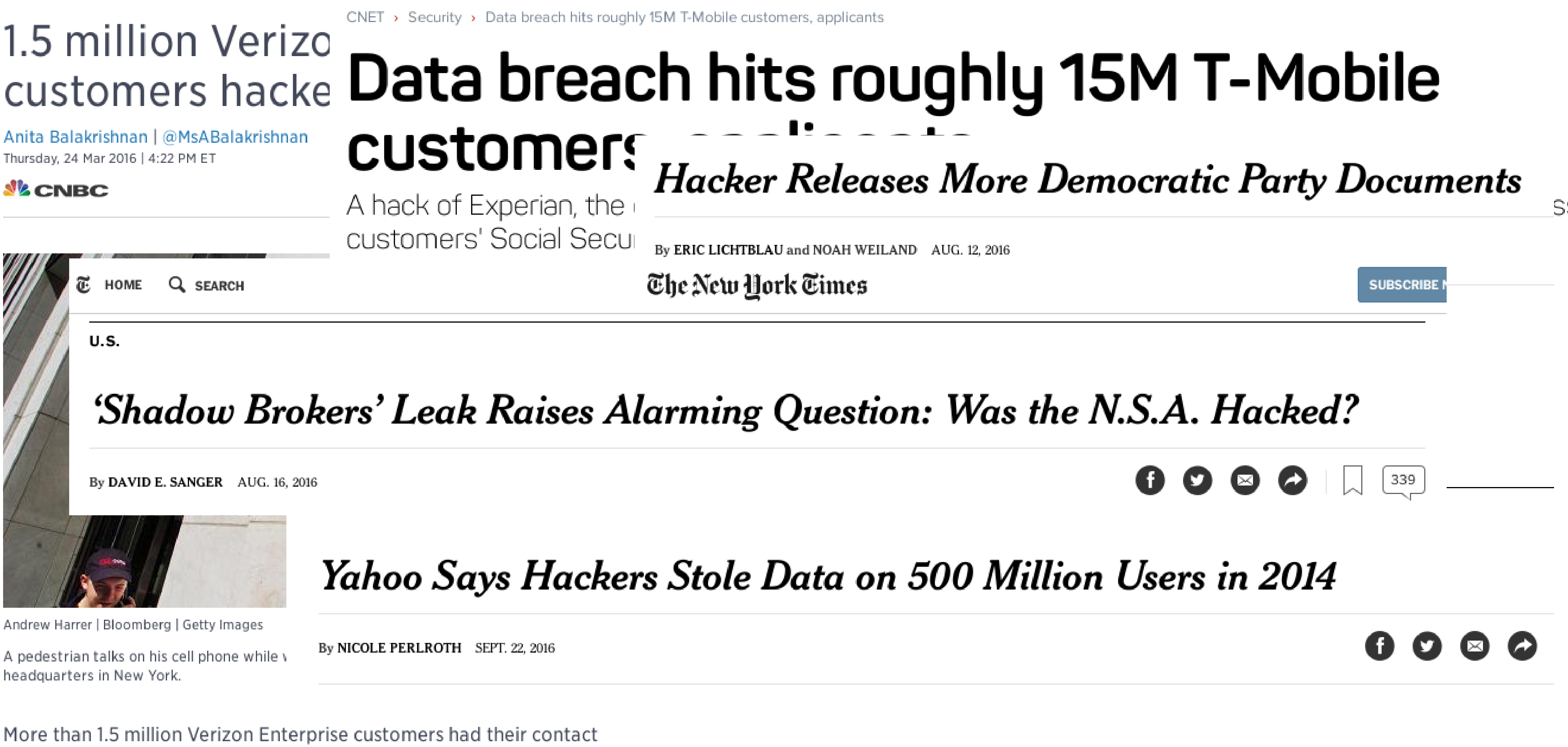
Shuffler: Fast and Deployable Continuous Code Re-Randomization

David Williams-King,
Graham Gobieski, Kent Williams-King, James P. Blake,
Xinhao Yuan, Patrick Colp, Michelle Zheng,
Vasileios P. Kemerlis, Junfeng Yang, William Aiello

OSDI 2016

Software Remains Vulnerable

- High-profile server breaches are commonplace



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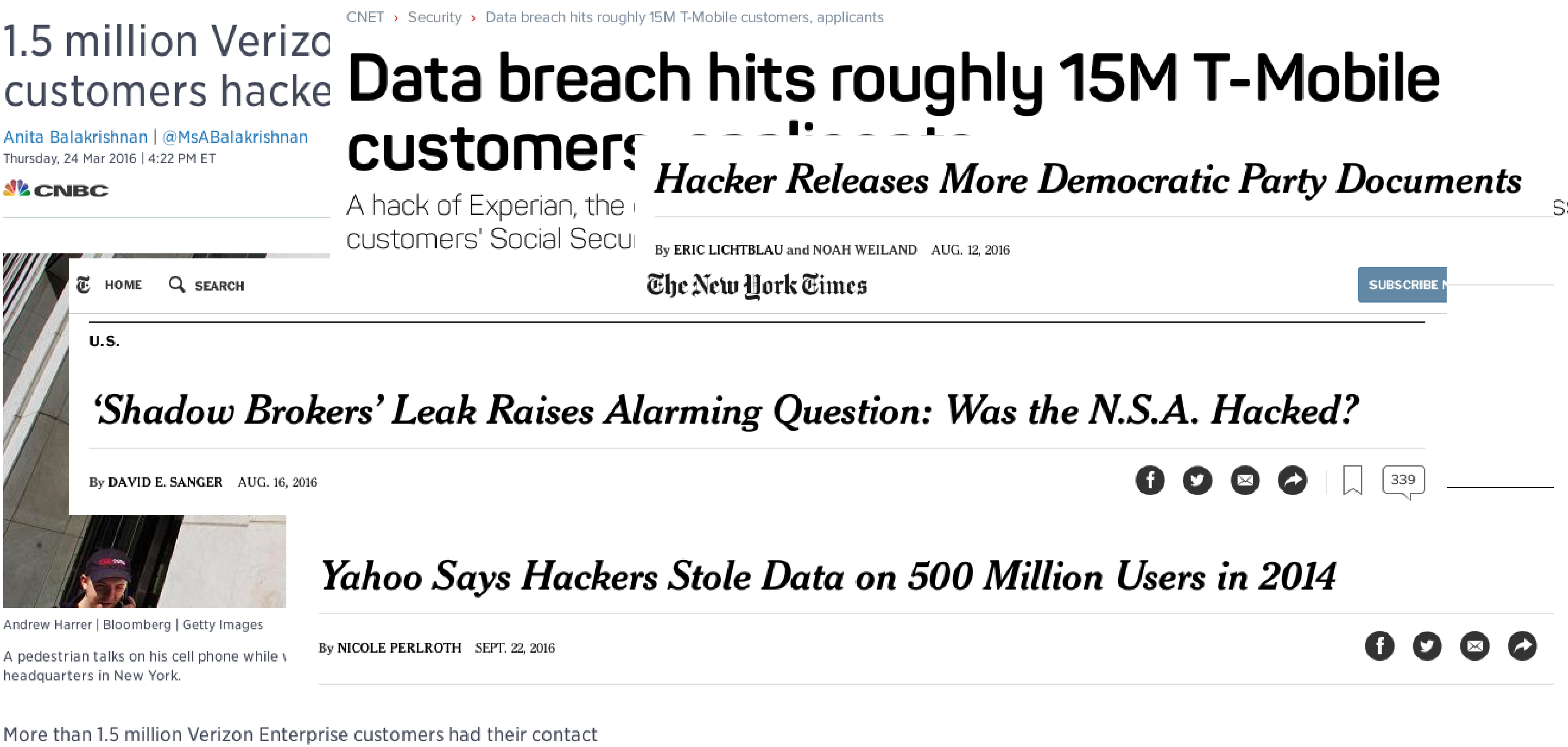
- High-profile server breaches are commonplace
- 90% of today’s attacks utilize ROP [1]



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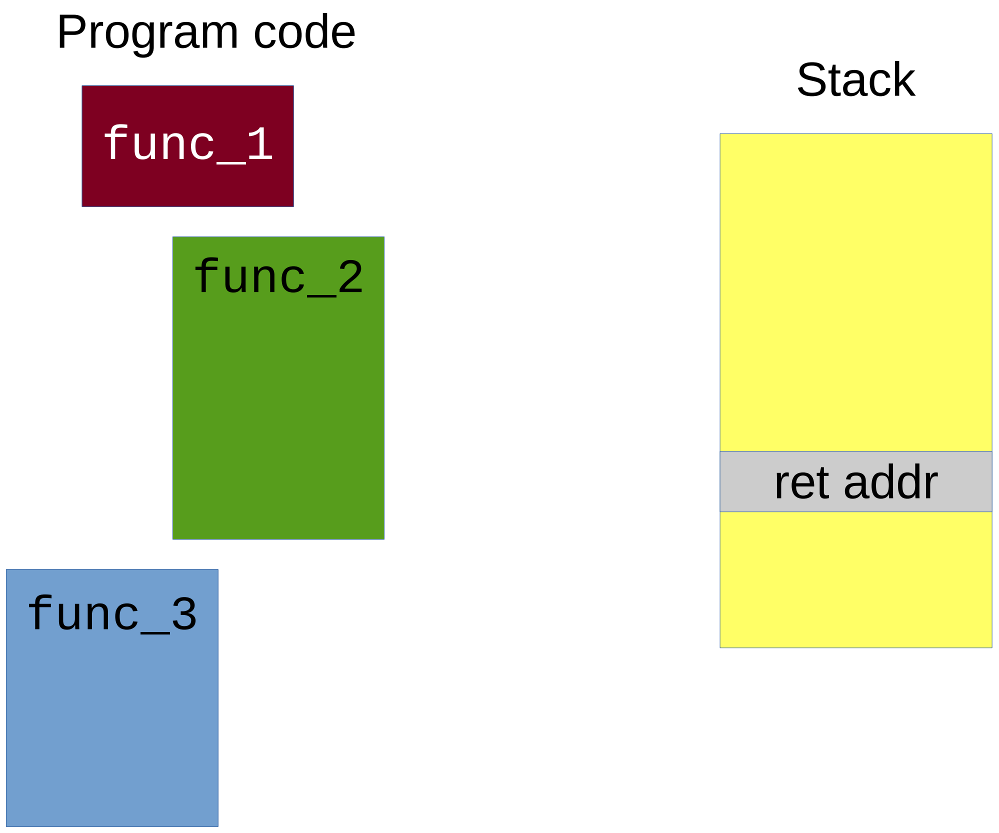

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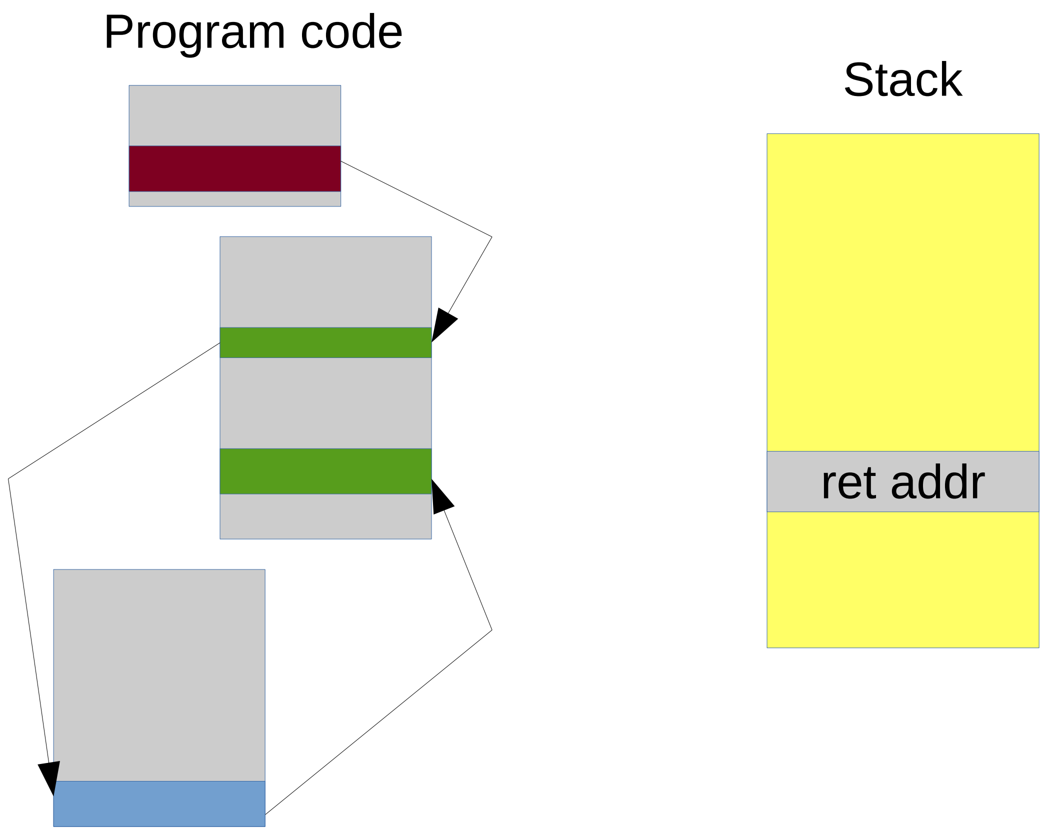

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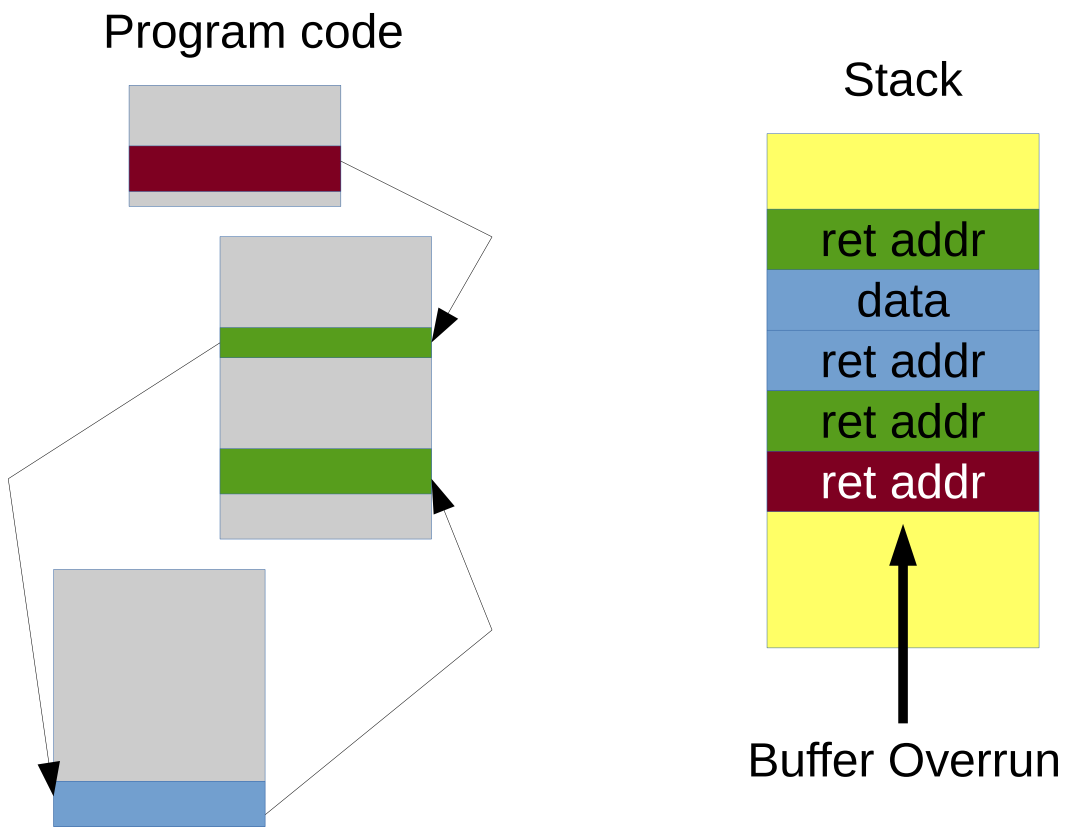

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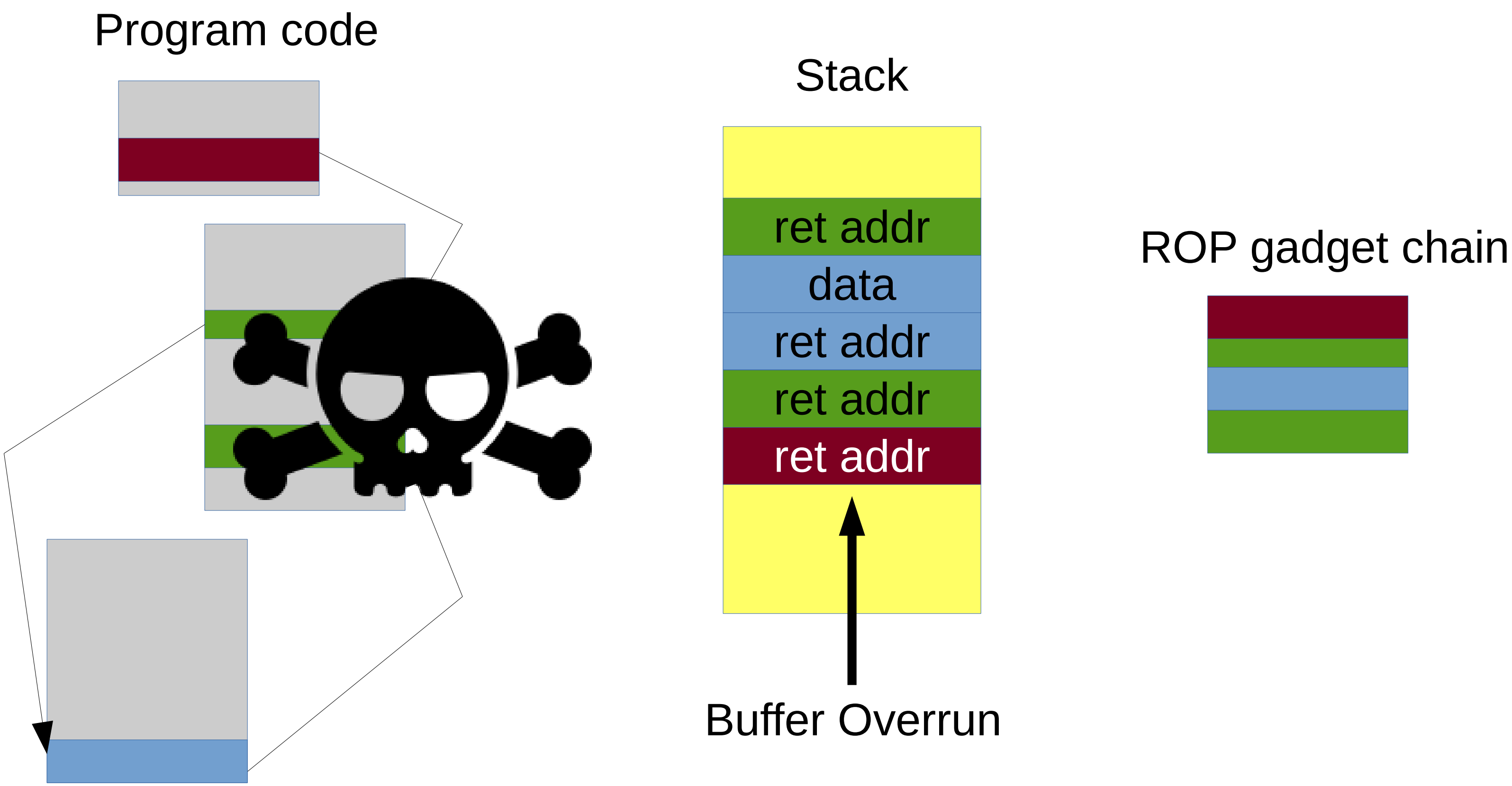

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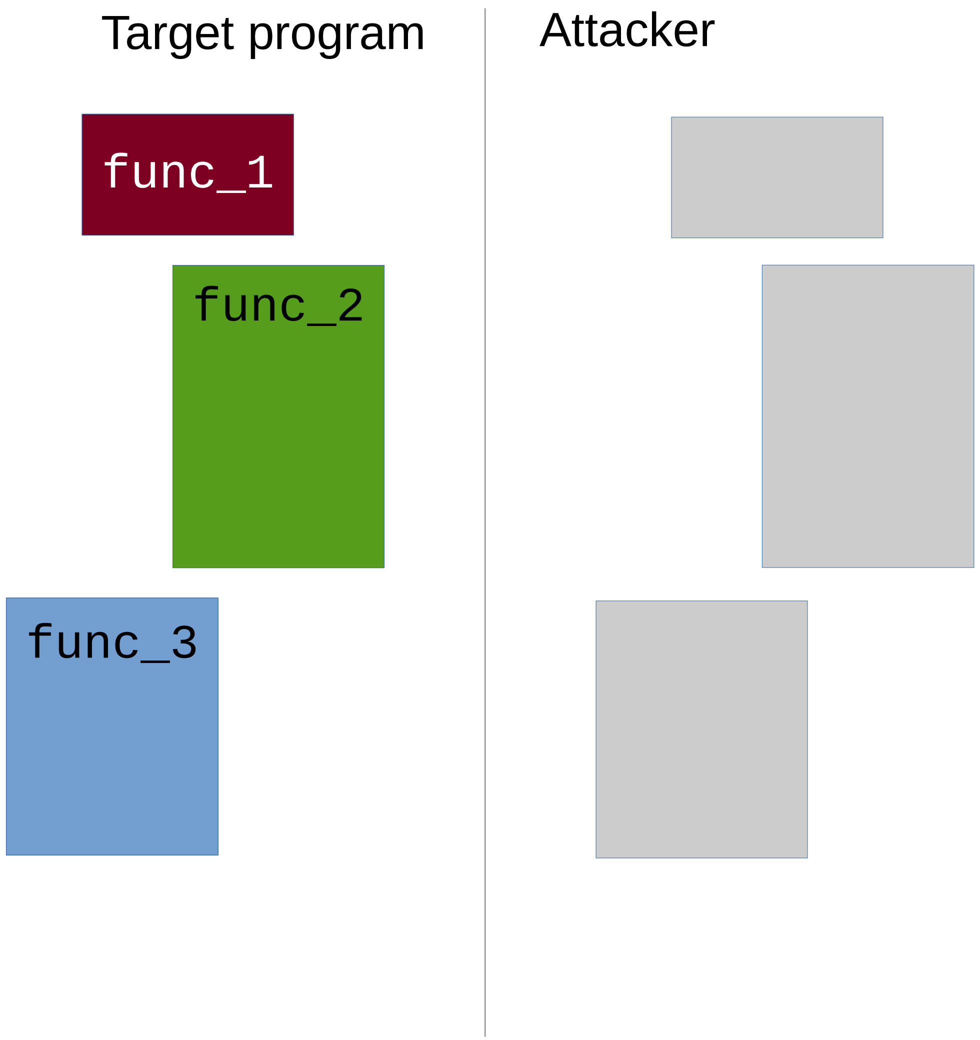

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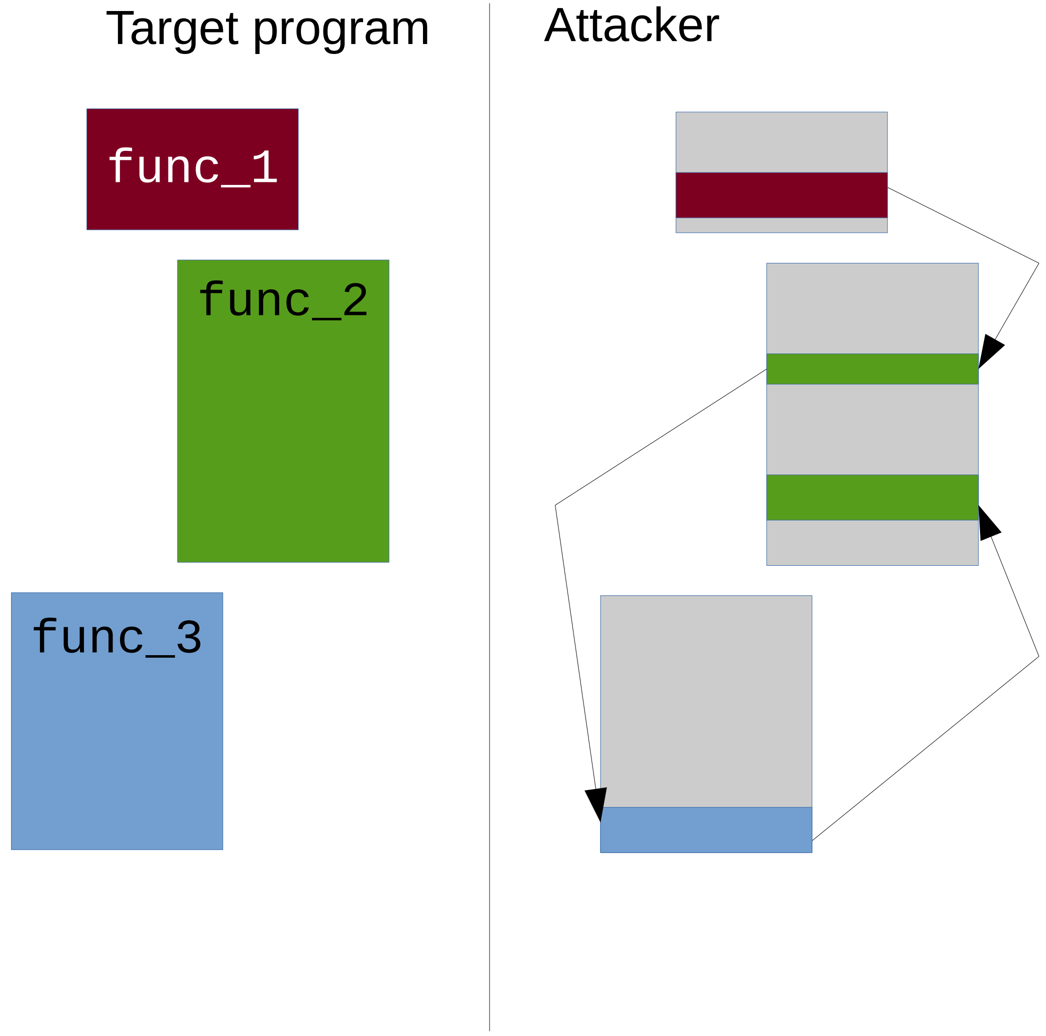

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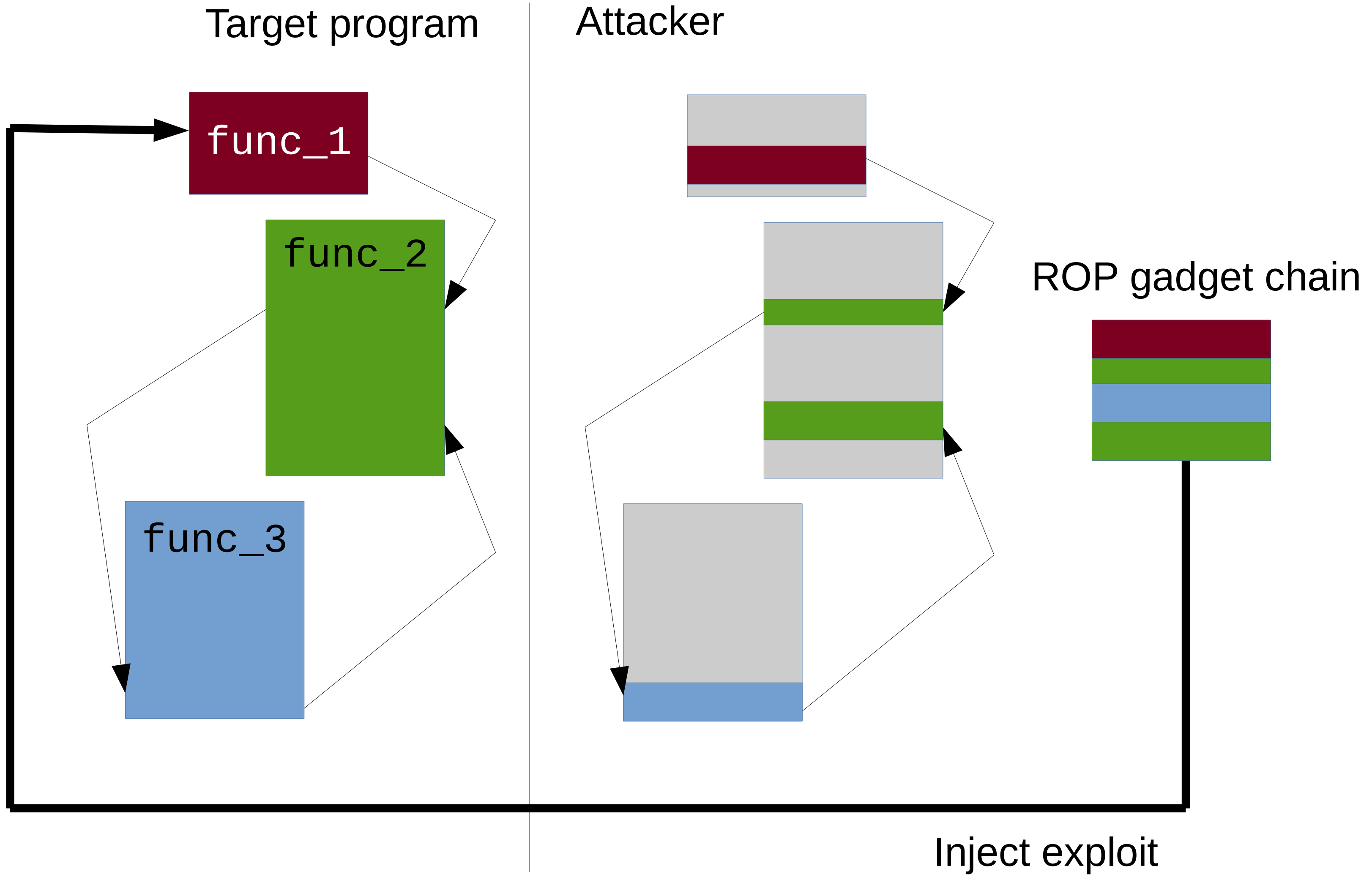

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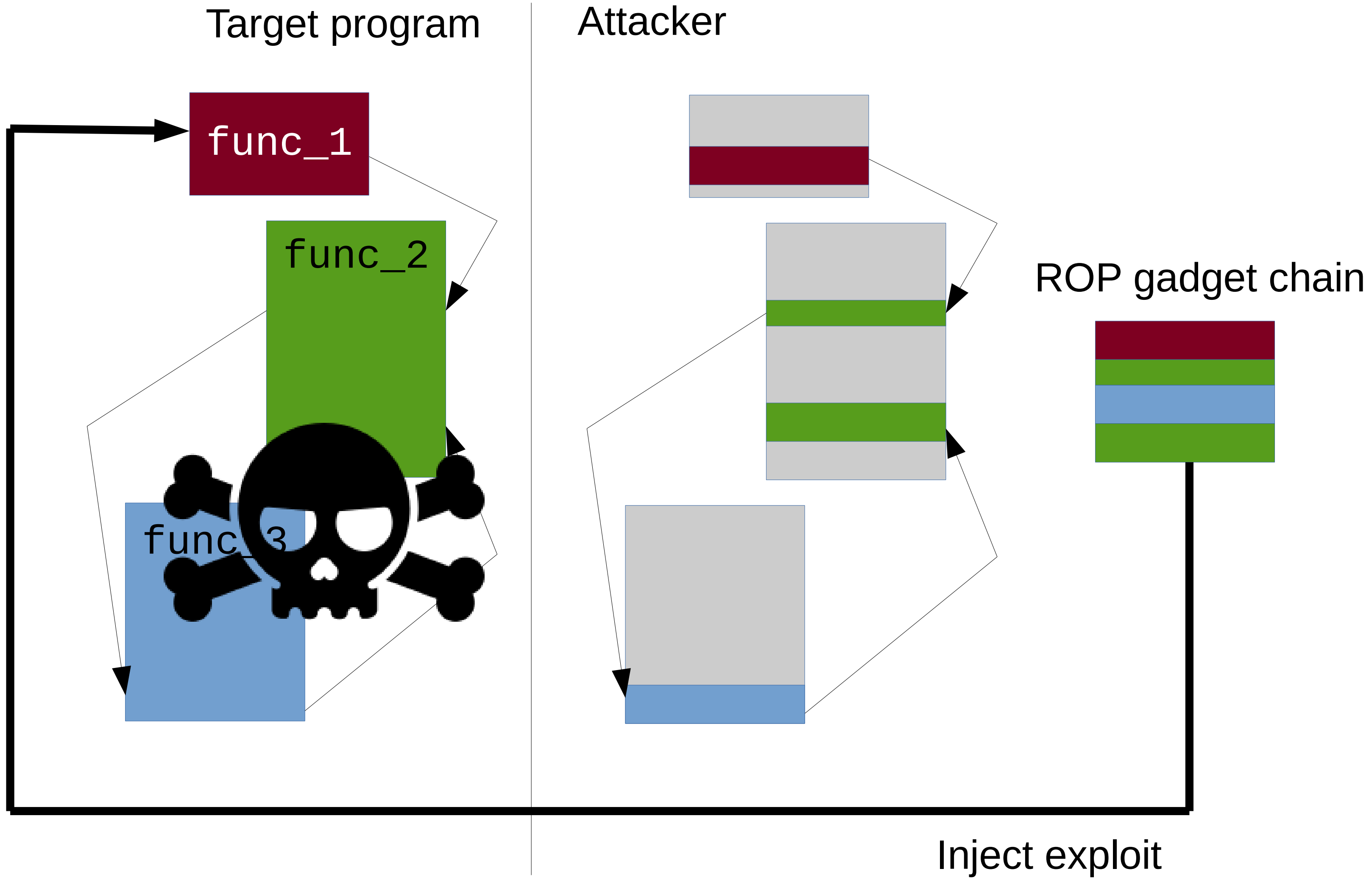
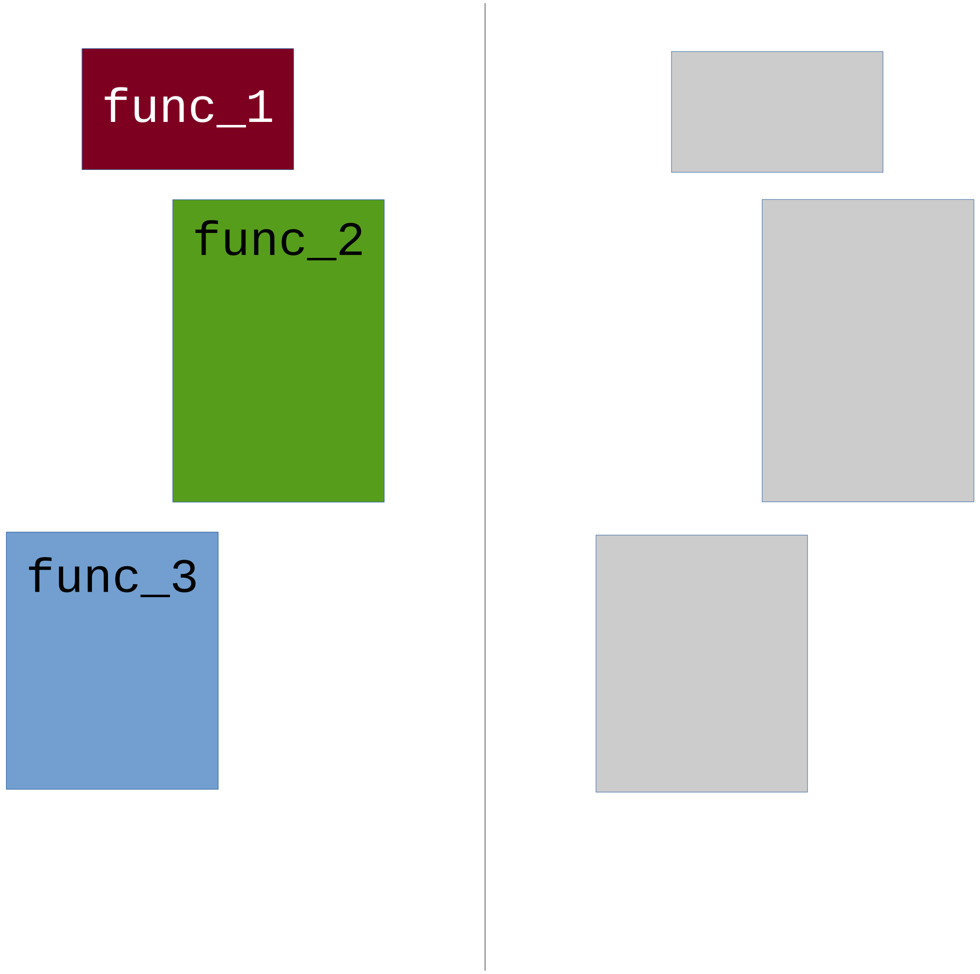


The Shuffler Idea

- What if we re-randomize code more rapidly than an attacker discovers gadgets?



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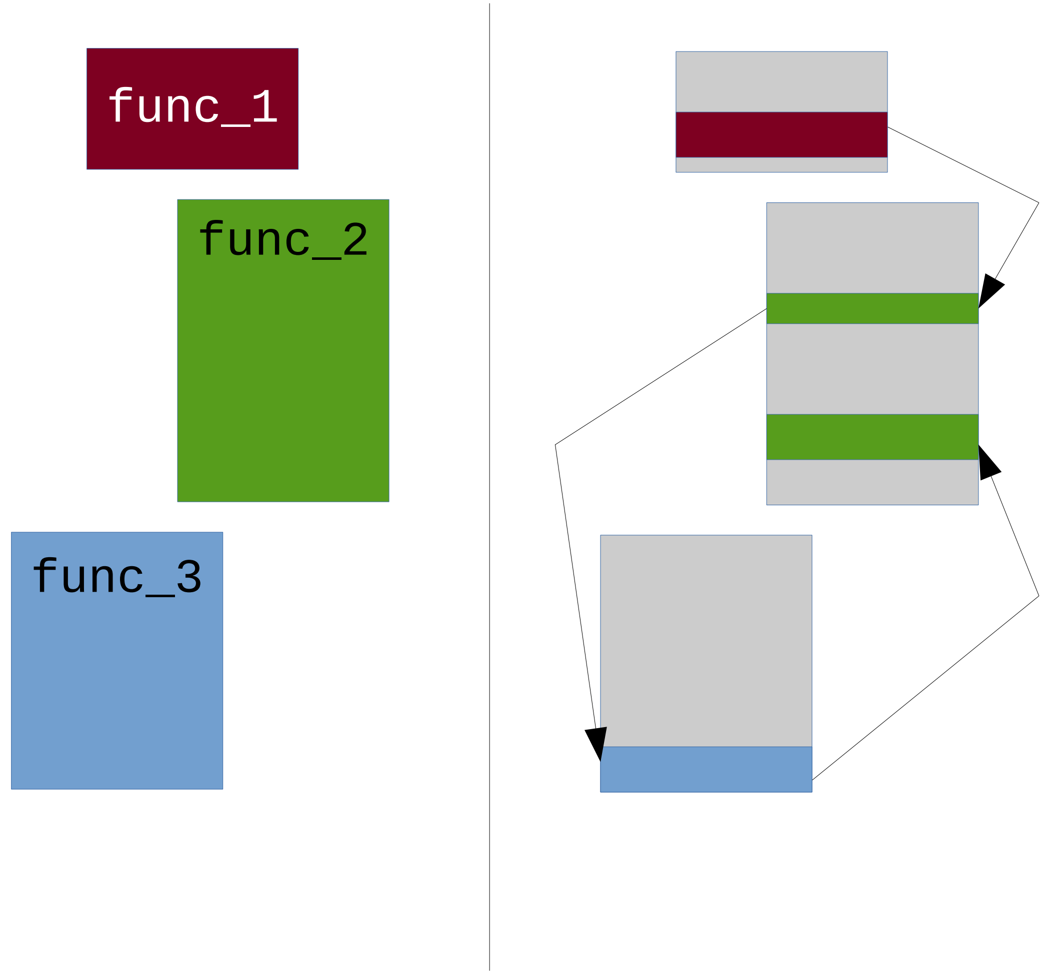

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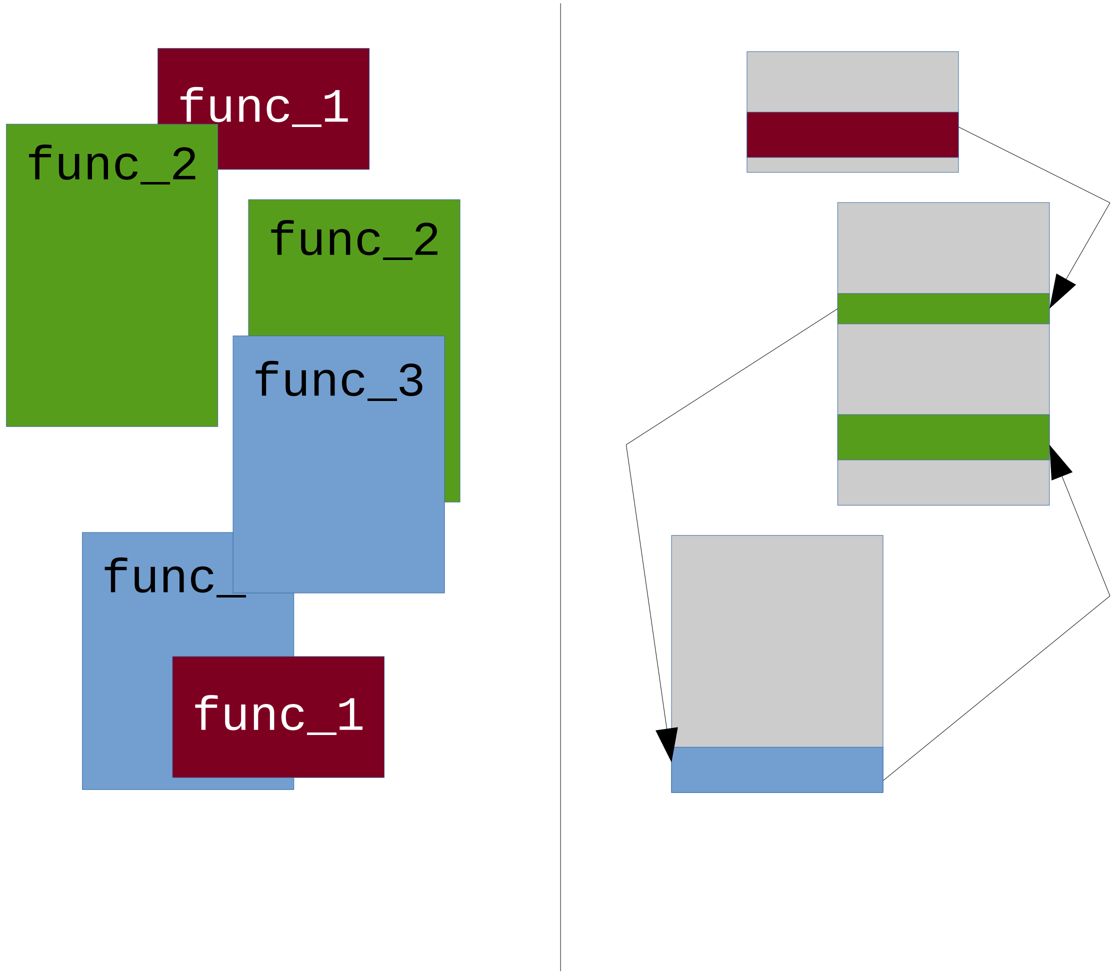

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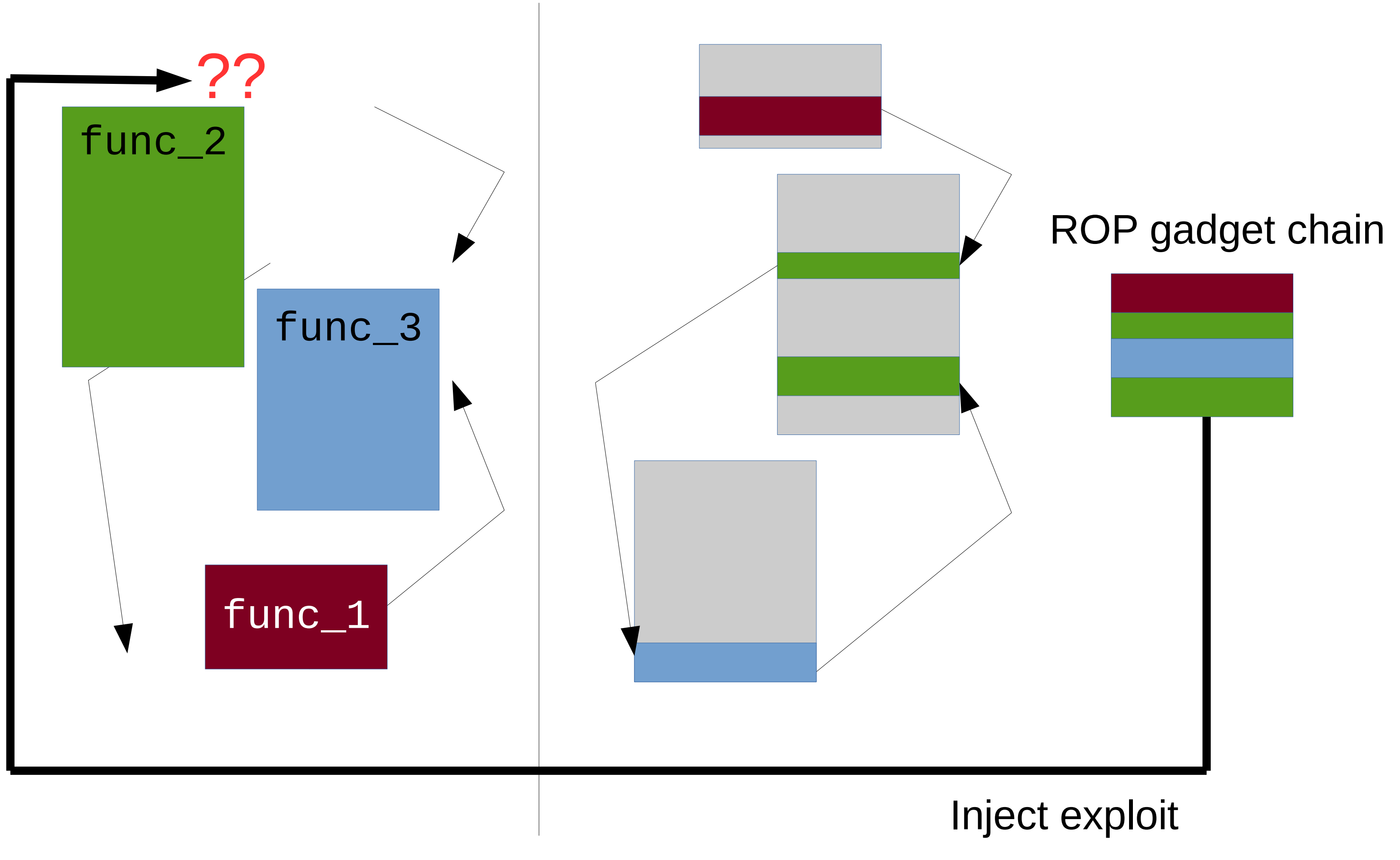

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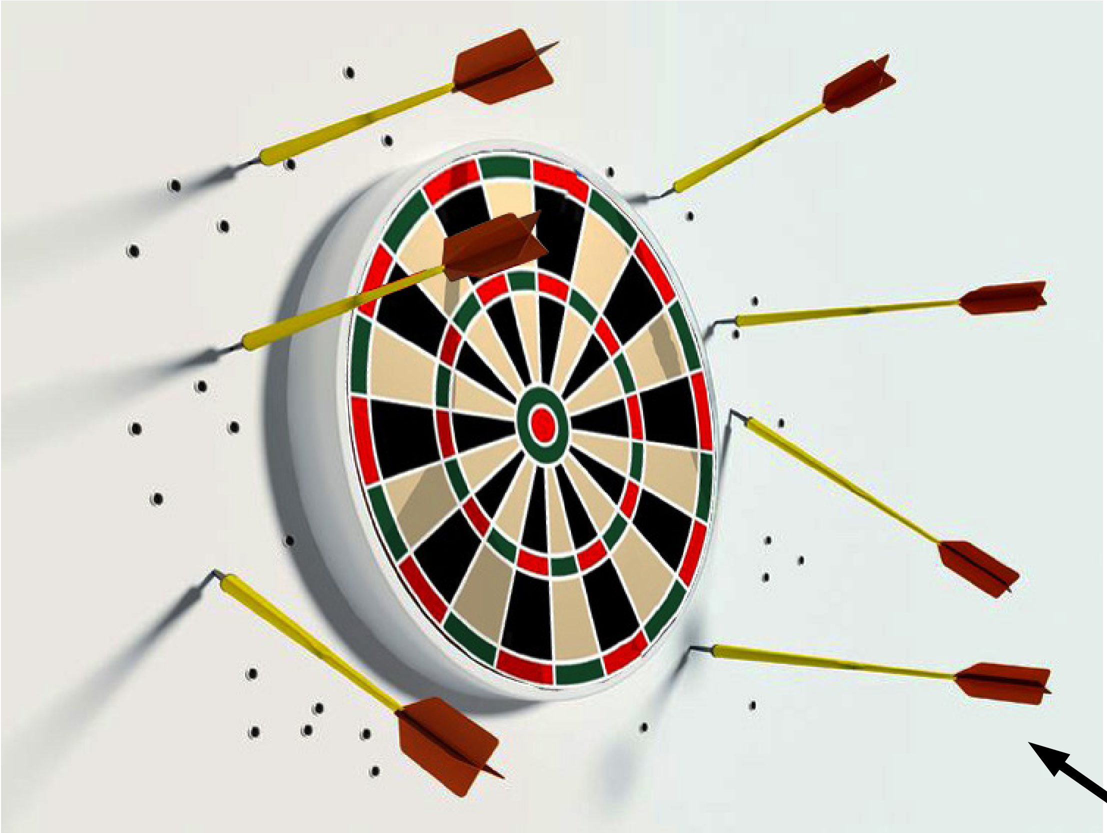

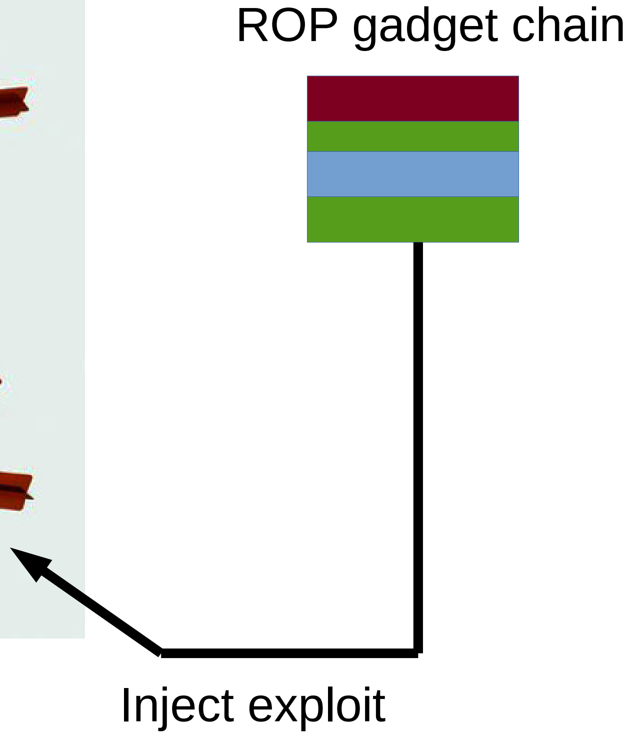

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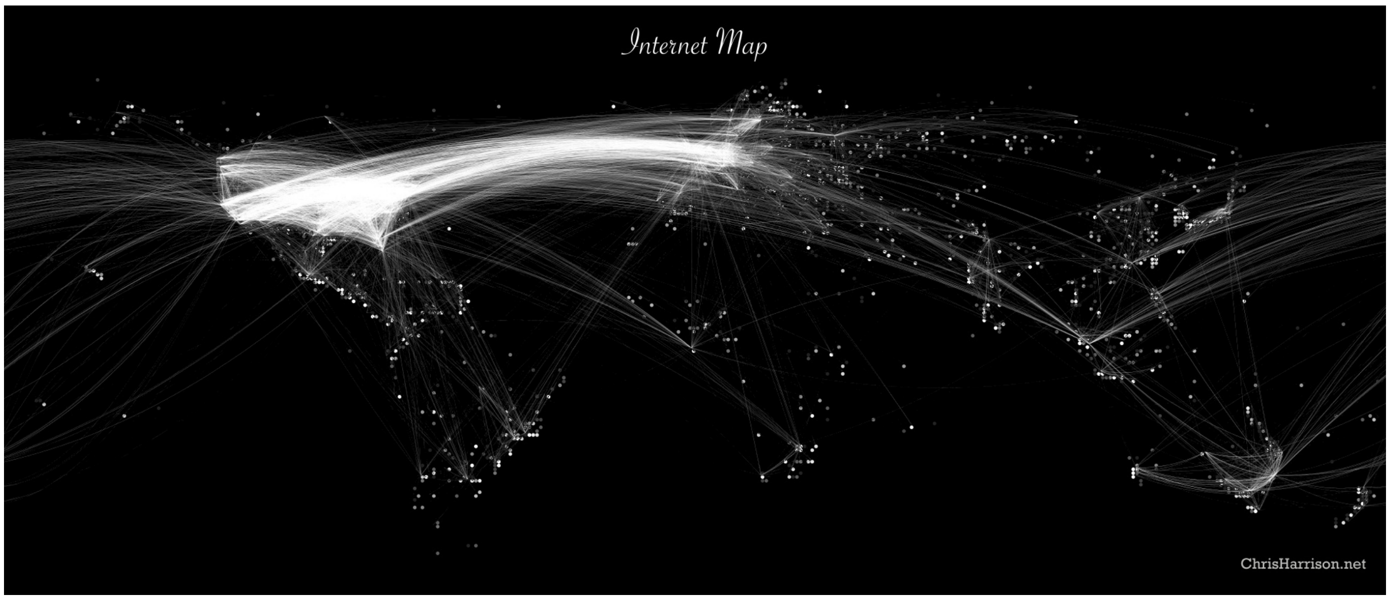

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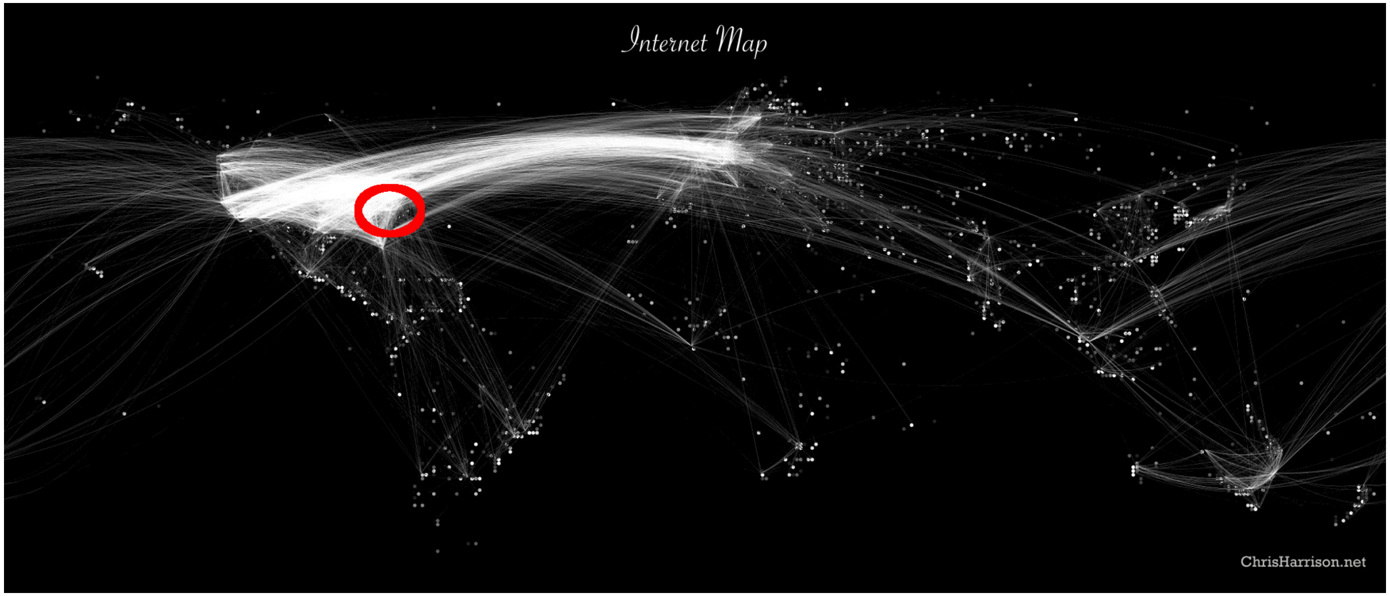
    - one memory disclosure can only travel 820 miles!



What Is Shuffler?

- Defense based on continuous re-randomization
  - Defeats all known code reuse attacks
  - 20-50 millisecond shuffling, scales to 24 threads
- Fast: bounds attacker’s available time
  - Defeats even attackers with zero network latency
- Deployable:
  - Binary analysis w/o modifying kernel, compiler, ...
- Egalitarian:
  - Shuffler runs in same address space, defends itself

Outline

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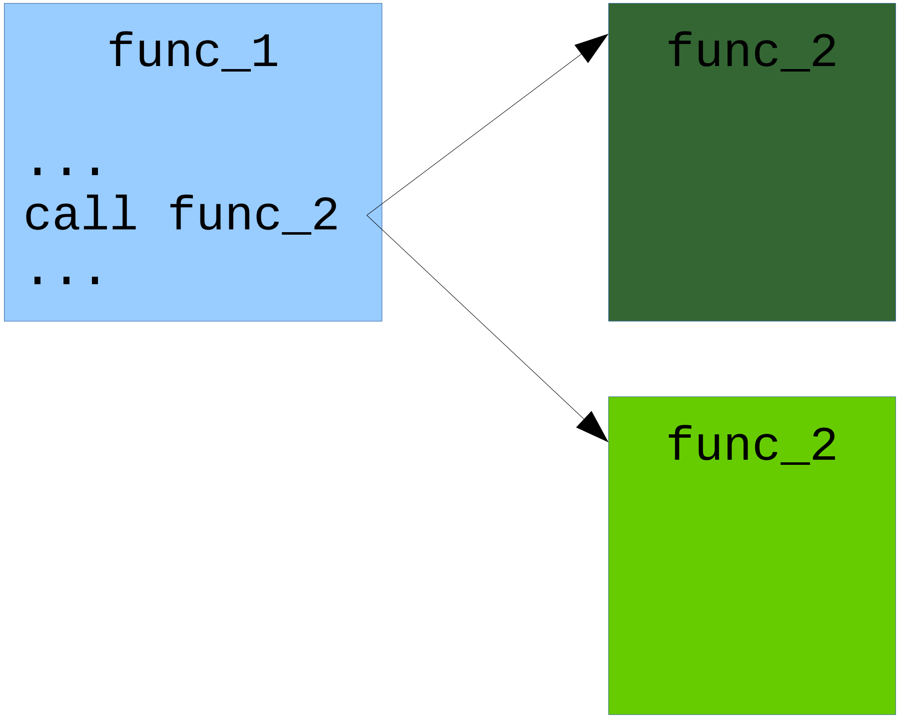
1. Continuous re-randomization
2. Accelerating our randomization
3. Binary analysis and egalitarianism
4. Results and Demo

Continuous Re-Randomization

- Easy to copy code & fix direct references



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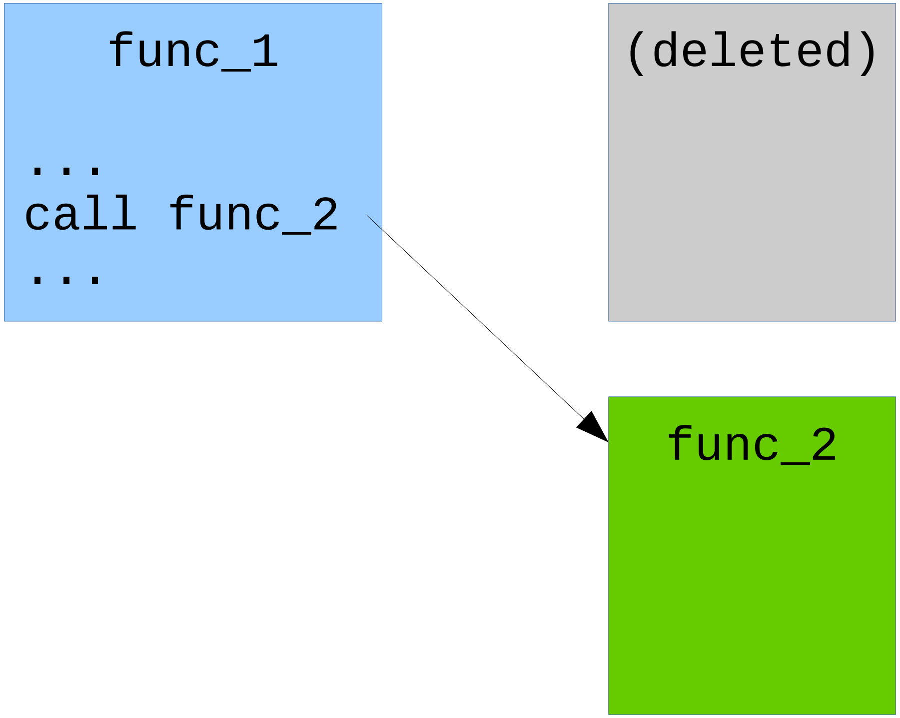

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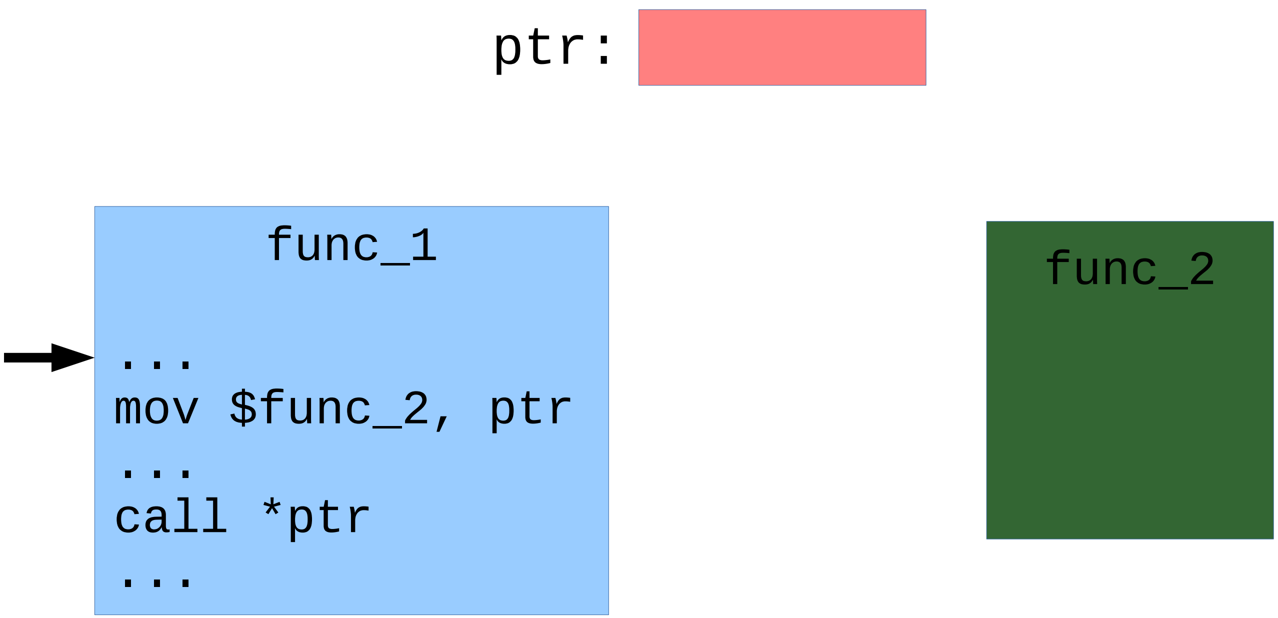

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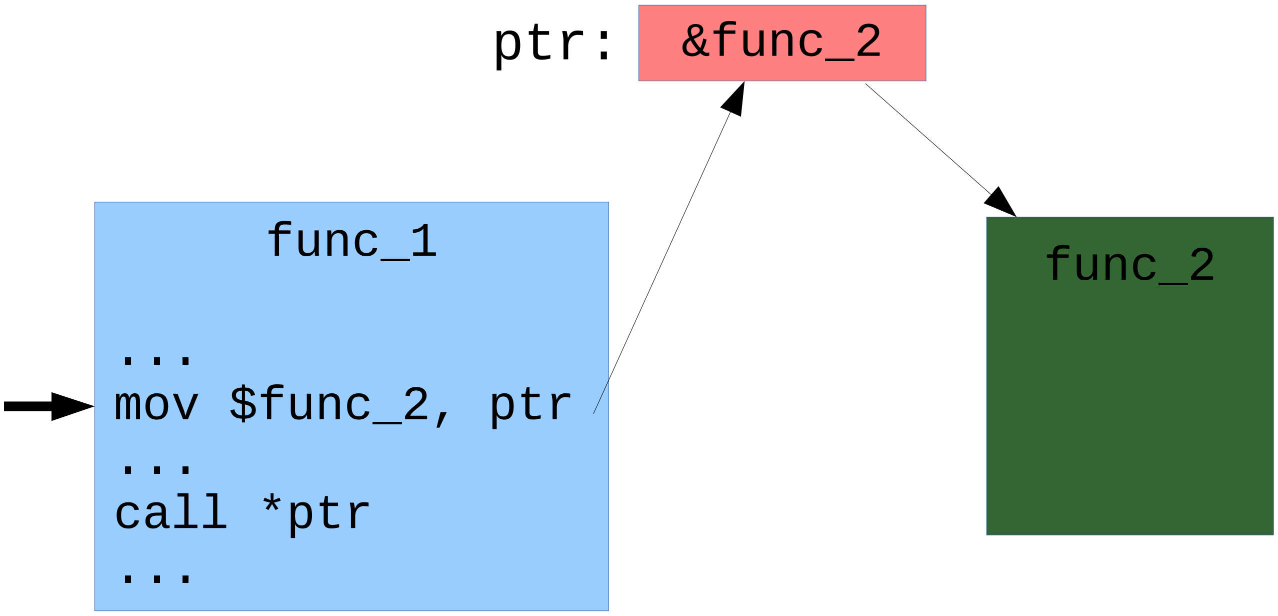

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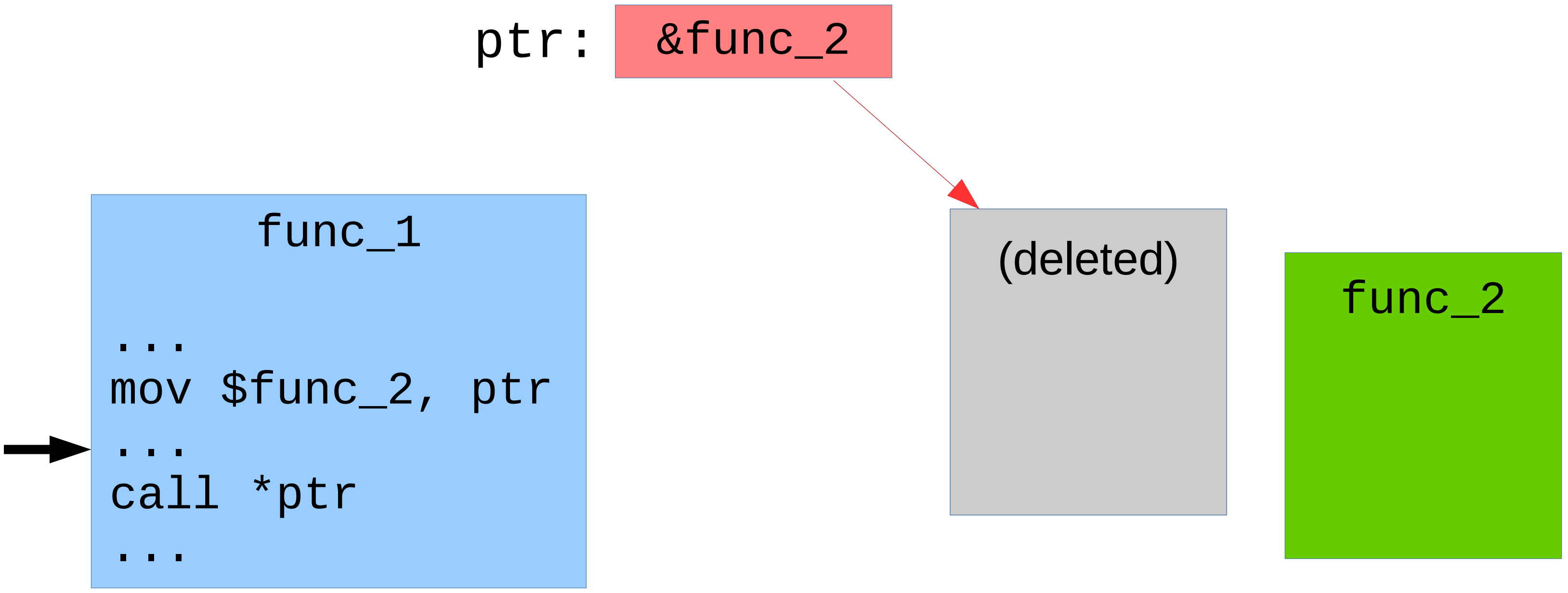

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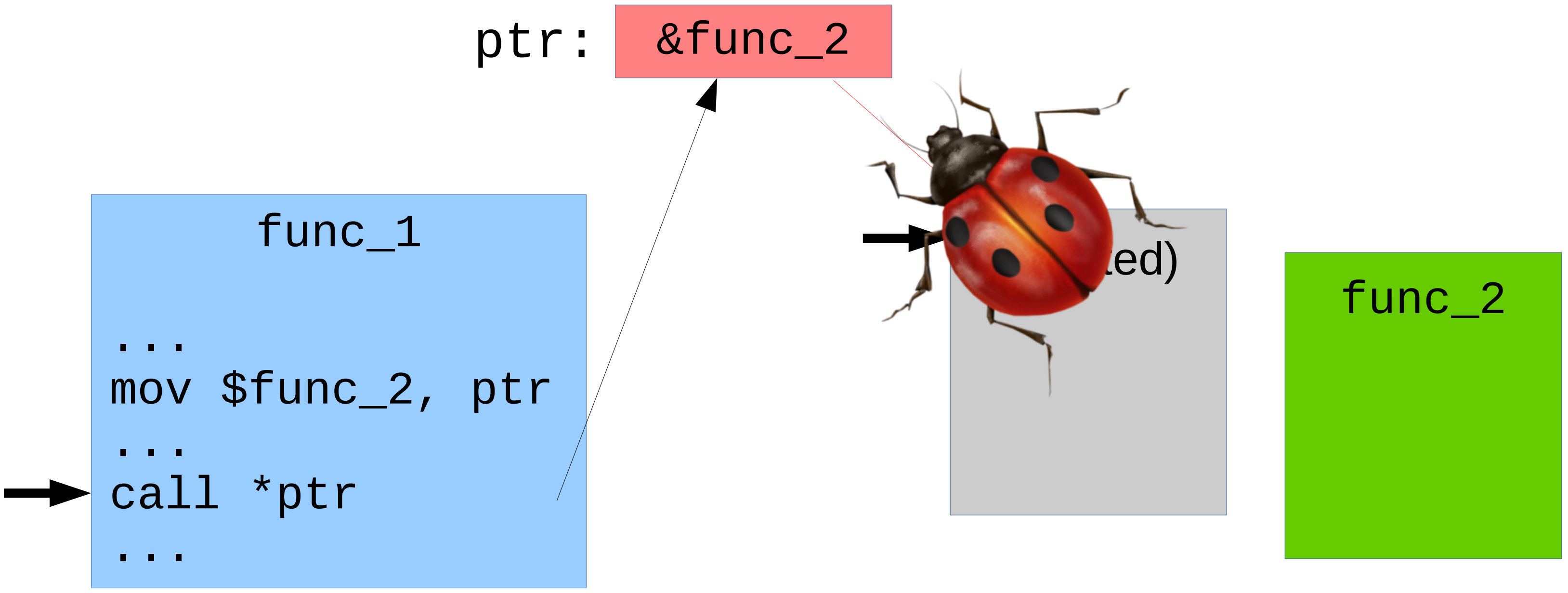

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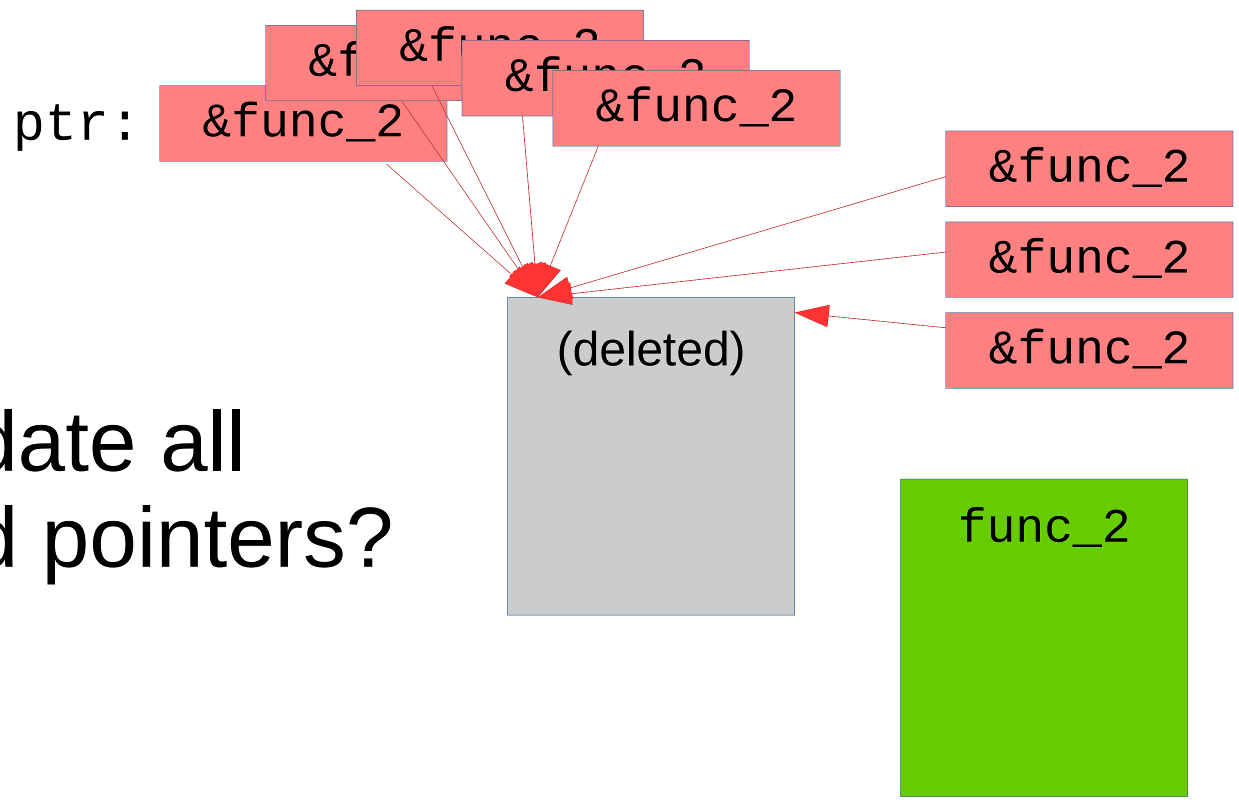
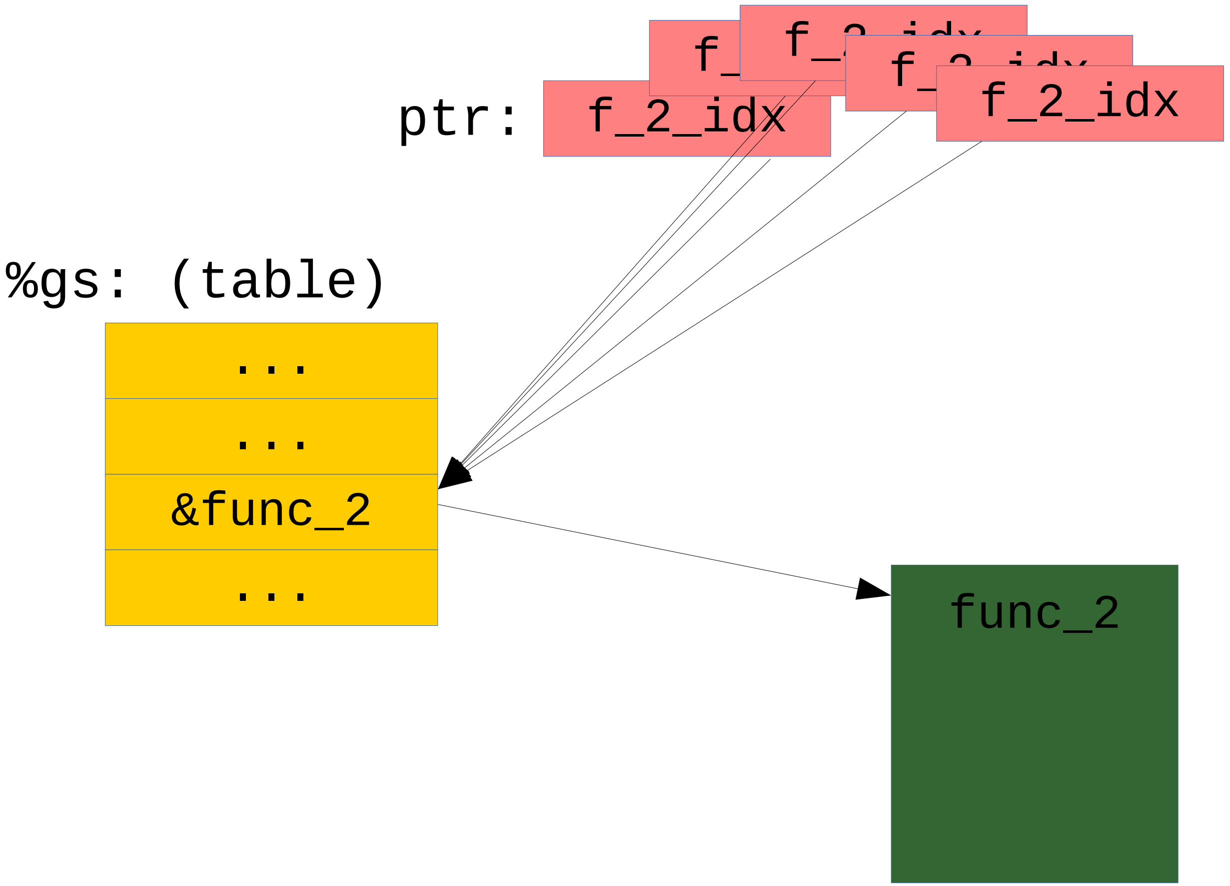


- How to update all propagated pointers?

Continuous Re-Randomization

- Solution: add extra level of indirection



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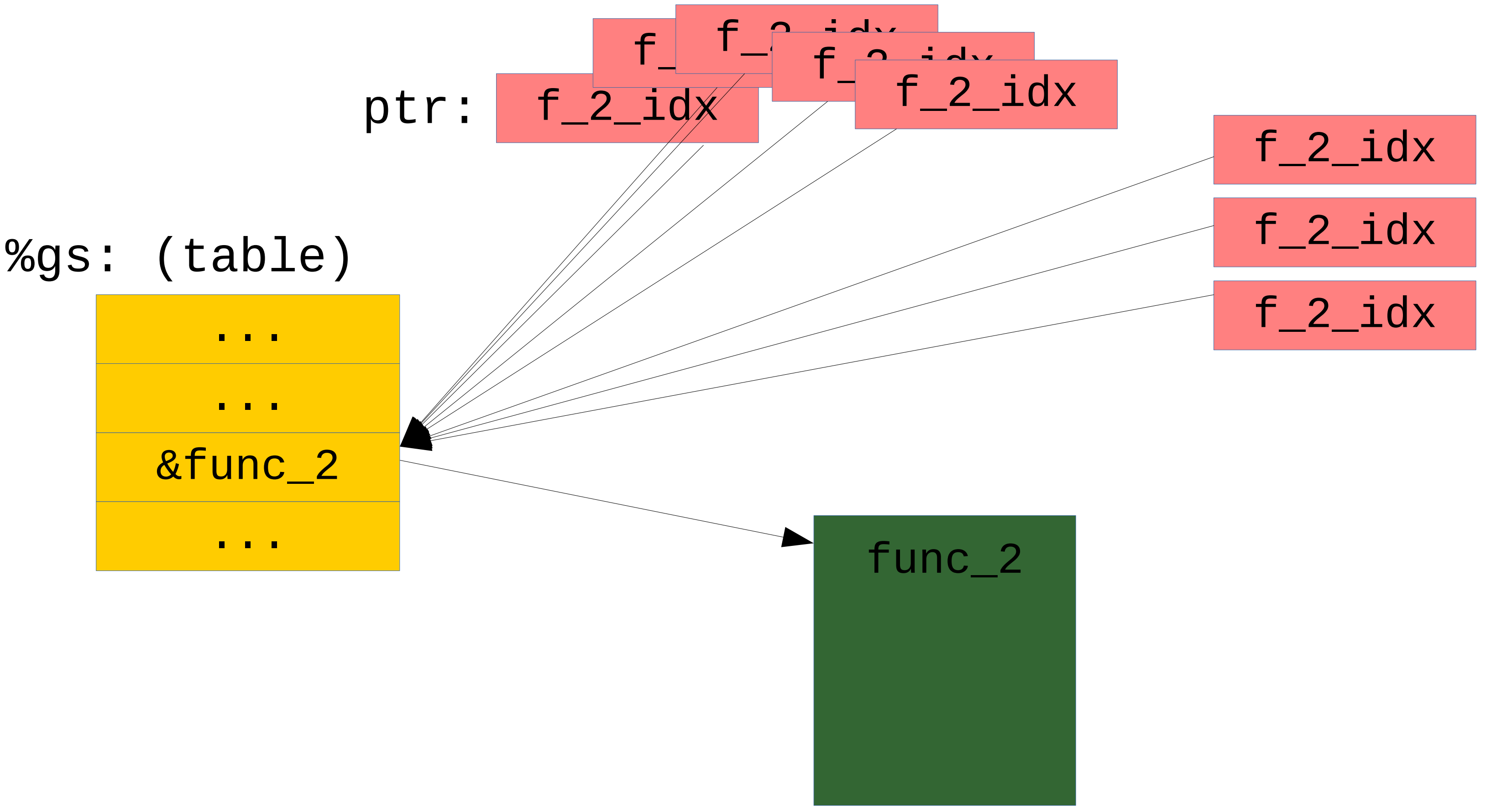

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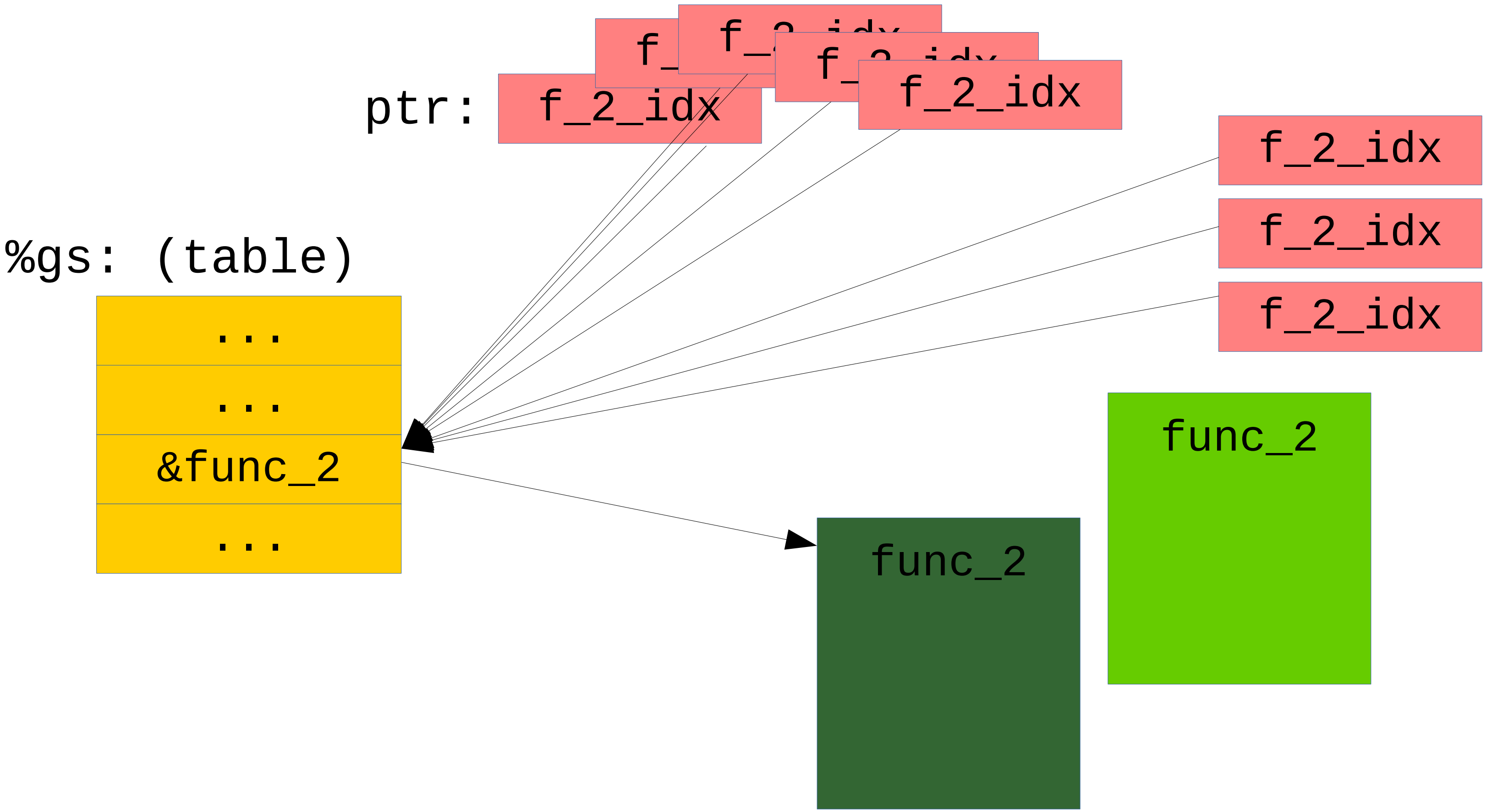

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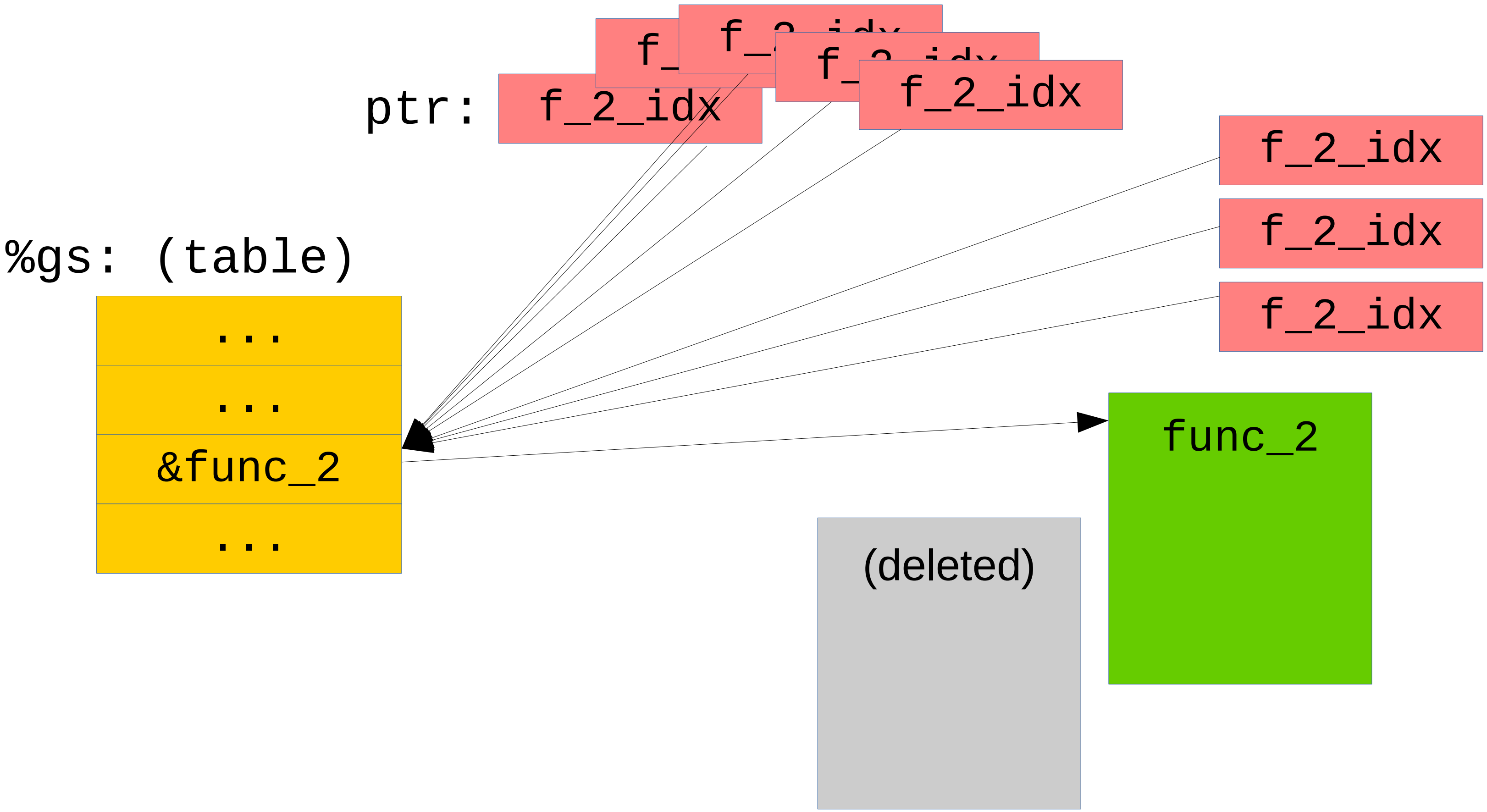

Code Pointer Abstraction

- Transforming *code_ptr into **code_ptr
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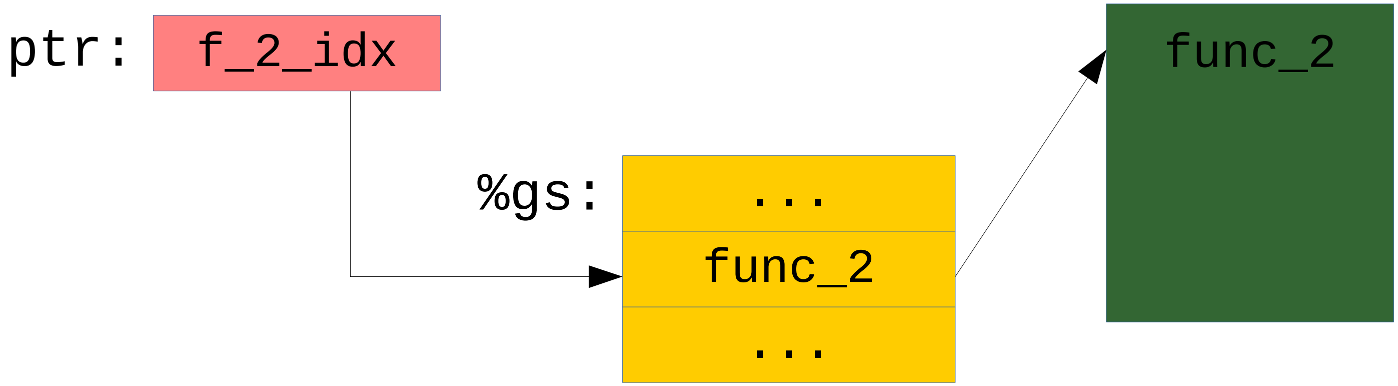

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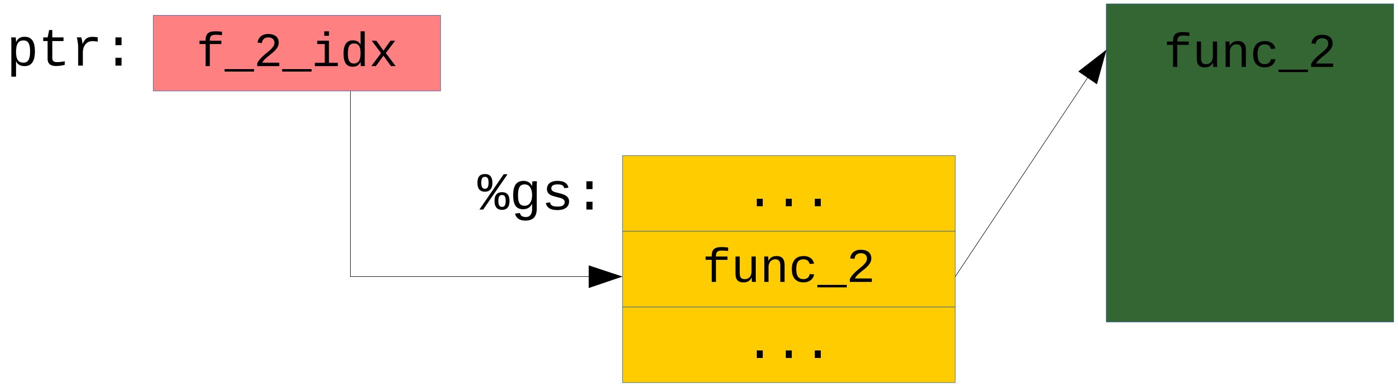

Rewrite call sites

```
    callq *%rax

=> callq *%gs:(%rax)
```

Rewrite initialization points

```
    mov  $0x40054d, %rax

=> mov  $0x20, %rax
```

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- Return addresses are code pointers too
- Could use code pointer table, but inefficient
  - call/ret instructions highly optimized
- Alternative mechanism – **correct** and **hidden**
  - Use normal call instructions
  - Encrypt return addresses with XOR key

Return Address Encryption

- Prevent return address disclosure

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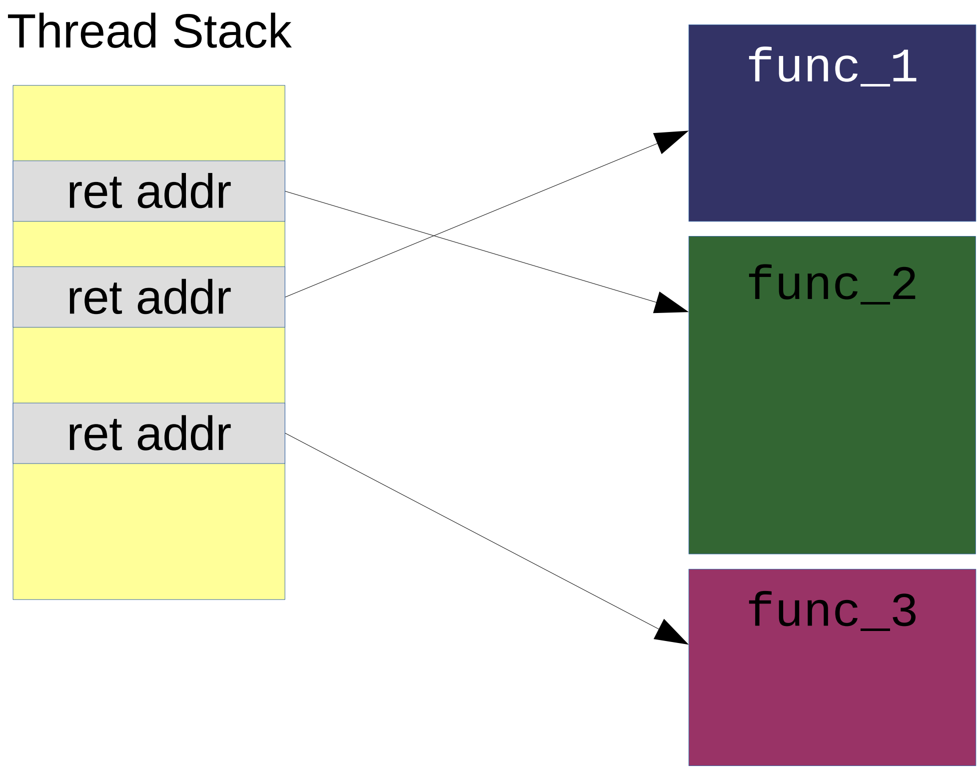

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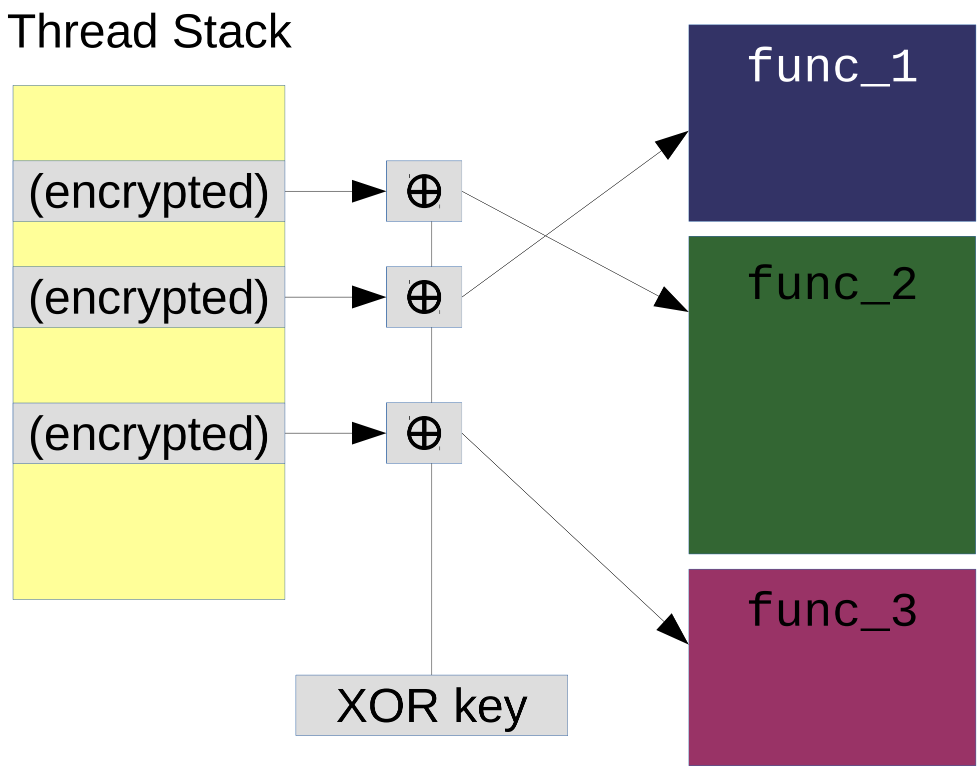

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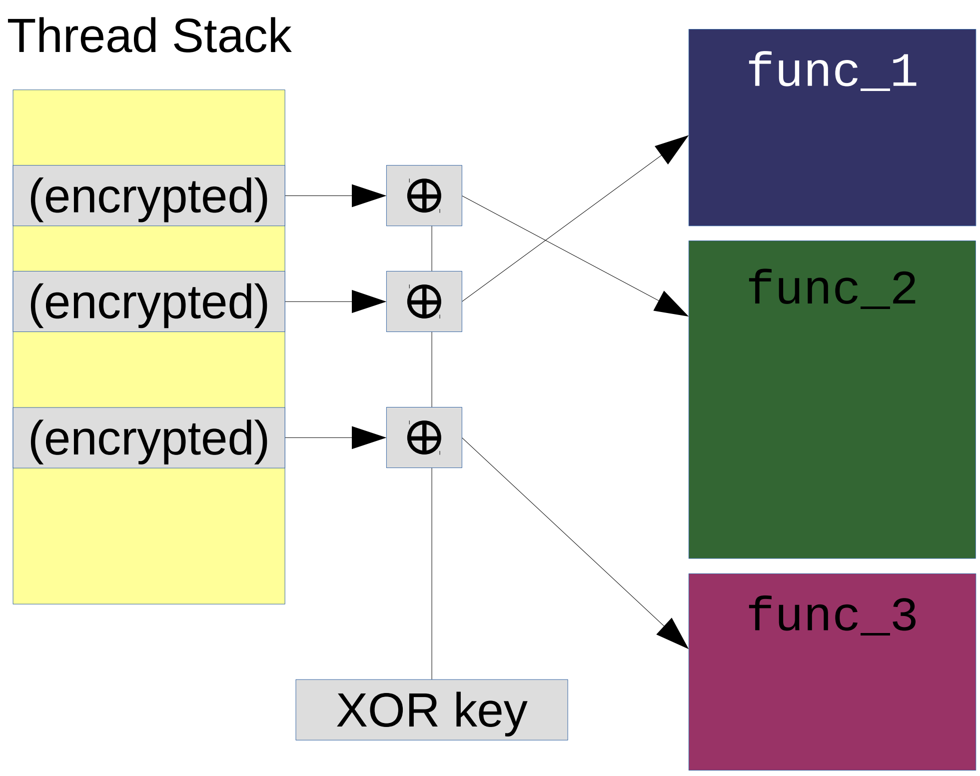


```
func:
    ; original code
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```
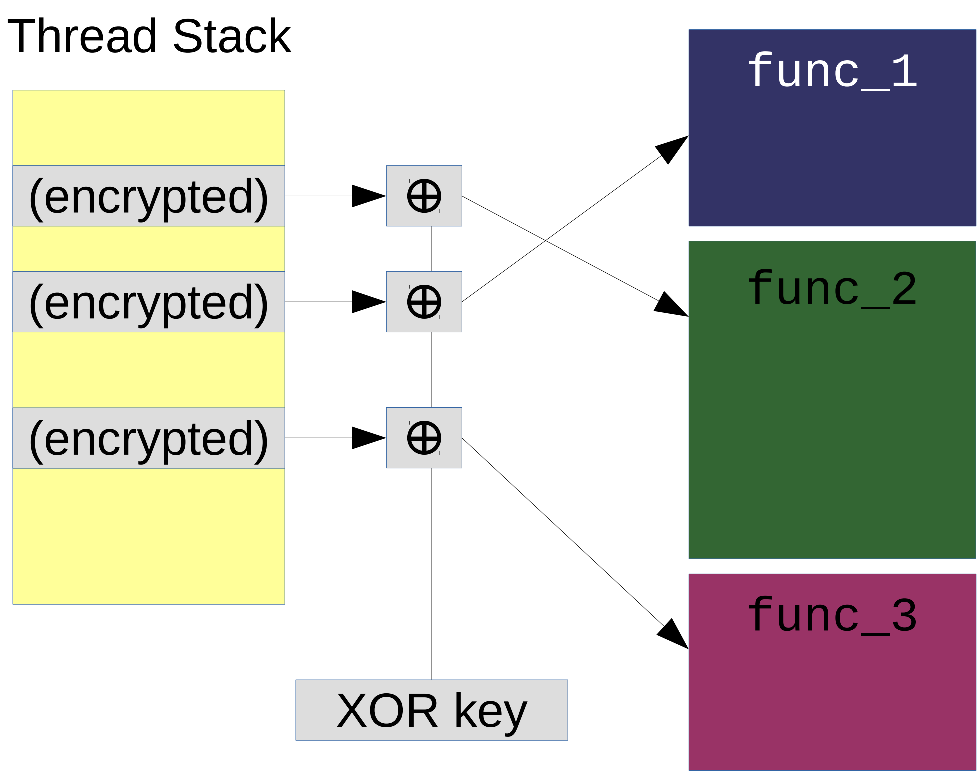

Return Address Encryption

- Prevent return address disclosure
- We use binary rewriting (expand basic blocks)




```
func:
    mov    %fs:0x28,%r11
    xor    %r11,(%rsp)
    ; original code
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    ret
```
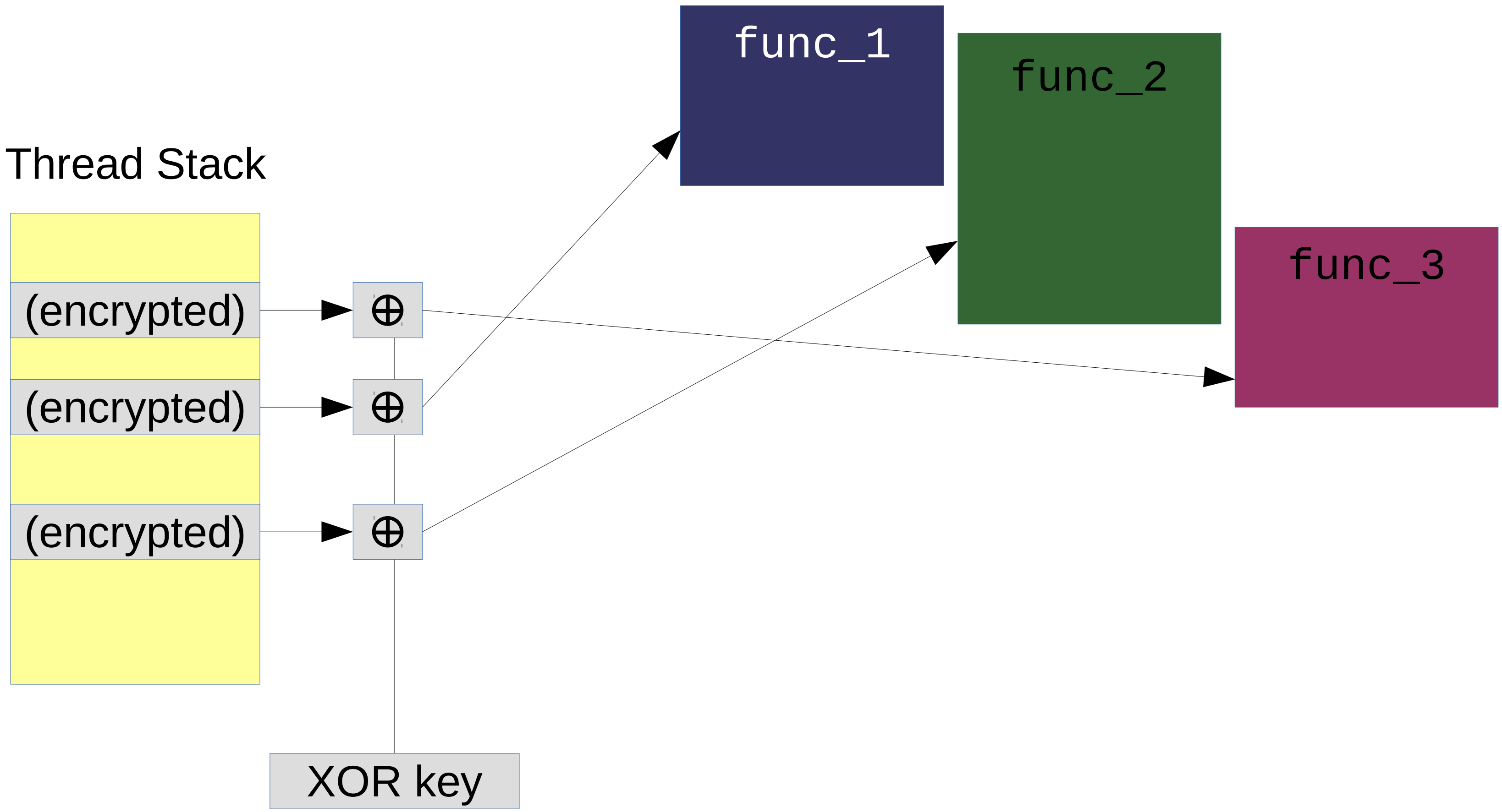

Return Address Migration

- Unwind stack and re-encrypt new addresses



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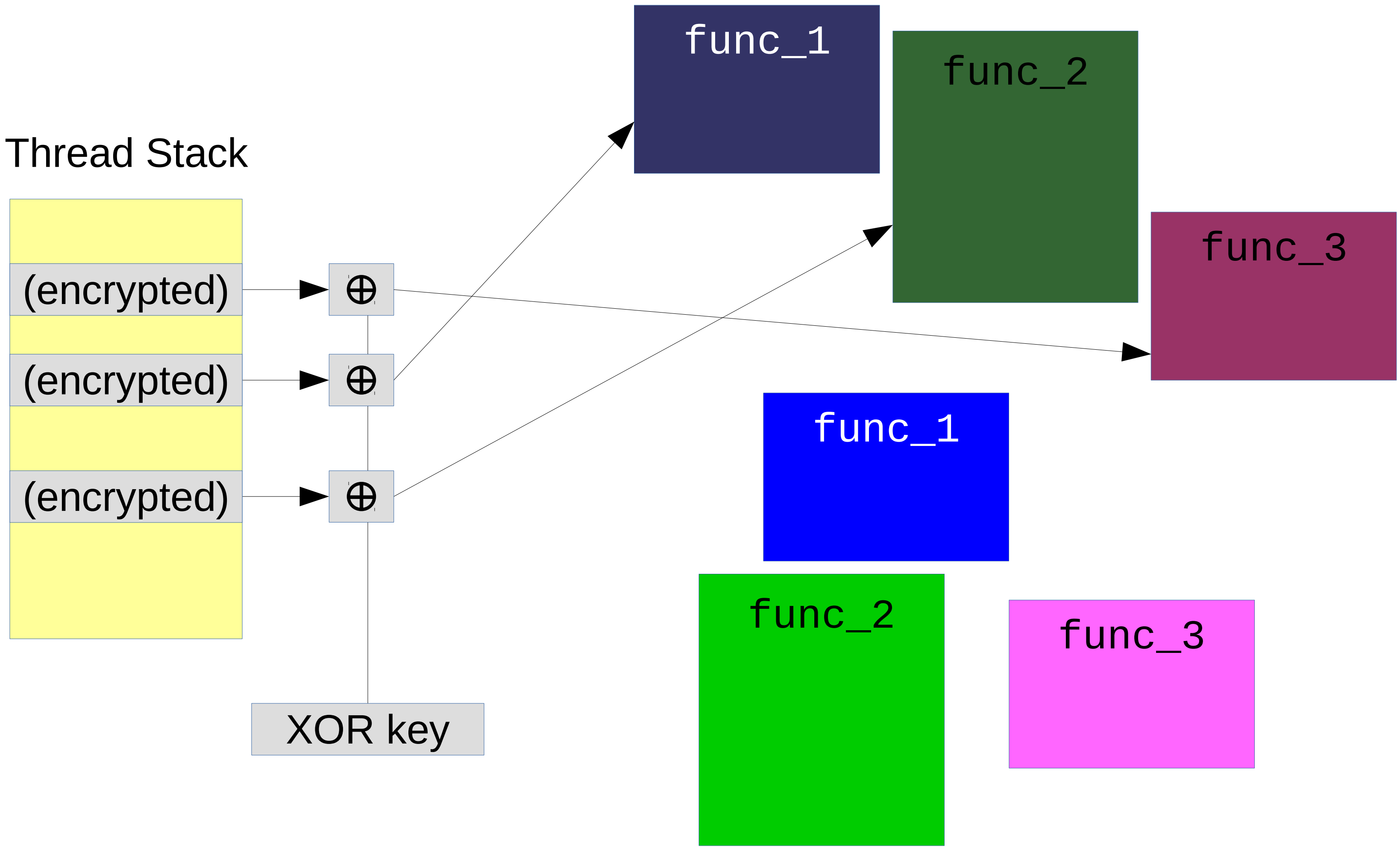

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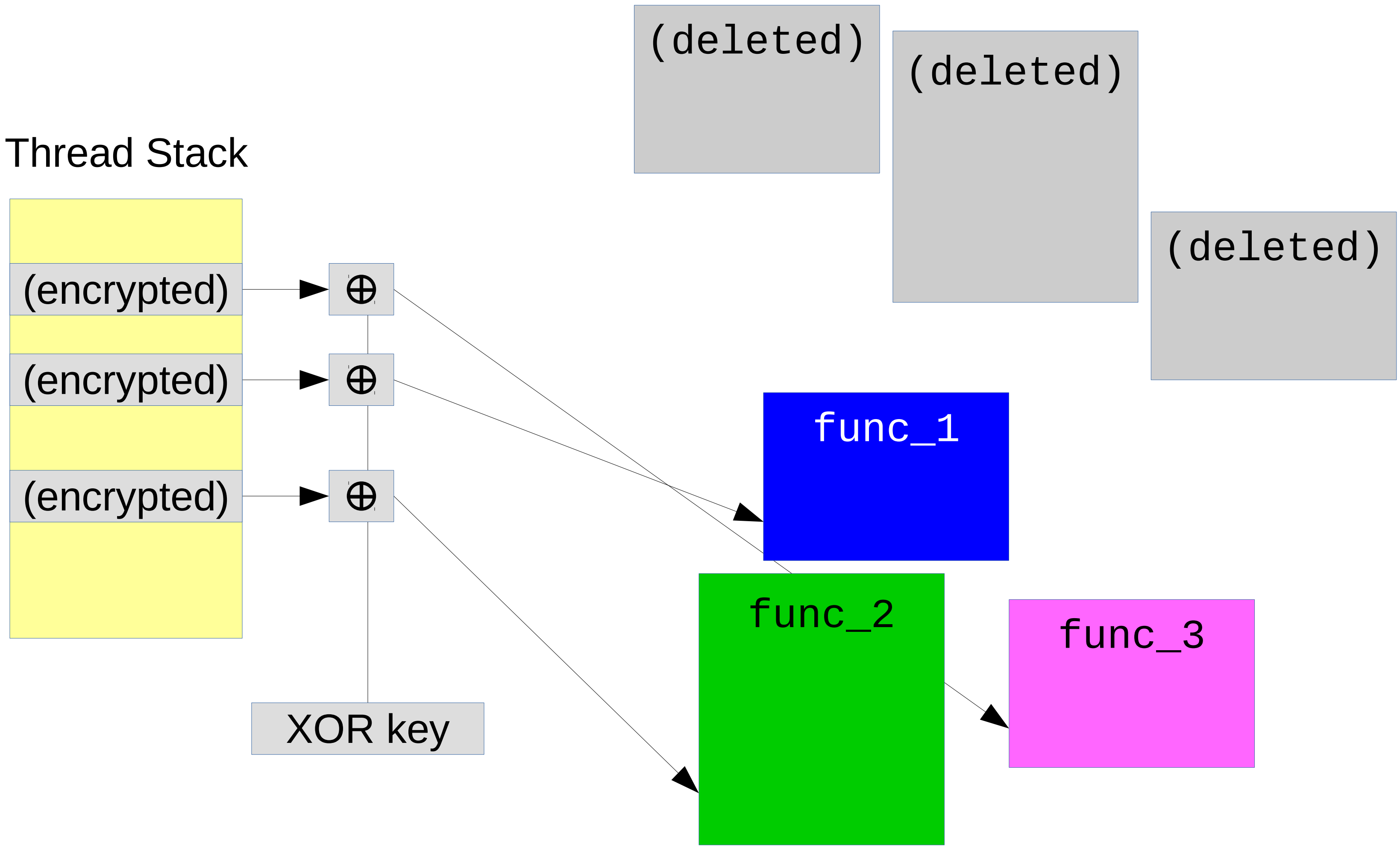

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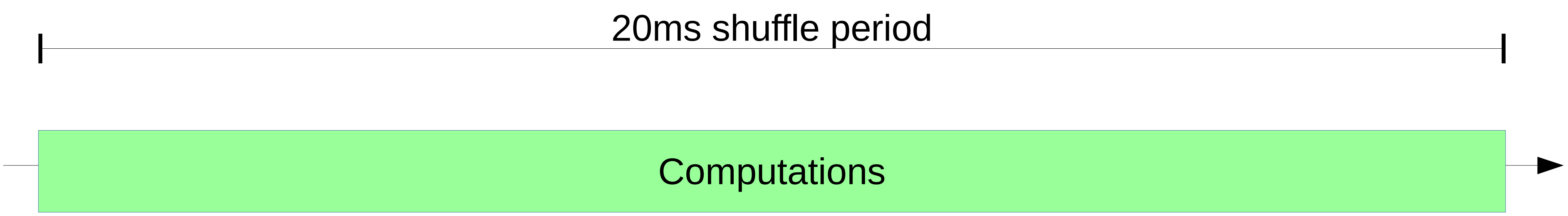

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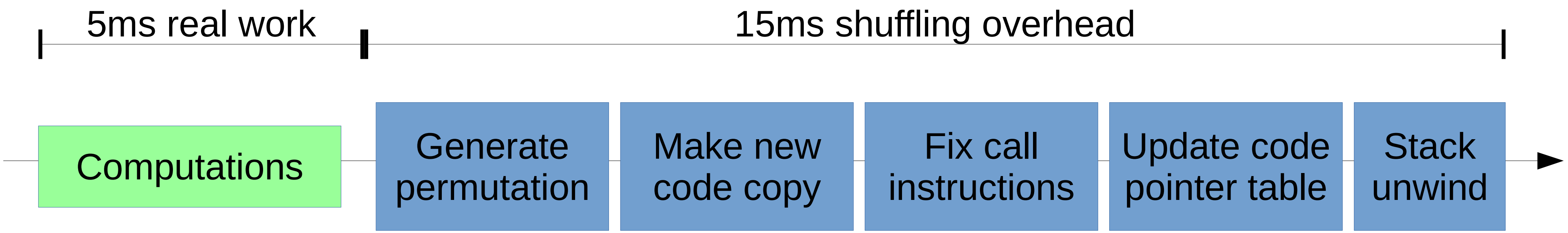

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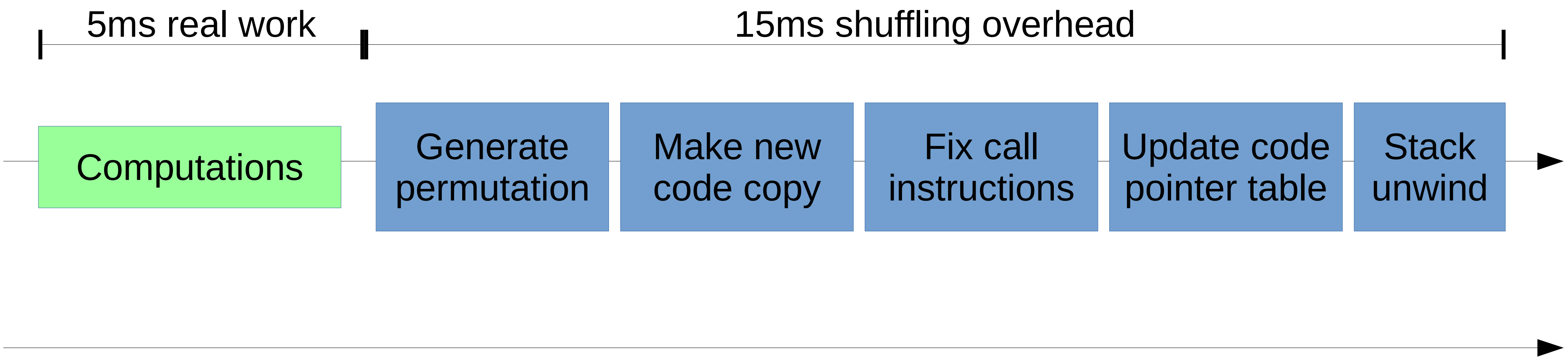

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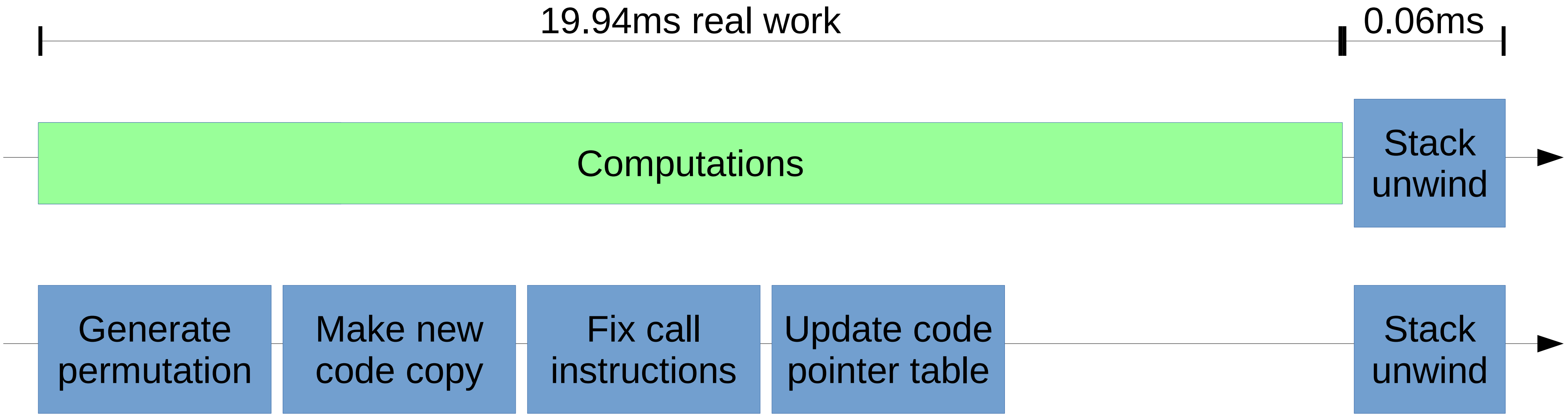

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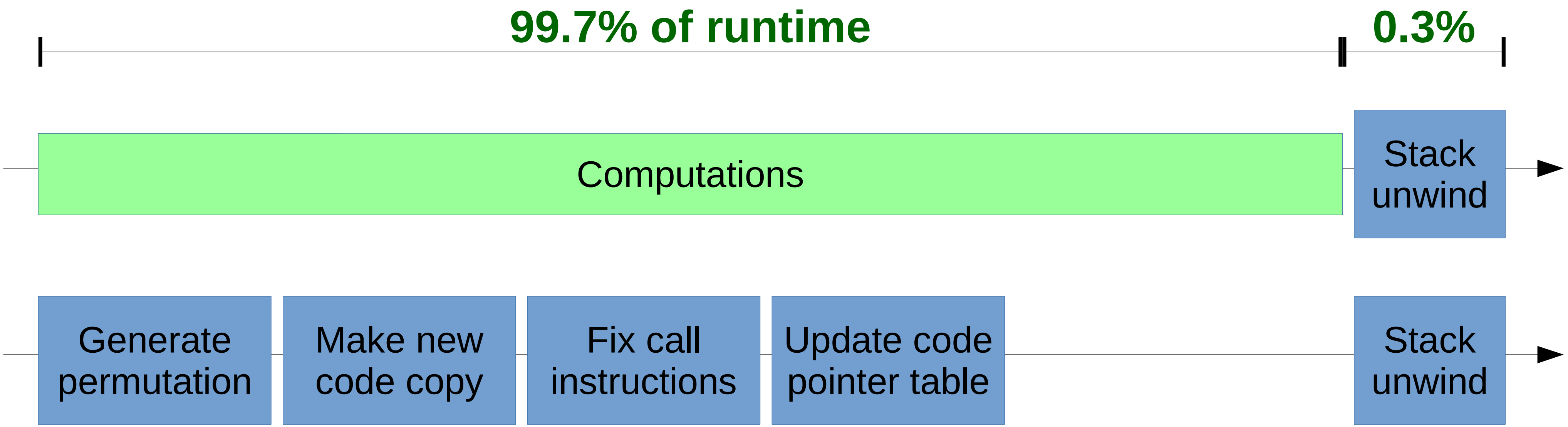
- Each thread unwinds its own stack in parallel



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Relocations (meta-data)

Augmented Binary Analysis

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  - Relocations, to find all code pointers (--emit-relocs)
    - ask linker to preserve relocations

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Relocations (meta-data)

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- Allows accurate and complete disassembly
- Many special cases, but we handle them

Issue	Description	How to handle
Missing symbol sizes	Internal GCC functions have a symbol size of zero.	Hard-code sizes; `_start` is 42 bytes.
Fall-through symbols	Functions implicitly fall through to the following function.	Attach a copy of the following code.
Overlapping symbols	Some functions are a strict subset of an enclosing function.	Binary search for targets very carefully.
Symbol aliases	Symbol tables have many names for the same function.	Pick one representative name.
Ambiguous names	One LOCAL name, multiple versions (`bsloww` in libm).	Look up address resolved by the loader.
Pointers to static functions	For pointers to functions within the same module, the offset is known, and object files contain no relevant relocations.	Determine if `lea` instructions target a known symbol (not completely sound).
`noreturn` function calls	GCC always generates a NOP after calls to `noreturn` functions like `longjmp`, but omits unwind information.	Detect when at a NOP following a call and use unwind info from at the call.
COPY relocations	Object initialized in one library, then `memcpy`'d to another.	Track data symbols, not just code.
IFUNC symbols	Return pointer to actual function to call (cached in PLT).	Statically evaluate from `lea` refs.
Conditional tail recursion	Does not appear in normal GCC-generated code. Used in hand-coded assembly by glibc (`lowlevellock.h`).	Can do XOR'ing both before and after, works whether or not the jump is taken.
Indirect tail rec.	Difficult to tell apart from jump-table jumps.	Use a function epilogue heuristic.
Finding jump tables	Jump tables are not clearly delineated.	See the text for a discussion on this.

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- Most defenses operate at higher privilege level
  - i.e. kernel, hypervisor, hardware
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- Most defenses operate at higher privilege level
  - i.e. kernel, hypervisor, hardware
  - Or else declare their own code “trusted”
- Shuffler is *egalitarian*
  - Same level of privilege, no system modifications
  - Defends itself from attack

Egalitarian Bootstrapping

- Problem: transformations break original code
  - e.g. memcpy uses code pointers

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  - e.g. memcpy uses code pointers

memcpy's code

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Rewrite `main`, `printf`, `...`, `memcpy`, `...`

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New memcpy code

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Invalidates `memcpy` jump table

But rewrite process uses (old) `memcpy`

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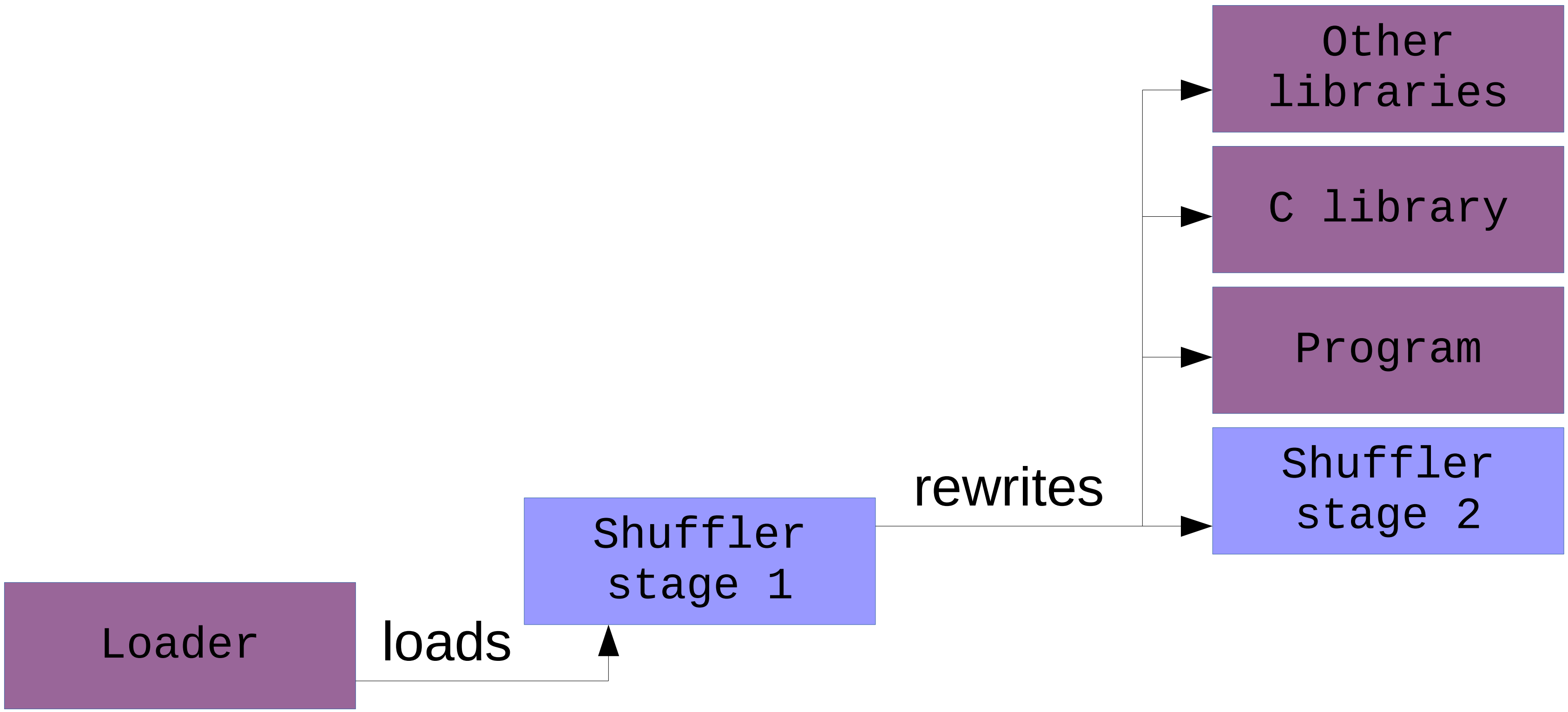

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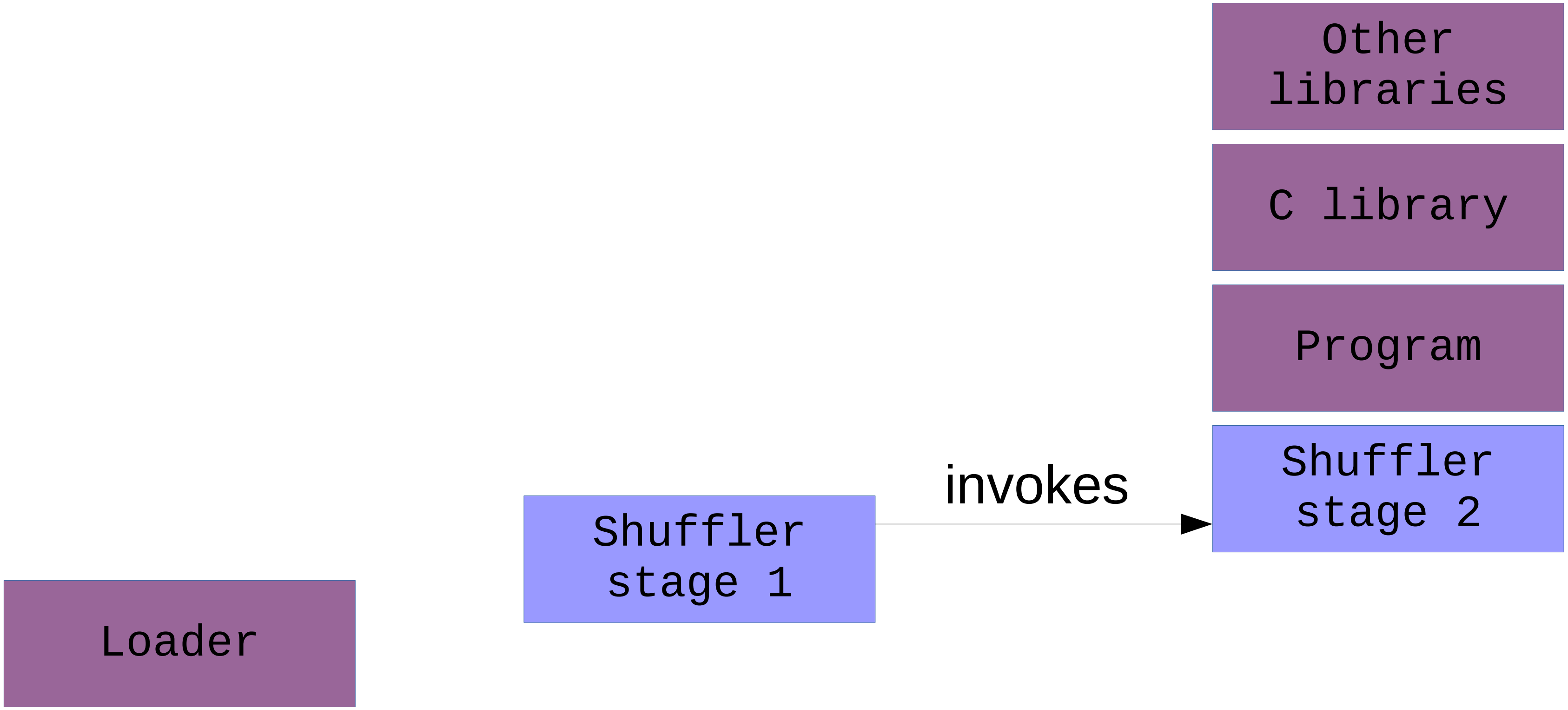

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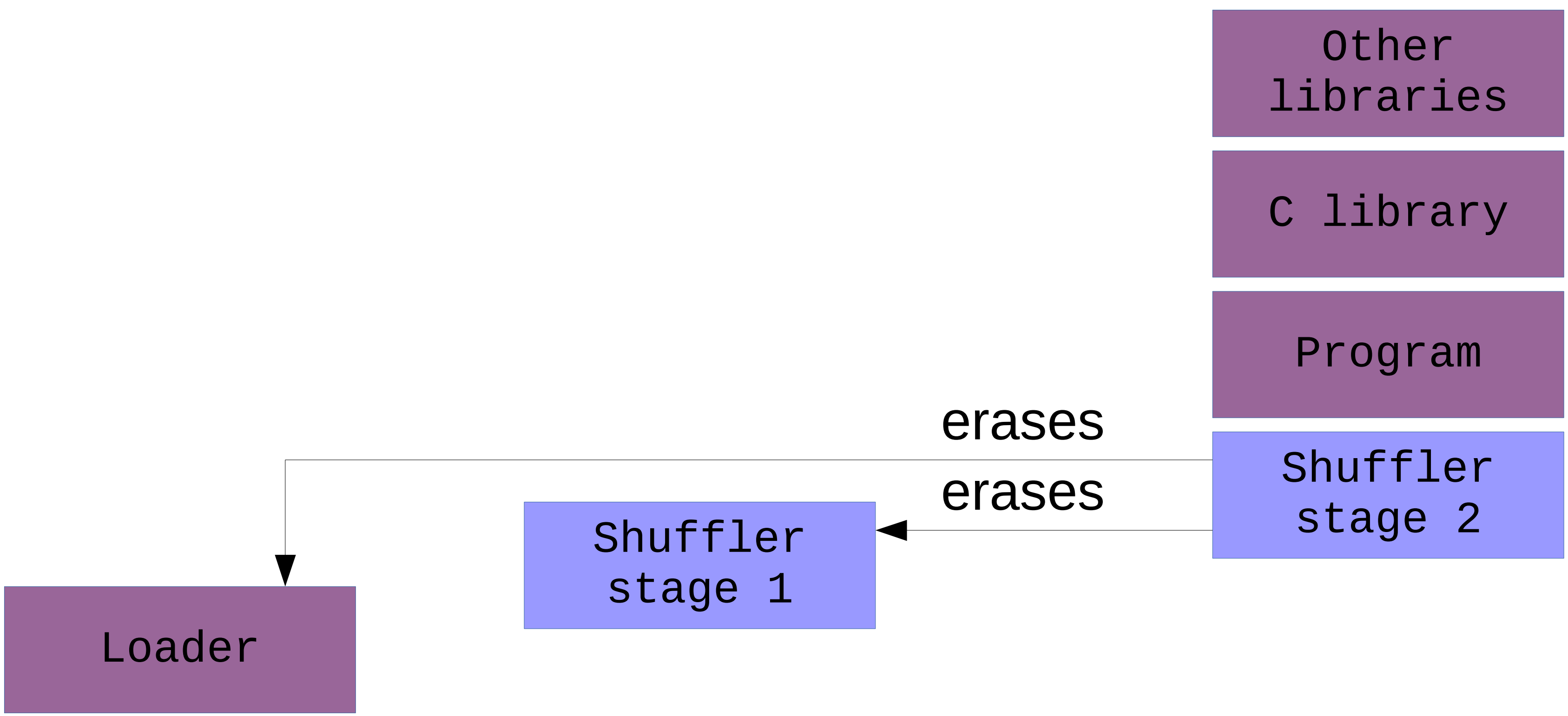

Egalitarian Bootstrapping

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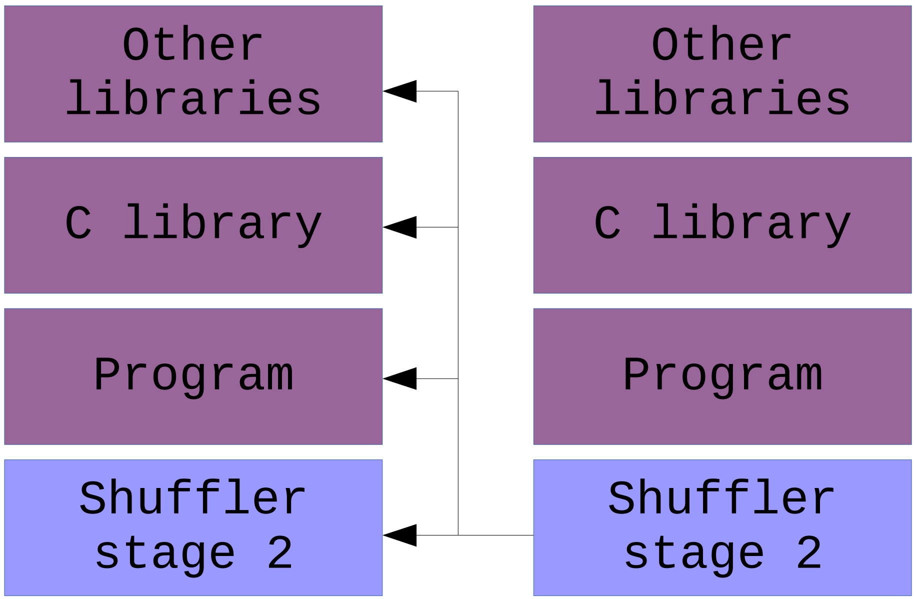

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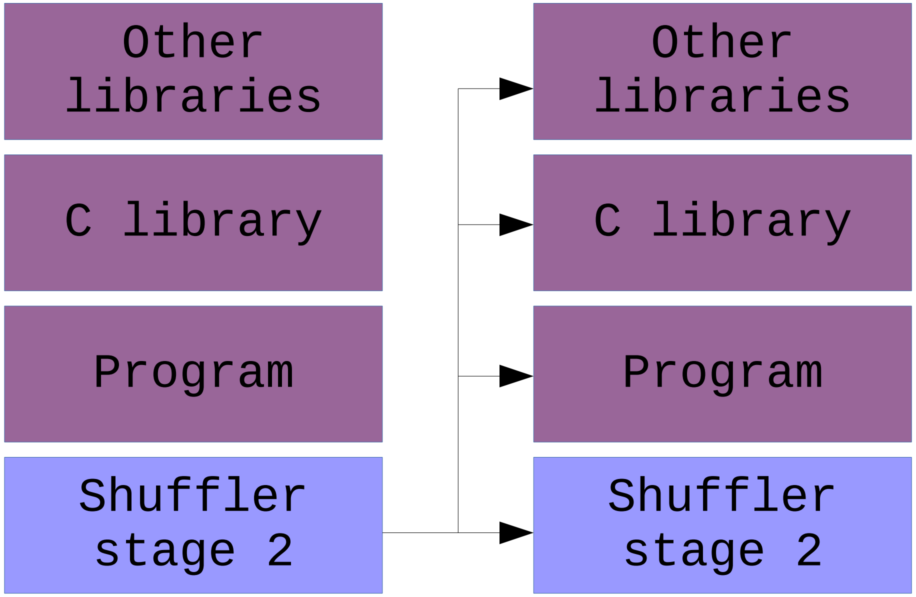

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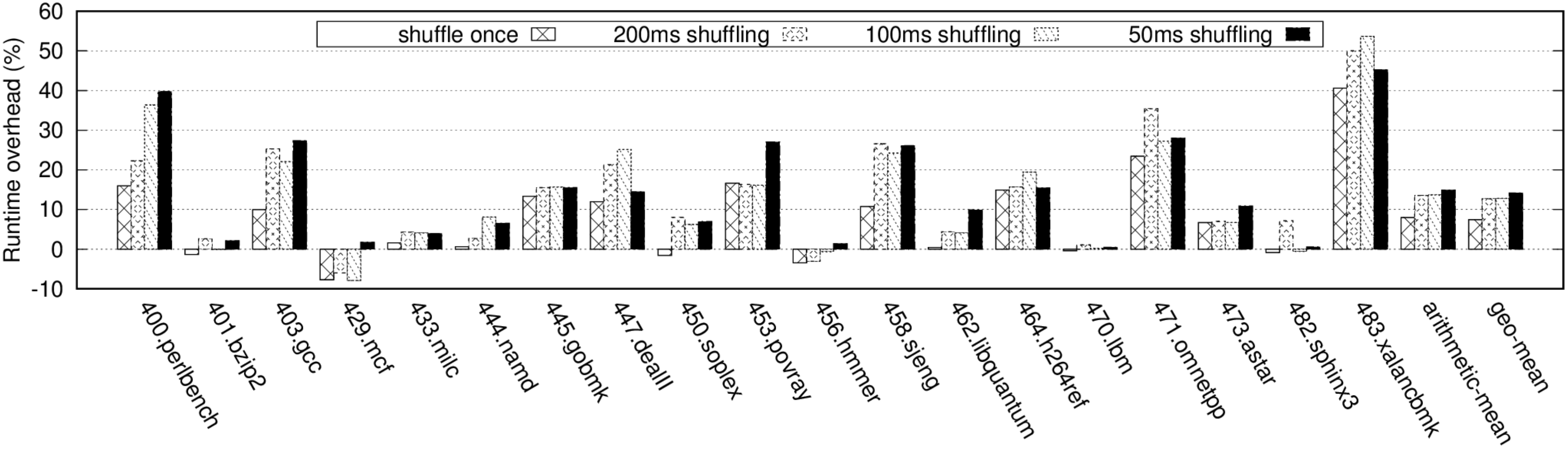
Outline

1. Continuous re-randomization
2. Accelerating our randomization
3. Binary analysis and egalitarianism
4. Results and Demo

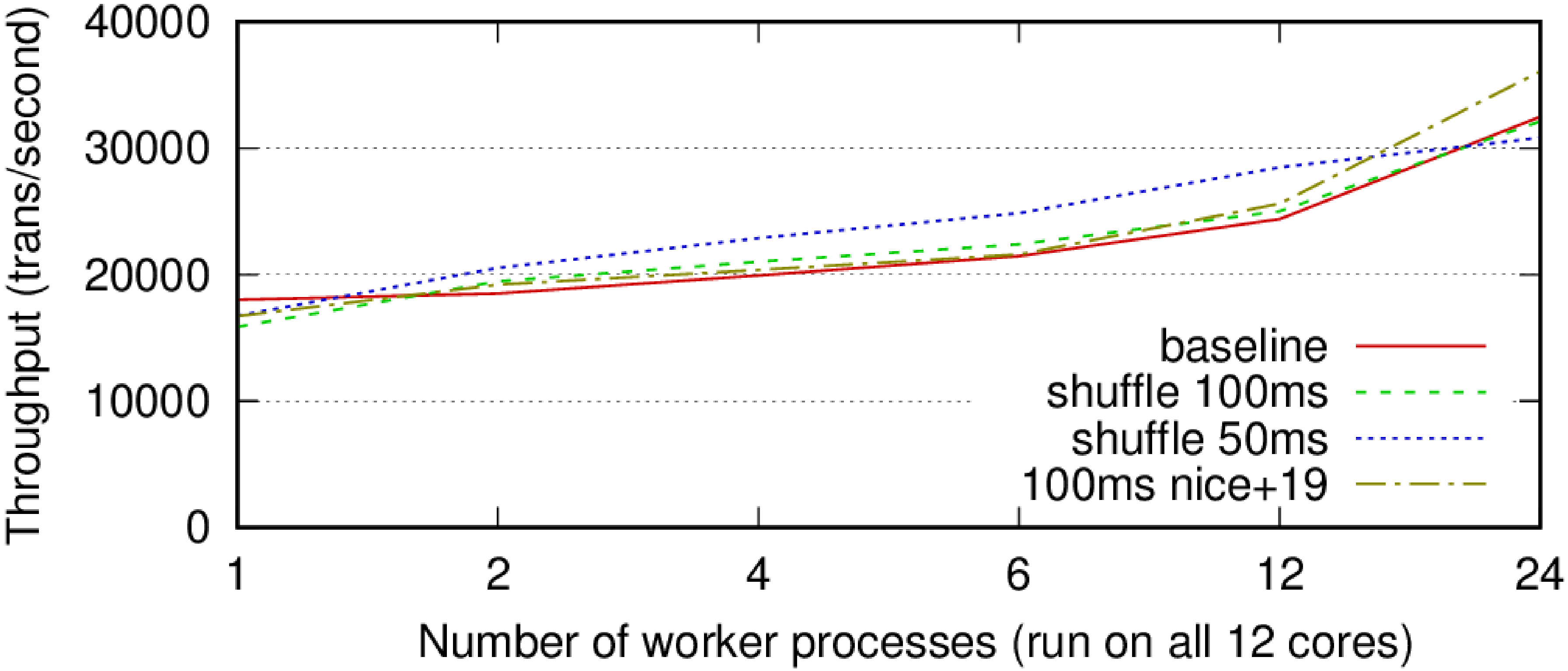
Performance Evaluation

- SPEC CPU overhead at 50ms = 14.9%



Performance Evaluation

- SPEC CPU overhead at 50ms = 14.9%
- Multiprocess Nginx up to 24 workers



Security Evaluation

- Two disclosure-based attack methodologies:
  - Scan many pages for the desired gadgets
    - impacted by disclosure time, network latency
  - Explore gadget space in small number of pages
    - impacted by ROP chain computation time (> 40 seconds)

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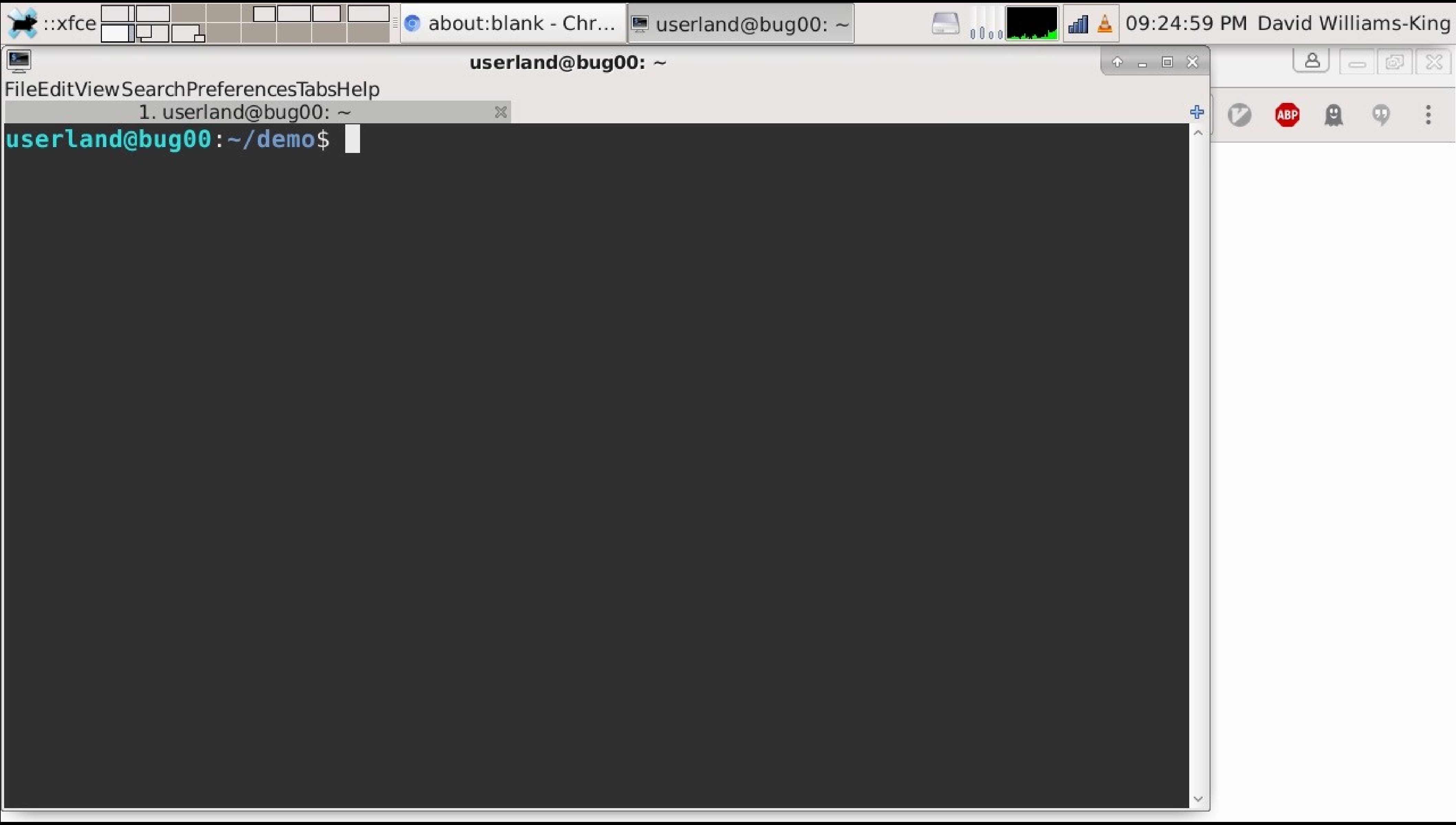
- Two disclosure-based attack methodologies:
  - Scan many pages for the desired gadgets
    - impacted by disclosure time, network latency
  - Explore gadget space in small number of pages
    - impacted by ROP chain computation time (> 40 seconds)
- Published JIT-ROP takes 2300-378000 ms
- We can re-randomize typically every 20-50 ms

Demo



::xfce
about:blank - Chr...
userland@bug00: ~
09:24:59 PM
David Williams-King
userland@bug00: ~
FileEditViewSearchPreferencesTabsHelp
1. userland@bug00: ~
ABP
userland@bug00:~/demo$

Conclusion

- Continuous re-randomization every 20-50 ms

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- Continuous re-randomization every 20-50 ms
- Fast:
  - Defeats all known code reuse attacks
  - Asynchronous shuffling offloads overhead
- Deployable:
  - Binary analysis w/o modifying kernel, compiler, ...
- Egalitarian:
  - No additional privileges required
  - Shuffler defends its own code

Questions?

Demo website: `http://shuffled.elfery.net:8000`

Related Work

- JIT-ROP, SOSP 2013
- Oxymoron, Usenix Sec 2014
- Code Pointer Integrity, OSDI 2014
- Stabilizer, SIGARCH 2013
- Remix, CODASPY 2016
- TASR, CCS 2015
- ...more related work in our paper

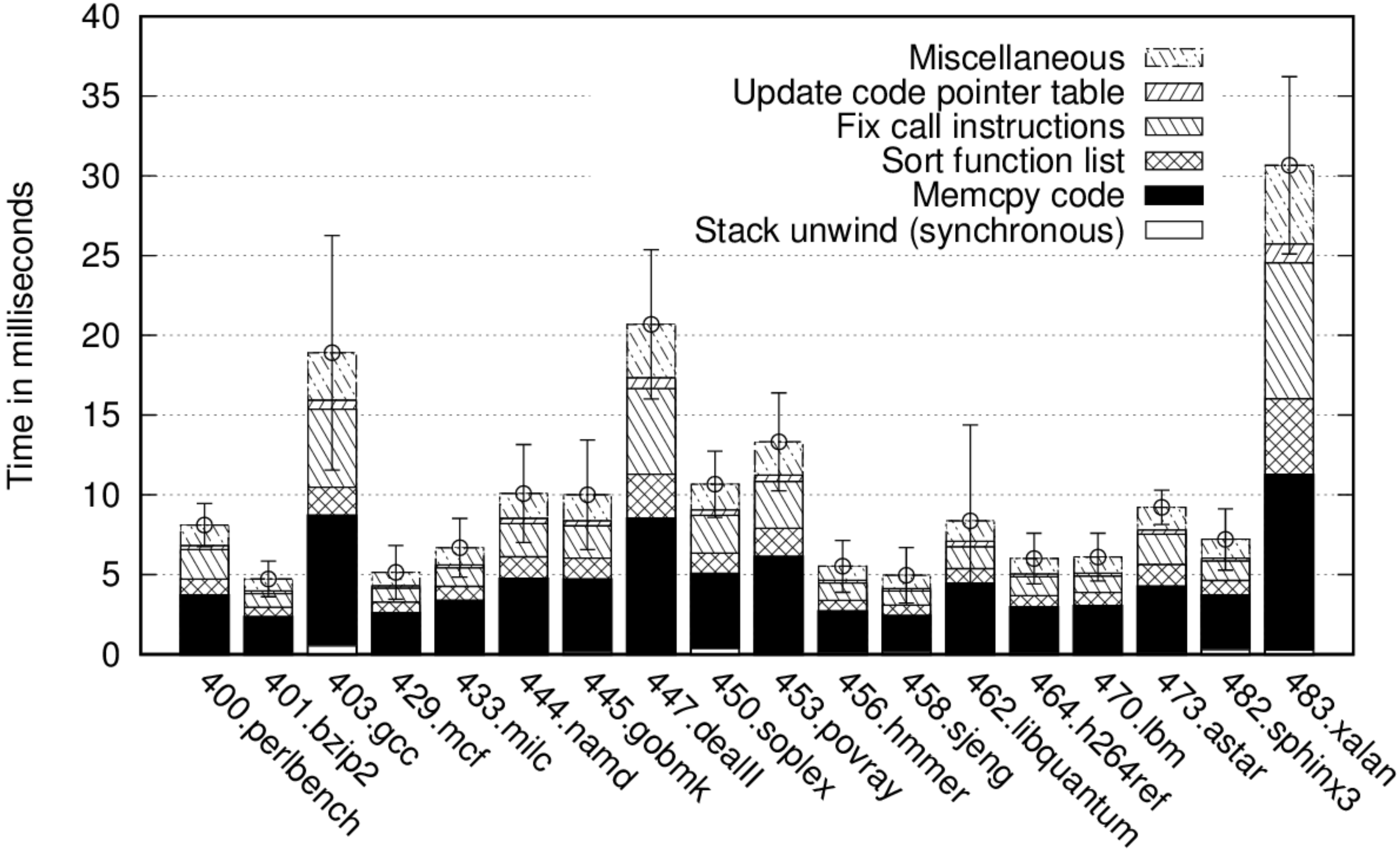
[1] https://securityintelligence.com/anti-rop-a-moving-target-defense/
[2] http://www.ieee-security.org/TC/SP2013/papers/4977a574.pdf

Future Work

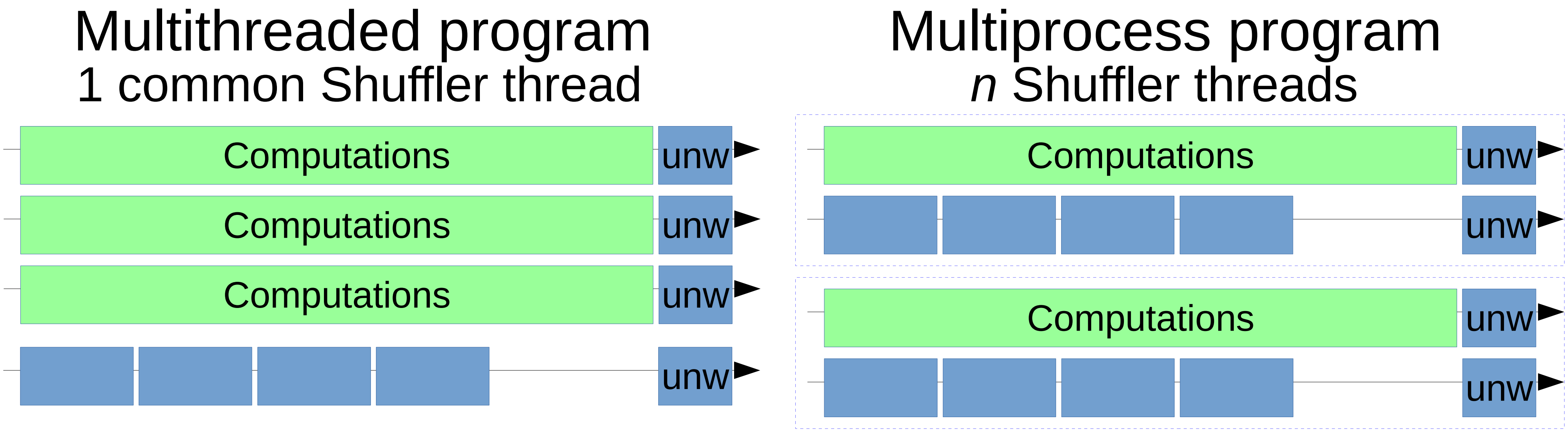
- Translating stack unwind information
  – Breaks C++ exceptions, pthread_cancel, etc.
- Cannot shuffle the loader currently
  – Breaks dlopen
- If shuffling takes too long, no mechanism to pause target program

Shuffler Thread Performance

- Asynchronous shuffling runs quickly
- Synchronous runtime is 0.3% of total runtime



Scalability



- Tradeoff for server workers
  - Multithreaded => better performance overhead
  - Multiprocess => no disclosures across workers
- Both techniques scale well in practice (up to 24x)