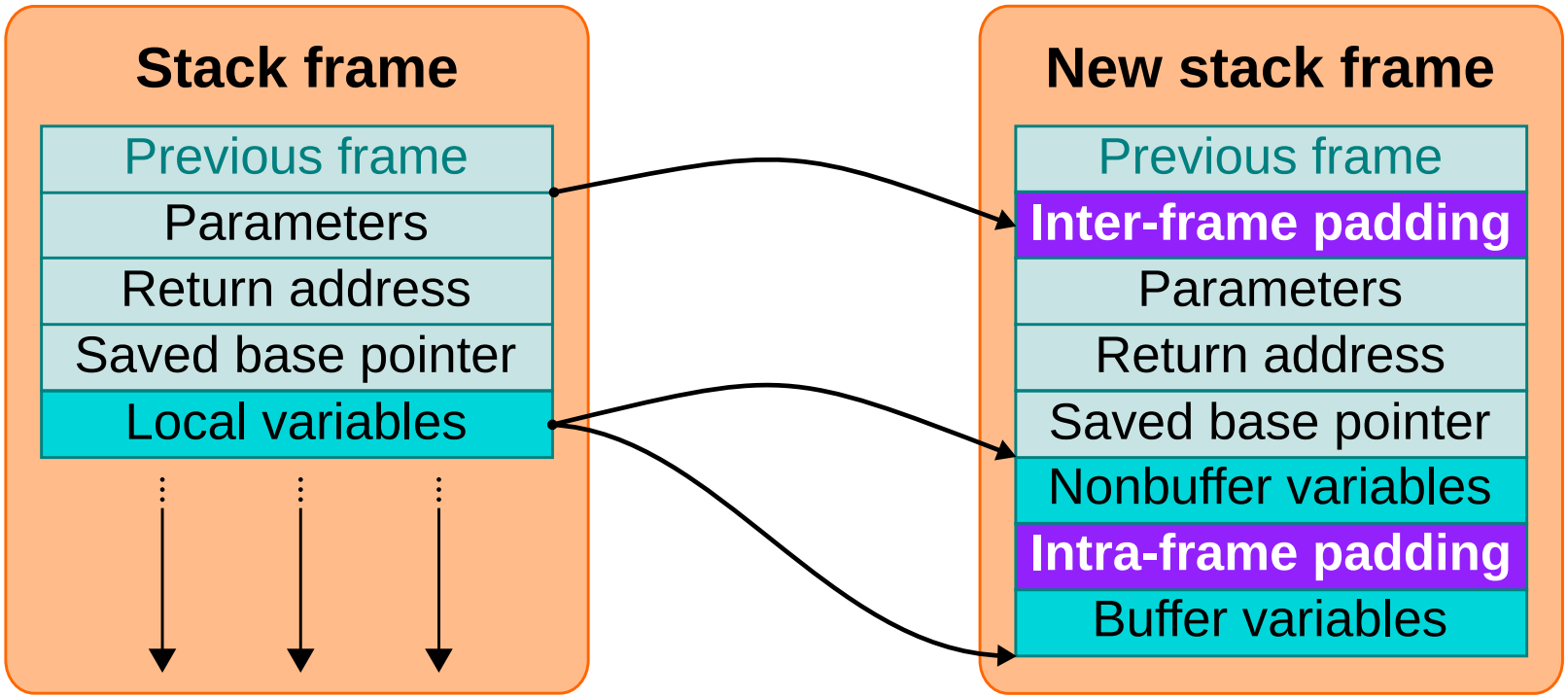
```
0x...a0 | @my_variable_padding = global [... x i8] zeroinitializer

0x...b4 | @my_variable = global %struct.my_struct zeroinitializer

        | %struct.my_struct = type {                ; randomized type
  +0x00 |   [... x i8] id_padding,
  +0xa0 |   i16 id,
  +0xa2 |   [... x i8] flags_padding,
  +0xb4 |   i32 flags,
  +0xb8 |   [... x i8] string_padding,
  +0xc8 |   [8 x i8] string,
  +0xd0 |   [... x i8] address_padding,
  +0xe0 |   i8* address,
  +0xe4 |   [... x i8] next_padding,
  +0xf4 |   %struct.my_struct *next
        | }
```

Internal layout randomization

Stack Randomization



Dynamic Data Randomization

- Support for `malloc()`/`mmap()`-like allocator abstractions.
- Memory mapped regions are fully randomized.
- Heap allocations are interleaved with random-sized padding.
- Full heap randomization enforced at live rerandomization time.
- ILR for all the dynamically allocated memory objects.

Live Rerandomization

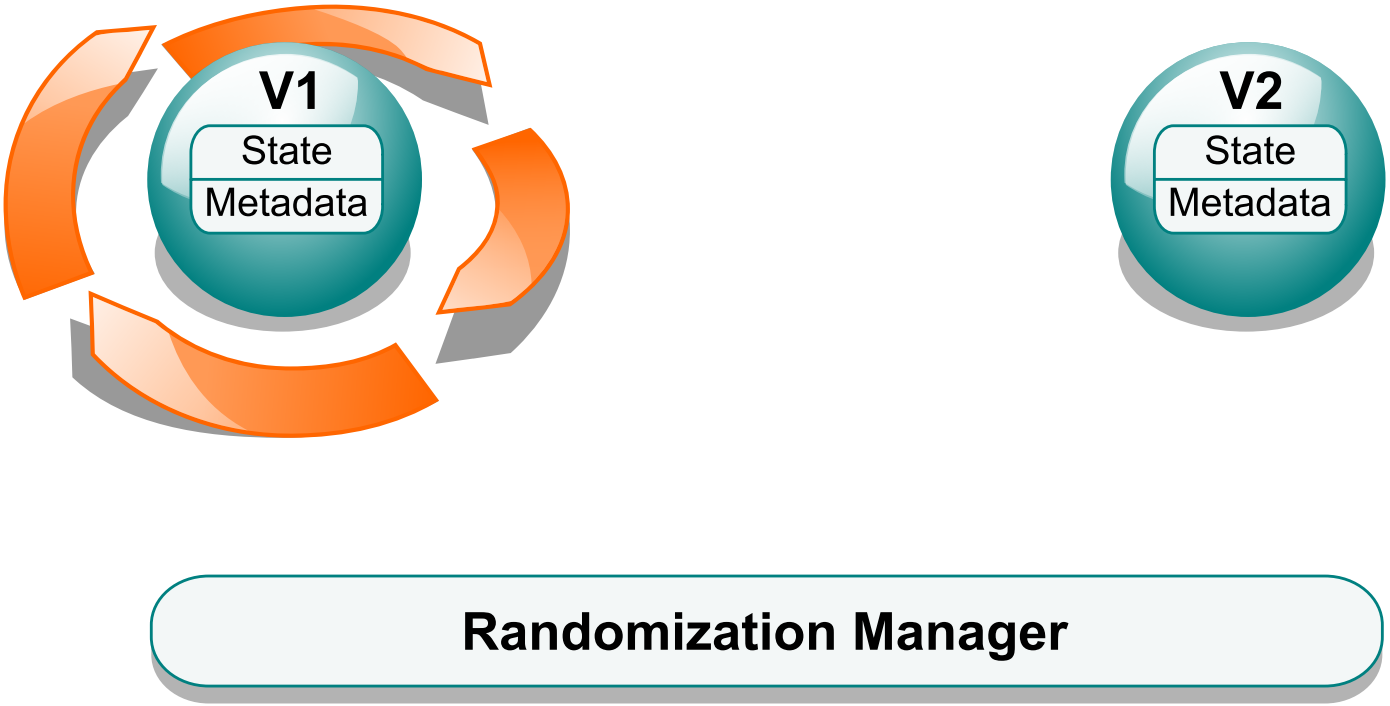
- First **stateful** live rerandomization technique.
- Periodically rerandomize the memory address space layout.
- Support arbitrary memory layout changes at rerandomization time.
- Support all the standard C idioms with minimal manual effort.
- Sandbox the rerandomization code to recover from run-time errors.

ASRR Transformations

ASRR Metadata

- Types
- Global variables
- Static variables
- String constants
- Functions
- Dynamic memory allocations

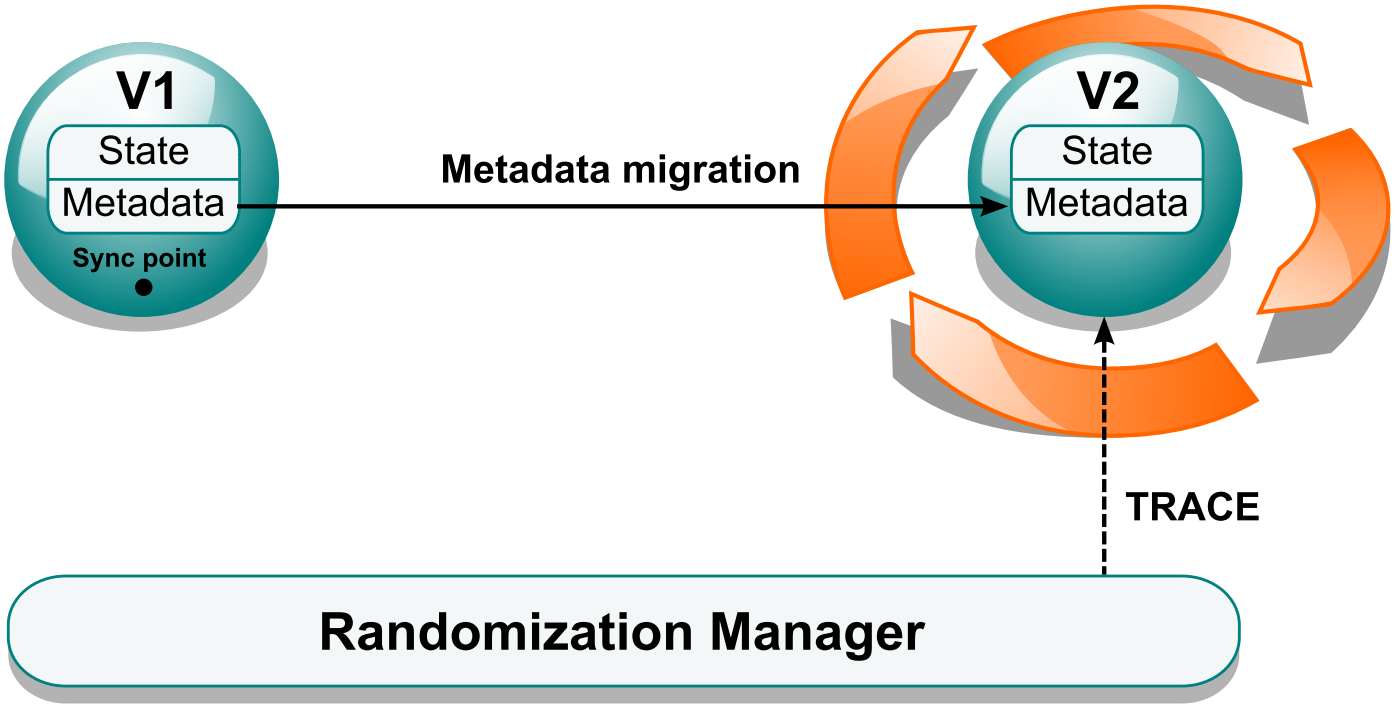
The Rerandomization Process



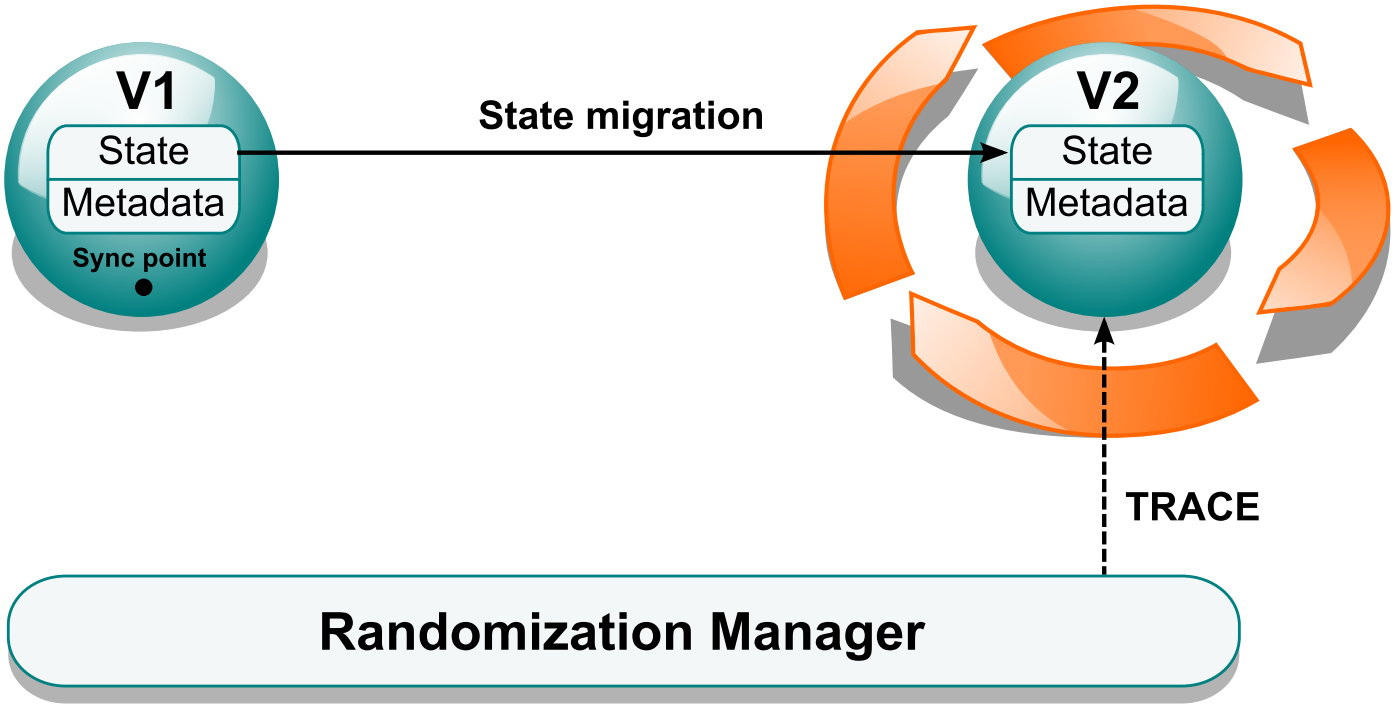
The Rerandomization Process

The Rerandomization Process

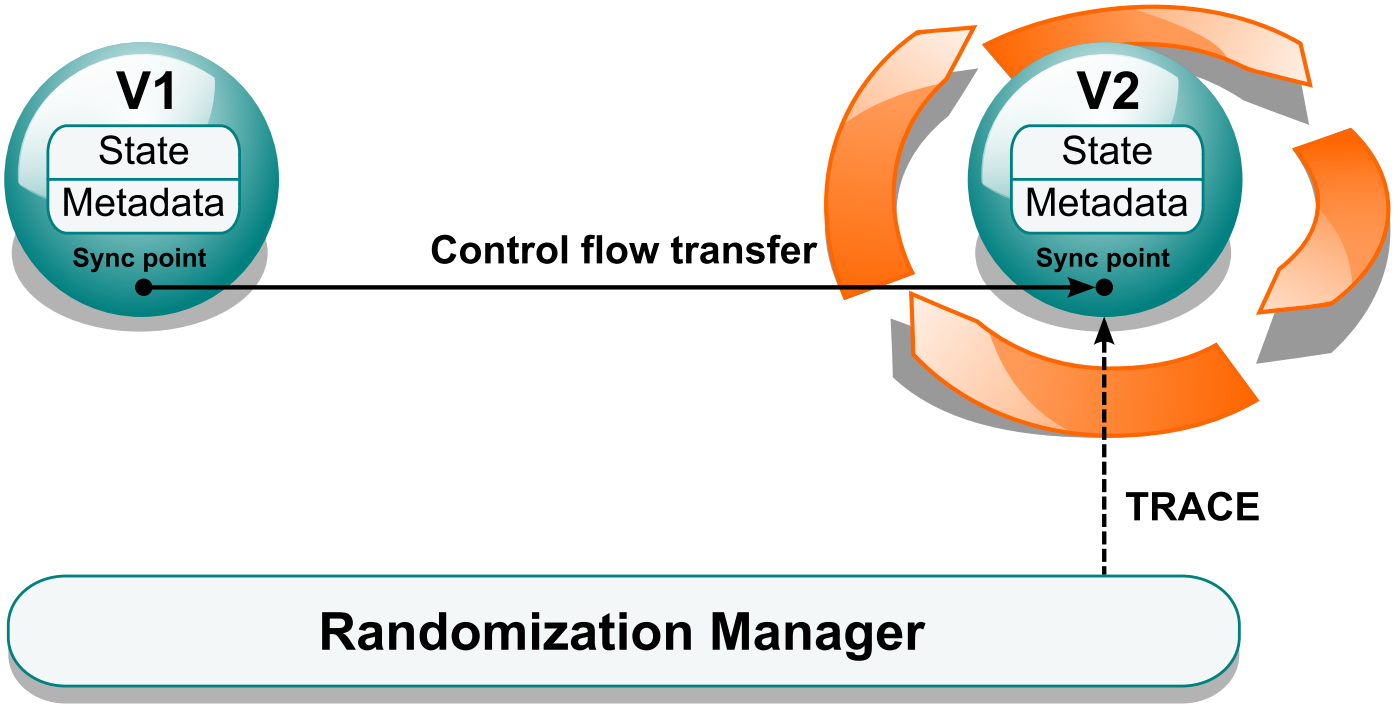
The Rerandomization Process



The Rerandomization Process

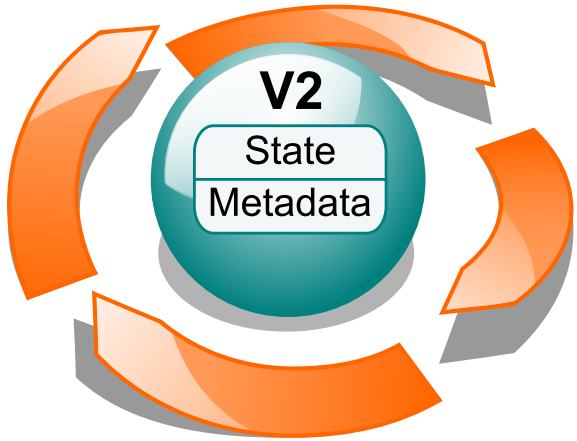


The Rerandomization Process



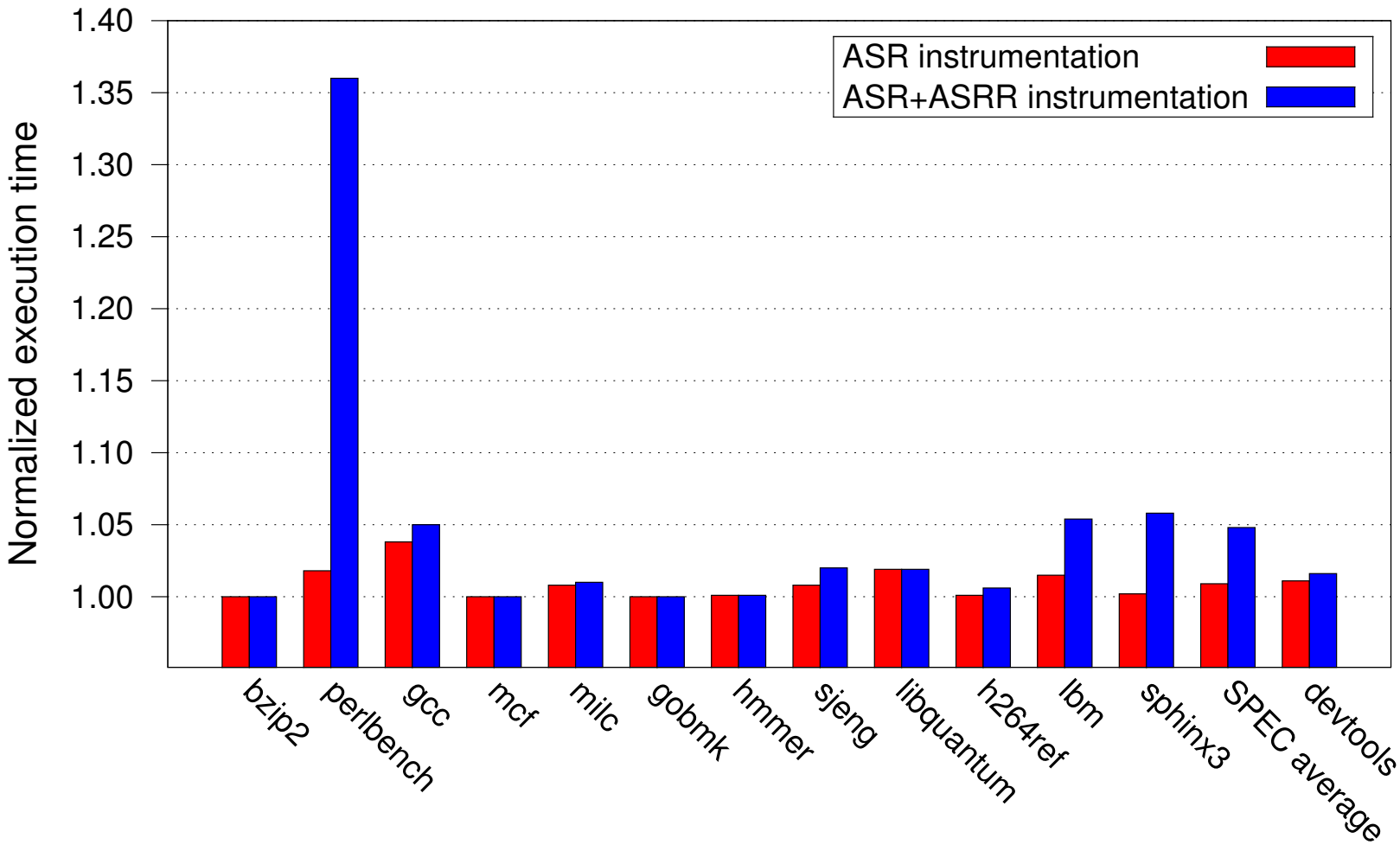
The Rerandomization Process

The Rerandomization Process

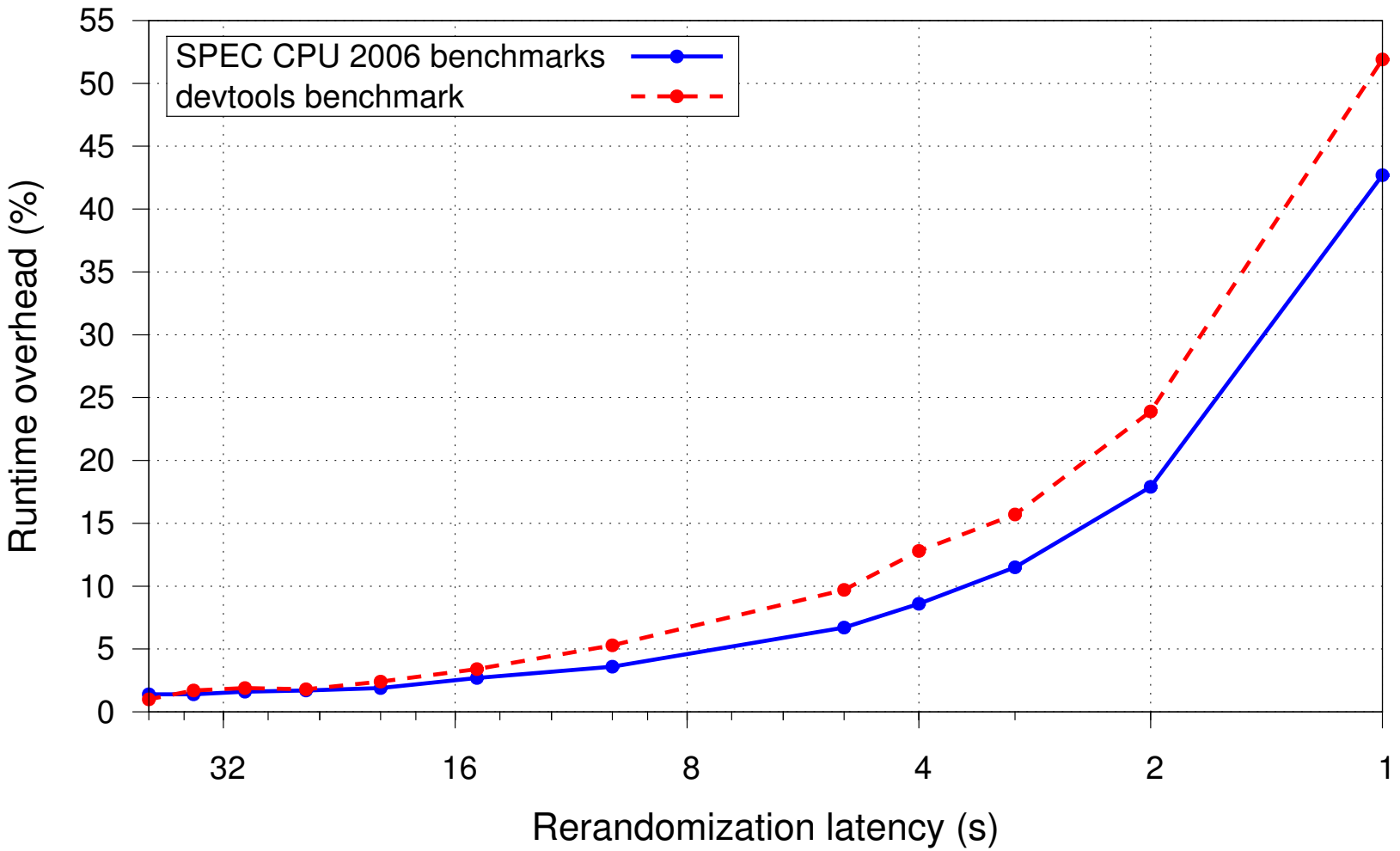


Randomization Manager

ASR Performance



ASRR Performance



Summary

- A new fine-grained ASR technique for operating systems.
- Better performance and security than prior ASR solutions.
- Live rerandomization and ILR to counter information leakage.
- No heavyweight instrumentation exposed to the runtime.
- Process-based isolation to recover from run-time ASRR errors.

Enhanced Operating System Security Through Efficient and Fine-grained Address Space Randomization

Thank you!
Any questions?

Cristiano Giuffrida, Anton Kuijsten, Andy Tanenbaum
{giuffrida,kuijsten,ast}@cs.vu.nl

Vrije Universiteit Amsterdam