MARDU: Efficient and Scalable Code Re-Randomization

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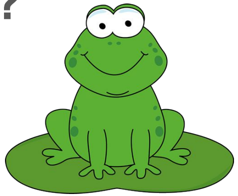
The Fight against Return Oriented Programming (ROP)

What is Return Oriented Programming?

- An attack that reuses program code to achieve ***arbitrary code computation***

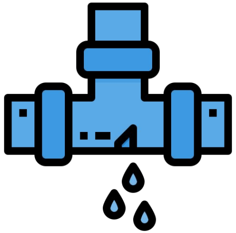
What are Gadgets?

- Snippets of code that perform specific actions
  - Arithmetic operations
  - Reading/writing to registers
  - Etc.



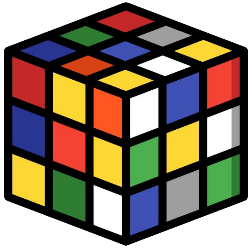
Attack	**Defense**
Code Injection →	Data Execution Prevention (DEP)
← Return Oriented Programming (ROP) →	Address Space Layout Randomization (ASLR)
← Just-In-Time ROP (JIT-ROP) →	Fine-Grained ASLR & eXecute-only Memory (XoM)
← Blind ROP (BROP) (Code Inference) →	Continuous Randomization

Current randomization techniques are good ...



Code Randomization

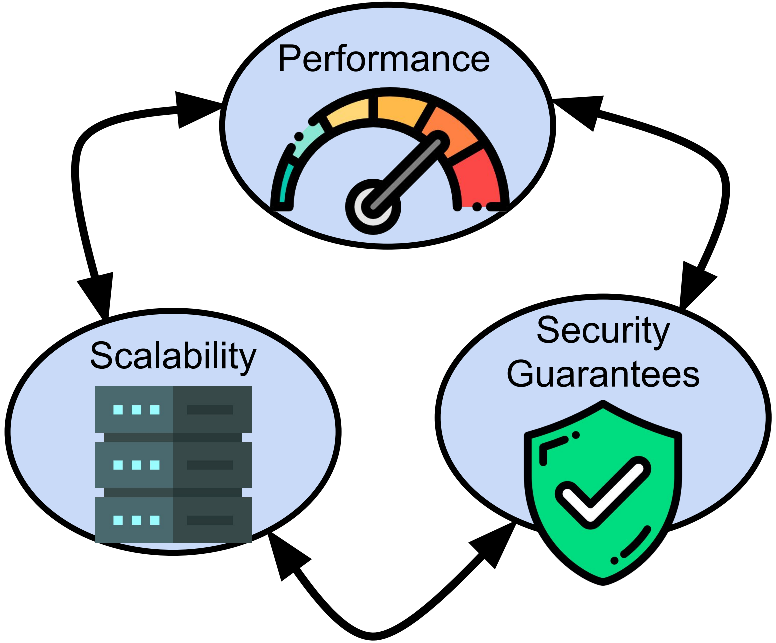
- Address Space Layout Randomization (ASLR)
  - \+ Light-weight
  - \- Static code layout
  - \- One leak can compromise entire code base



- Re-Randomization Techniques
  - \+ Continuous churn makes gadgets hard to find
  - \- High overhead
  - \- Rely on predictable thresholds such as
    - \- Time interval
    - \- Syscall invocation
    - \- Call history

But they are not practical. Why?

- Users desire **acceptable performance** (<10% avg & worst-case)
- Users desire **strong defenses**
- Users desire **scalability** as more computation is moved to the cloud
    - Have system-wide security coverage including shared libraries
- Achieving <u>all three</u> *together* is ***hard***



Outline

- Introduction
- **Challenges**
- MARDU Design
- Implementation
- Evaluation
- Conclusion

Challenges for making a practical randomization defense

- **Security** challenges
  - Code disclosure: a single leaked pointer allows attacker to obtain code layout of a victim process

- **Performance** challenges
  - Avoiding useless overwork: Active randomization wastes CPU cycles in case of “what-if”

- **Scalability** challenges
  - Code Tracking: to support runtime re-randomization tracking and updating of pc-relative code is a necessary and expensive evil

  - Stop-the-world: Updating shared code on-the-fly is challenging especially in concurrent access

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  - **Security: Leveraging code trampolines**
  - Scalability: Enabling code sharing
  - Performance: Re-randomization without stopping the world
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Example: Code Control Flow

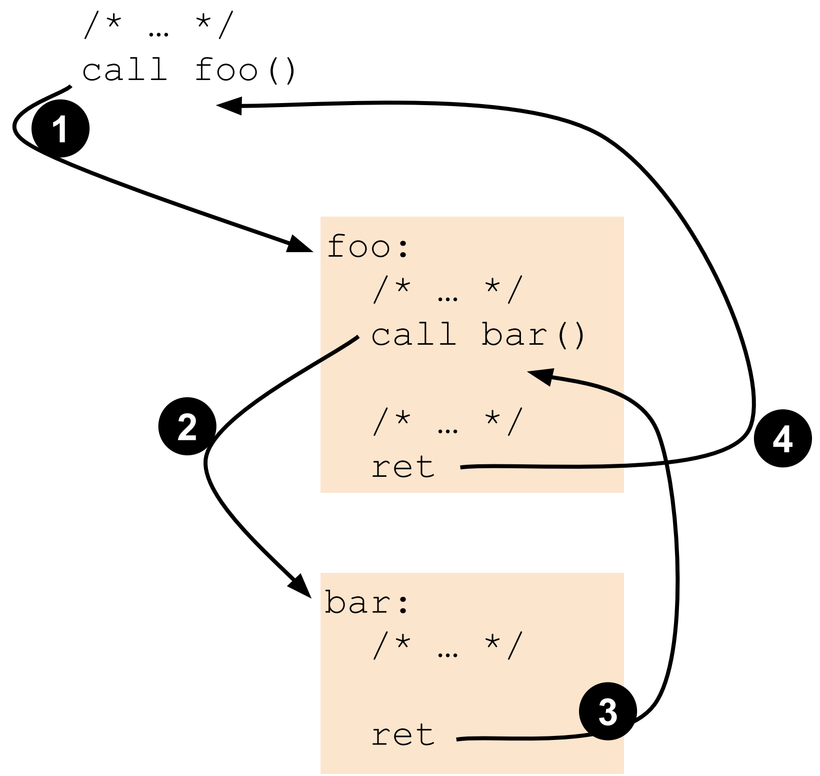
Source Code

```
void foo(){
 /* … */
 bar();
 /* … */

}
```

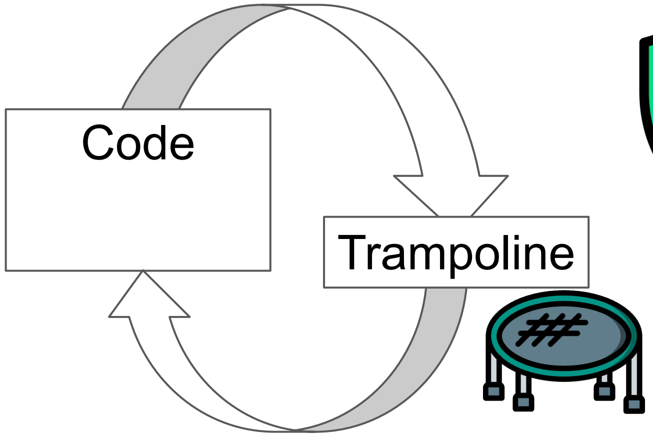
```
void bar(){
  /* … */
}
```

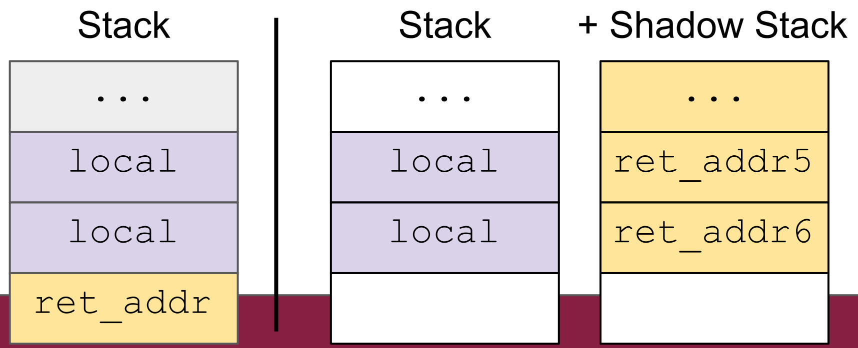
Traditional Control Flow



MARDU is secure

- Code and Trampoline regions protect *forward* edge
  - Trampolines are immutable code targets
  - Protects against code disclosure
- Shadow stack protects *backward* edge
- Randomization occurs at:
  - Process startup AND
  - Whenever an attack is detected (***on-demand***)
    - Process crash
    - Execute-only memory violation





Example: Securing MARDU Code

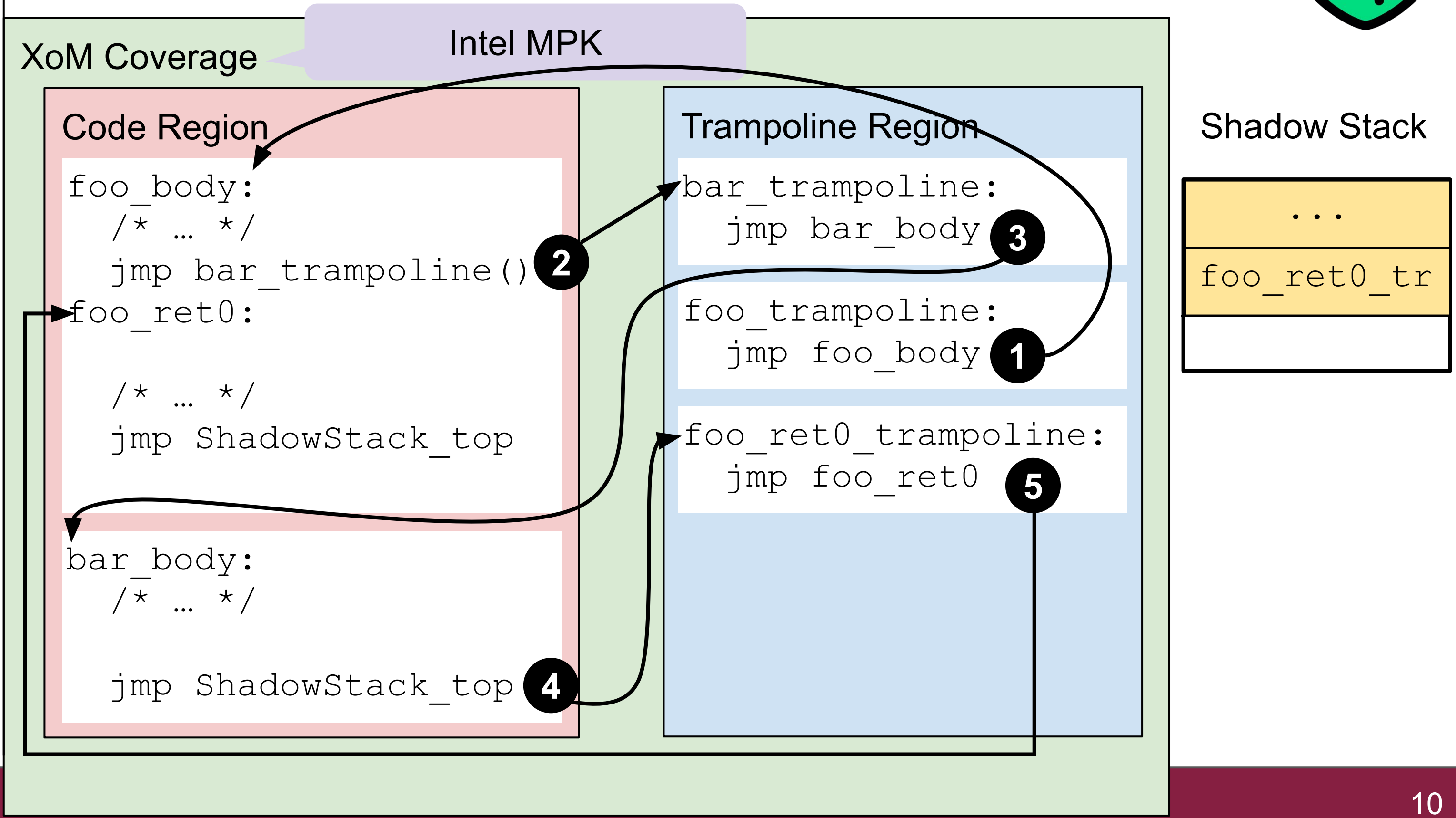
Source Code

```
void foo(){
 /* … */
 bar();
 /* … */

}
```

```
void bar(){
  /* … */
}
```

Using Code Trampolines Control Flow



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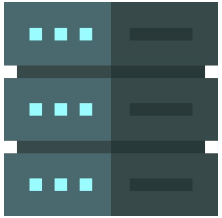
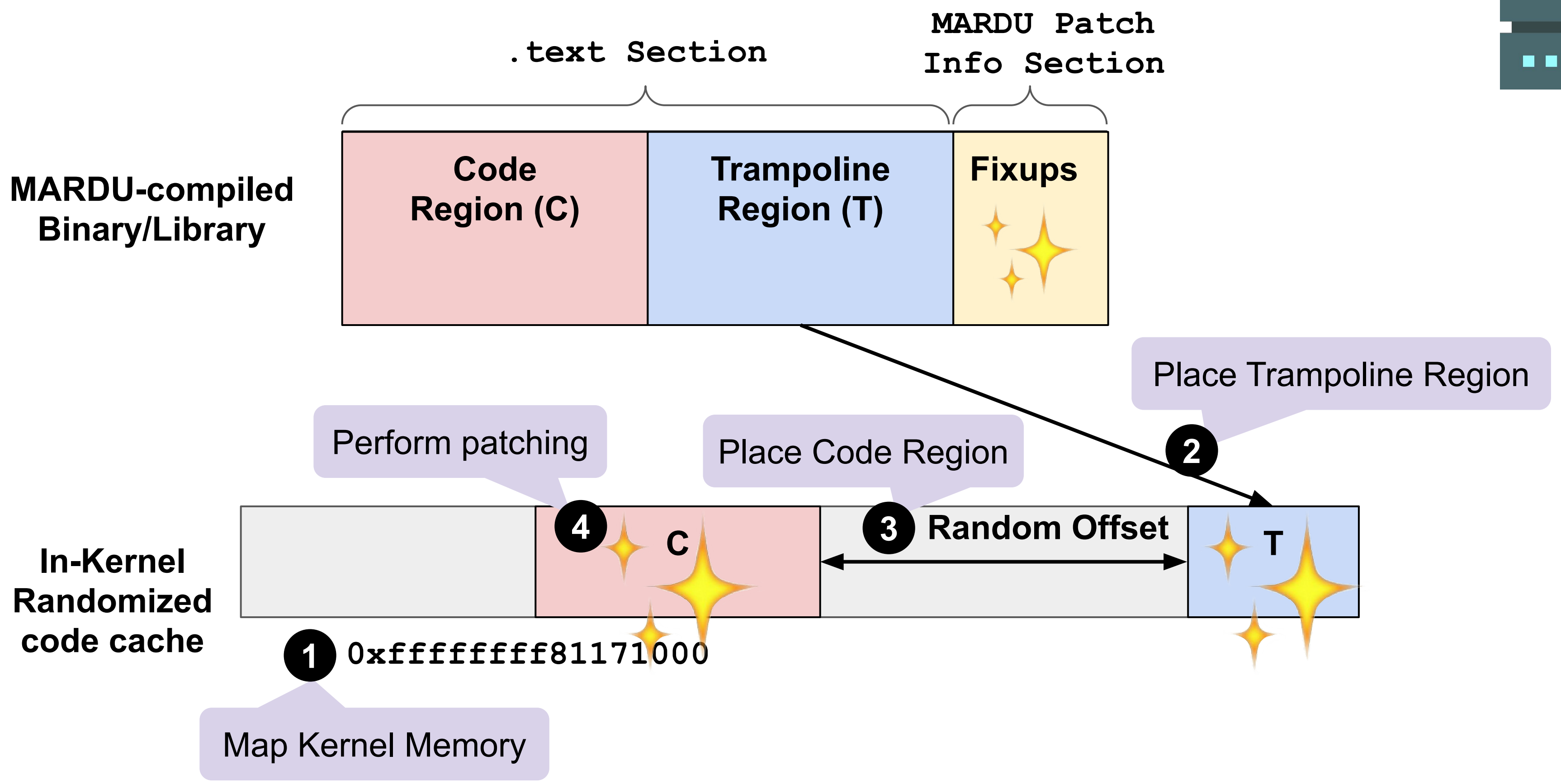
MARDU is scalable

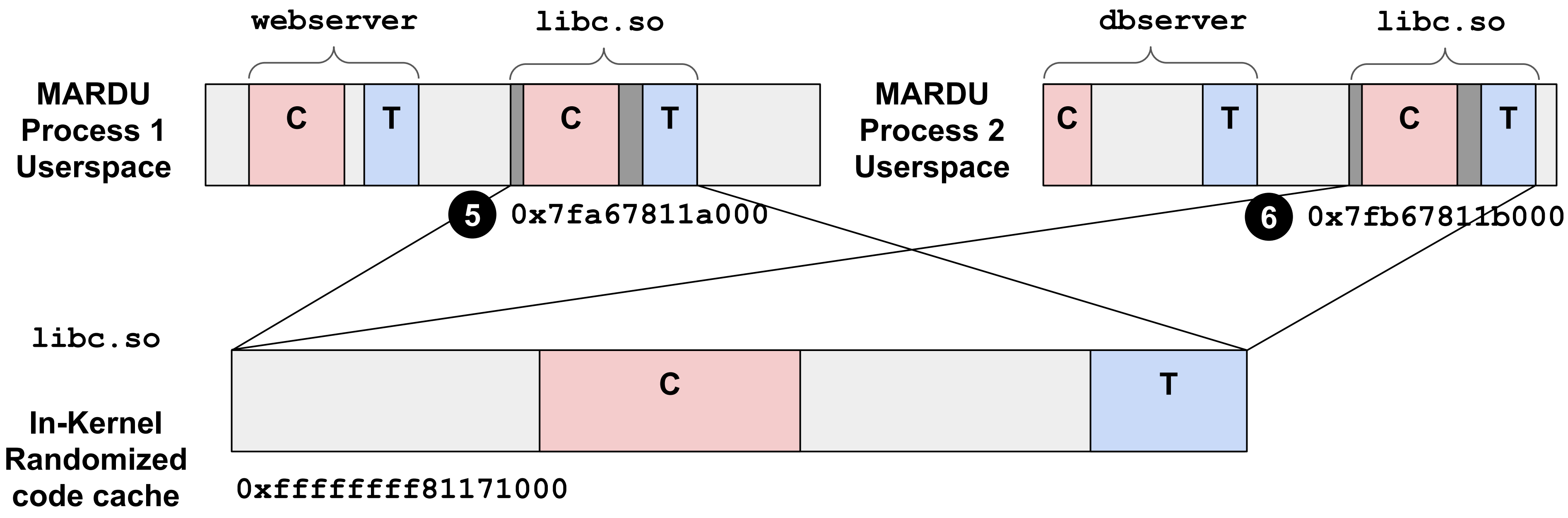


- MARDU is capable of code sharing (e.g., shared libraries)
  - No previous randomization scheme is capable of runtime re-randomization **AND** code sharing
- MARDU leverages position independent code (`-fPIC`) for easy fixups of `PC-relative` code.
- MARDU supports mixed instrumented and non-instrumented libraries

Example: Sharing MARDU code



Example: Sharing MARDU code



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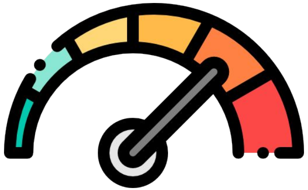

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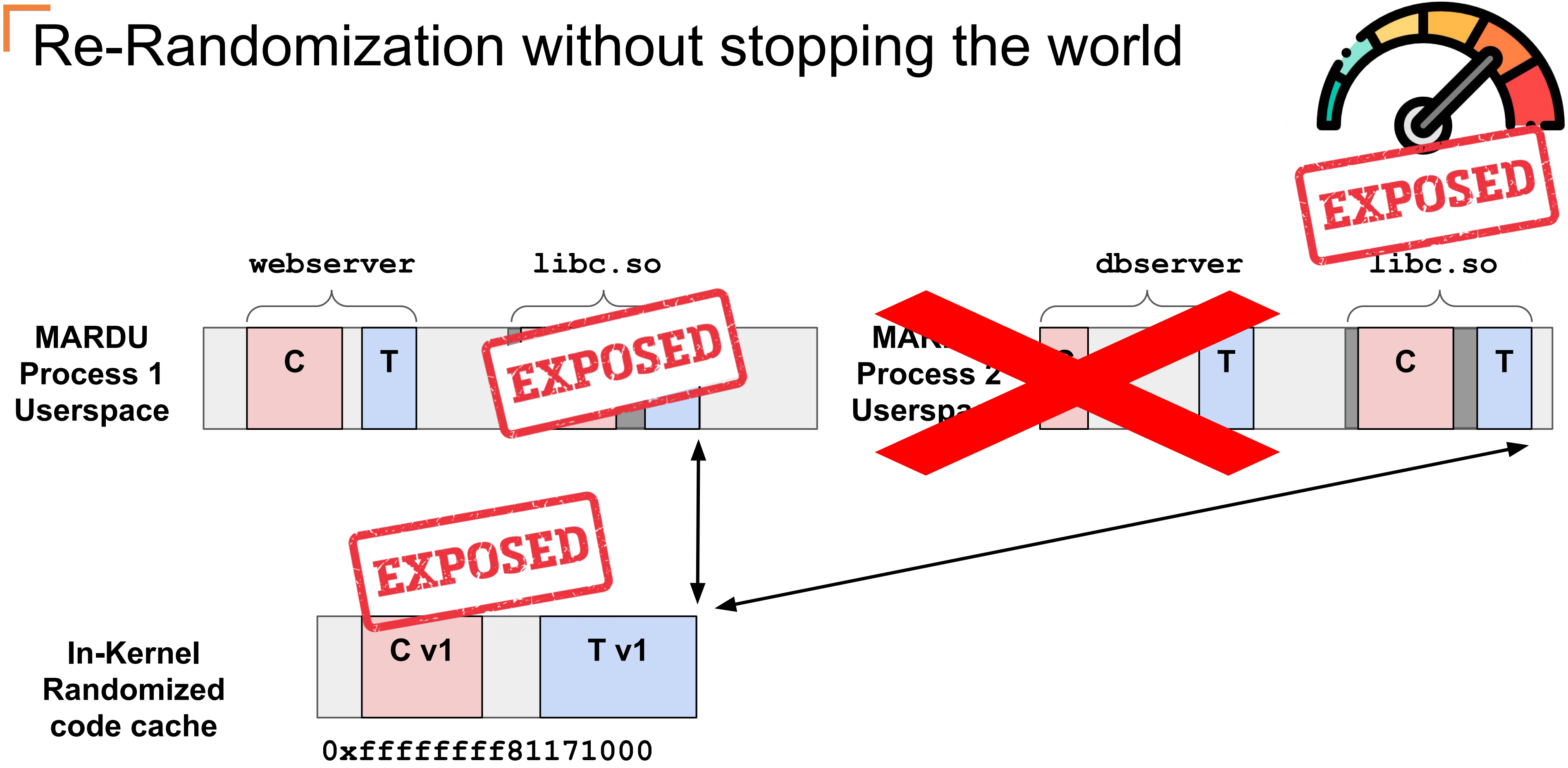
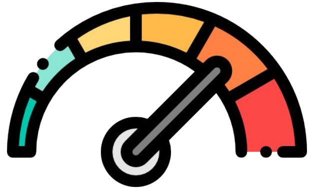
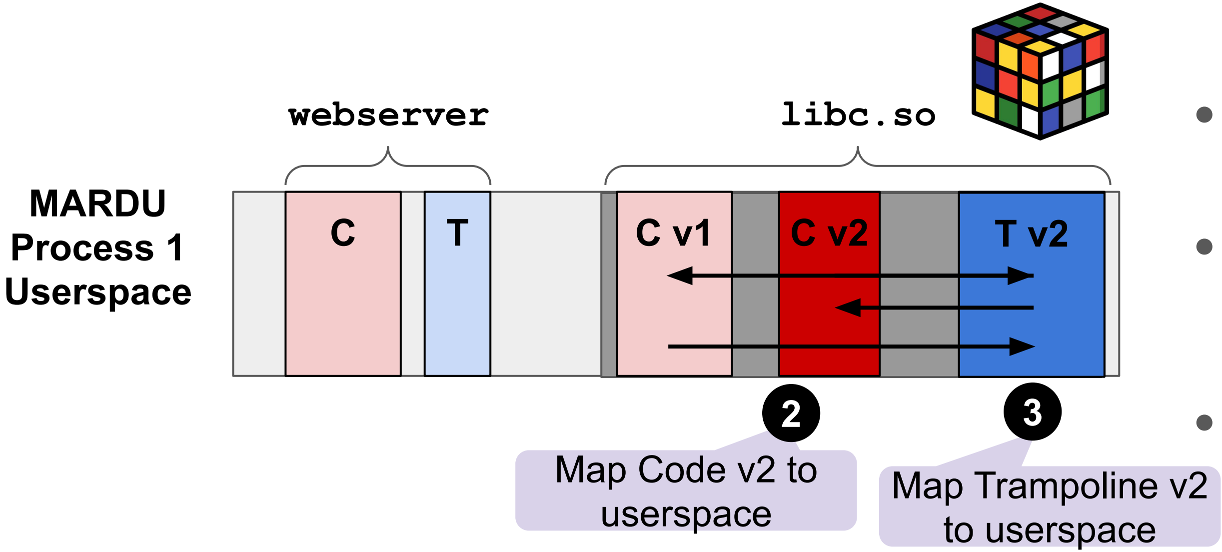
Re-Randomization without stopping the world

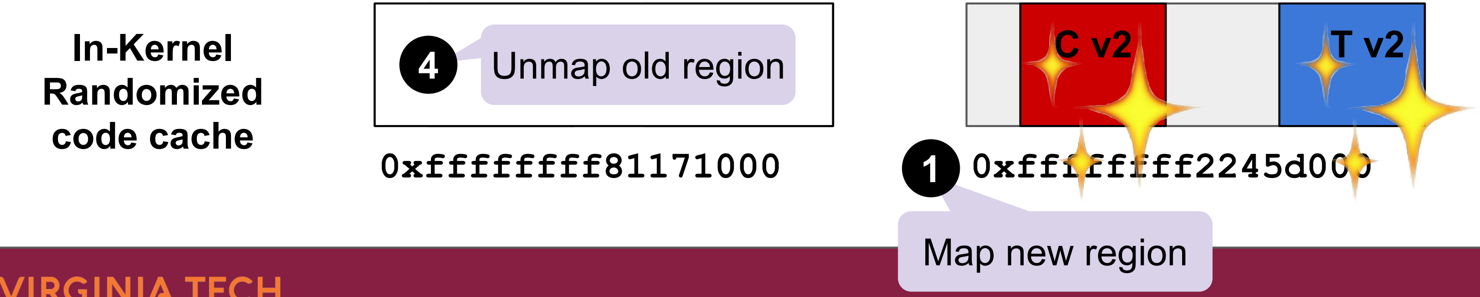


Re-Randomization without stopping the world

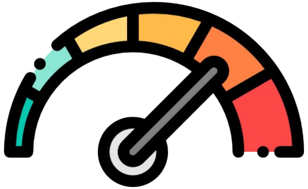




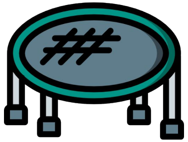
- Gadgets previously deduced are now *stale*
- Randomization is repeated whenever another attack event is detected
- Randomization is replicated for **ALL ASSOCIATED** shared code of a victim process



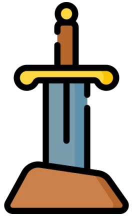
MARDU is performant



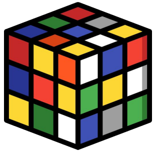
- Trampolines
  - No Runtime Instrumentation Tracking



- Trampolines leverage immutable code
  - No stop-the-world mechanisms



- Re-active re-randomization
  - Only when attack detected (***on-demand***)
  - Responsibility of exiting (crashed) process/thread



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MARDU Implementation

- Working Prototype

- Compiler
  - LLVM/Clang 6.0.0
  - 3.5K LOC

- Kernel
  - X86-64 linux 4.17.0
  - 4K LOC

- `musl LibC`
  - General C library

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- **Evaluation**
  - **How to evaluate MARDU?**
  - Security: MARDU against popular ROP attacks
  - Performance: Compute Bound -> minimal runtime overhead
  - Scalability: Concurrent Web server -> negligible runtime overhead and scalability
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How to evaluate MARDU?

1) How <u>secure</u> is MARDU, against current <u>known and popular</u> attacks on randomization?

2) How much <u>performance overhead</u> does MARDU impose?

3) How <u>scalable</u> is MARDU in terms of load time, memory savings, and re-randomization, particularly for concurrent processes (such as a real-world web server)?

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How MARDU defends against popular ROP

- Blind ROP (BROP) & Code Inference Attacks
  - **MARDU:** XoM protected code triggers a permission violation and re-randomization of code
  - **MARDU:** Re-randomization makes all previous collected layout information stale
  - **MARDU:** Usage of trampolines & function granularity randomization makes correlation prediction challenging for attackers

- JIT-ROP Attacks
- Low Profile Attacks
- Code Pointer Offsetting Attacks

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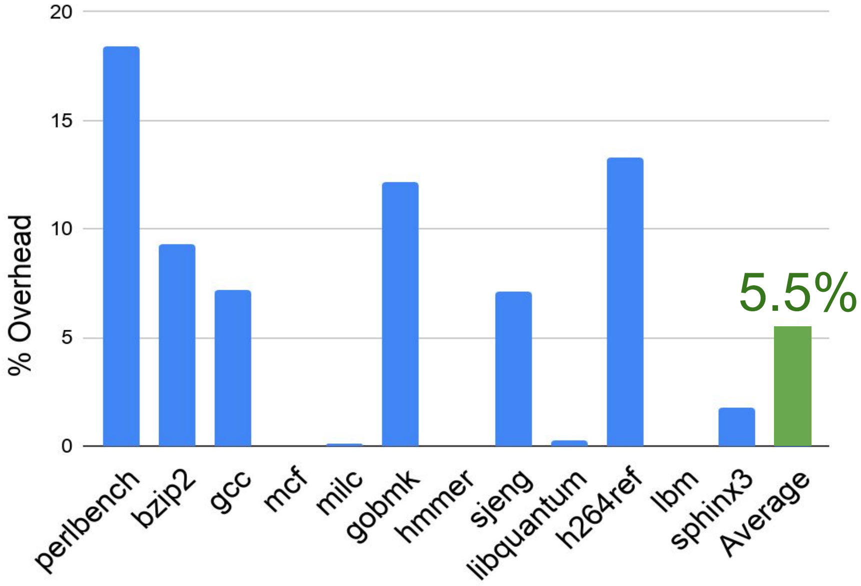
Experimental Setup and Applications

- Experimental Setup
  - All programs compiled with MARDU LLVM compiler and `-O2 -fPIC` optimization flags
  - Platform:
    - 24-core (48-Hardware thread) machine with two Intel Xeon Silver 4116 CPUs (2.10 GHz)
    - 128 GB DRAM

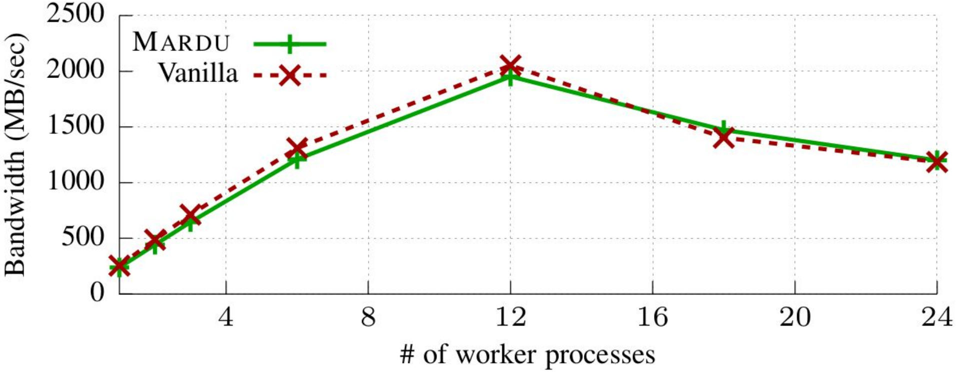
- Applications
  - SPEC CPU 2006 (All C applications)
  - NGINX web server

How MARDU performs

CPU Intensive Benchmark (SPEC CPU 2006)



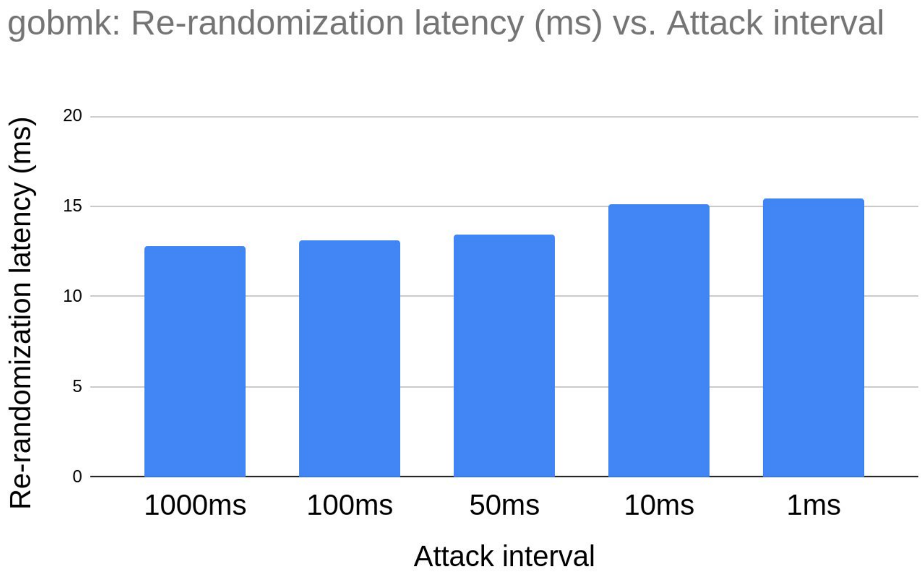
Web server (NGINX)



NGINX AVG Degradation: 4.4%

MARDU randomization with scalability

- Re-randomization latency scales approximately linearly with number of fixups required
- Cold start randomization latency for any number of workers for NGINX is **61ms**
- Re-randomization latency plateau’s even when under attack



Conclusion

We propose MARDU, an re-randomization approach to thwart return oriented programming (ROP) attacks

- MARDU randomizes ***re-actively, on-demand*** to minimize performance overhead
    - Active randomization is relic of the past

- MARDU is the first randomization scheme capable of runtime re-randomization ***with*** code sharing
    - Scalable to apply across entire system
    - Randomization of all shared code associated with compromised process/thread

Thank You !