RandCompile Removing Forensic Gadgets from the Linux Kernel to Combat its Analysis

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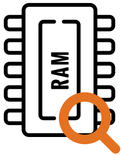
Outline

1. Current State of Memory Forensics
2. How to combat Modern Forensic Tools: RandCompile
3. Evaluation
4. Future Research & Conclusion

Current State of Memory Forensics

Intro

- **Memory-Forensic:** The science of deducting information about an operating system state out of a memory dump
- Allows to reason about
  - Process List
  - (Cryptographic-)Secrets
  - IPs/MAC-Addresses of devices in proximity
  - ...
- Complexity depends on available information.
  - Debugging Symbols of operating system



Recent Developments in Linux Memory Forensics

New Challenges for analysts:

- **Structure Layout Randomization** (since 2017)
  - Binary Layout of data structures is modified at compile time.
  - Primarily a Binary Exploitation defense, but effective against forensic tools

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Research Progress:

- Tools are capable to deal with **Structure Layout Randomization**
- OS-agnostic tools
  - Certain implementation characteristics are shared between OSes
  - Operate with minimal additional information on MacOS, Linux, Windows, and other operating systems

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- **Order of Fields** - The data structure layout (especially without Structure Layout Randomization) is forseeable.
- **Pointer Graph** - The pointers between the kernel objects form a characteristic graph revealing e.g. the process list uniquely out of the set of objects.

Systematization of Last Generation Tools

Tool	Year	Analysis Subject	FG 1: Special comm	FG 2: Symbol Tables	FG 3: ABI Constraints	FG 4: Order of Fields	FG 5: Pointer Graph	Recovery Scope
Linux-specific								
KATANA	2022	Offset Revealing Instructions		✗	✗			All structures
Trustzone Rootkit	2022	Kernel Runtime Data	✗					Selected structures
LOGICMEM	2022	Kernel Runtime Data	✗	✗		✗	✗	Selected structures
AUTOPROFILE	2021	Offset Revealing Instructions		✗	✗	✗		All structures
OS-agnostic								
FOSSIL	2023	Kernel Runtime Data	✗				✗	All structures
HYPERLINK	2016	Kernel Runtime Data	✗				✗	Selected structures

How to Combat Modern Memory Forensic Tools?

Design Goals of RandCompile

Harden **Linux** systems against automated forensic analysis

Design

	Forensic Gadgets					Transformation	
	FG-1	FG-2	FG-3	FG-4	FG-5	GCC Plugin	Manual
String and Pointer Encryption	✓				✓		✓
Better Data-Order Randomization				✓			✓
Externalize `printk` Format Strings			✓			✓	
Adding Bogus Parameters with Artificial Memory Accesses			✓			✓	

- Perform selected transformations on the kernel to remove four out five forensic gadgets.
  - two are automatically applied (by a compiler plugin)
  - two applied manually in form of kernel patch
- **Disclaimer:** Perfect Obfuscation is in general not possible! This is a hardening mechanism against automated tools.

ABI Randomization

Katana and AutoProfile target FG 3

- Offset Revealing Instructions reveal layout of data structures
- ABI mandates calling convention
  - Allows a structural matching of generated machine code with the source code

Example:

```
do_stuff(current->mm ❶, current->
    ↪ cred ❷, &g ❸);
```

↓

```
mov     rdx❸,0xffffffff82019c60
mov     rax,QWORD PTR gs:0x16d00
mov     rsi❷,QWORD PTR [rax+0x10]
mov     rdi❶,QWORD PTR [rax+0x440]
call    ffffffff811bacd0 <do_stuff>
```

ABI Randomization

Countermeasures by RandCompile

- Shuffle the order of the arguments at call site and implementation site
- Applied automatically to all functions through a compiler plugin.

Issues

- Functions with few parameters have few possibilities for randomization

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```

ABI Randomization

We can add bogus parameters to functions with few parameters

- This can be undone by an analysis tool that has access to the source code
- Also add bogus assembly code hurting performance

Example:

```
int64_t bogusstuff[6];
do_stuff(current->cred❶, current->mm ❷, bogusstuff[0]❸, &g❹, bogusstuff[3]❺, bogusstuff[5] ❻);
```

↓

```
mov     rcx❹,0xffffffff82019c60
mov     r8❺,QWORD PTR [rsp+0x18]
mov     r9❻,QWORD PTR [rsp+0x28]
mov     rax,QWORD PTR gs:0x16d00
mov     rsi❷,QWORD PTR [rax+0x440]
mov     rdx❸,QWORD PTR [rsp]
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call    ffffffff811bacd0 <do_stuff>
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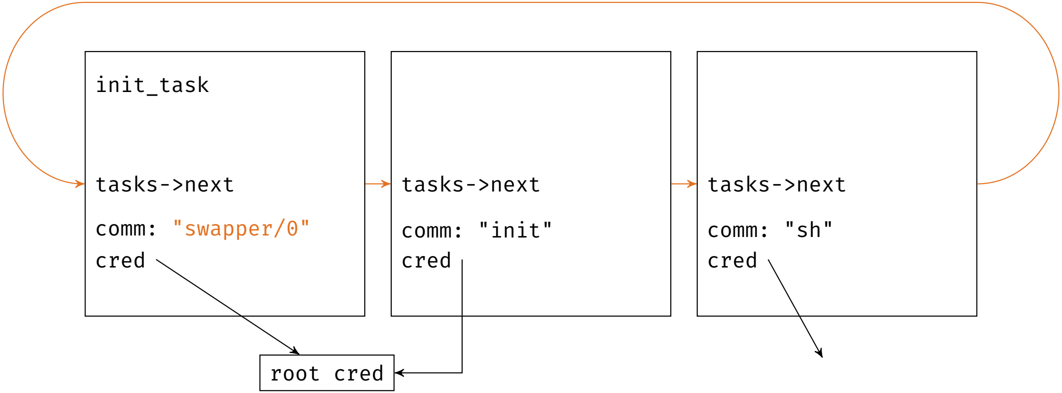
Pointer & String Encryption

HyperLink and Fossil analyse the pointer graph of kernel objects (FG 5).

- e.g. the process information objects are connected by a linked list.
- first process in list contains well-known string (FG 1).



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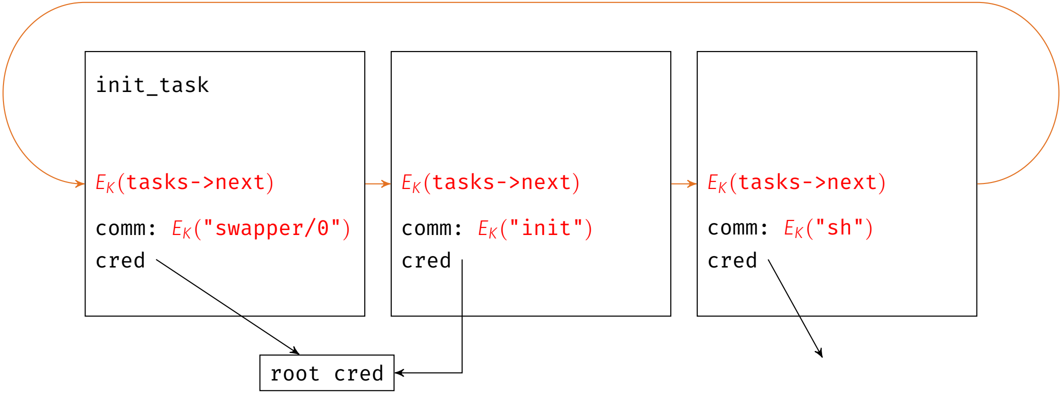

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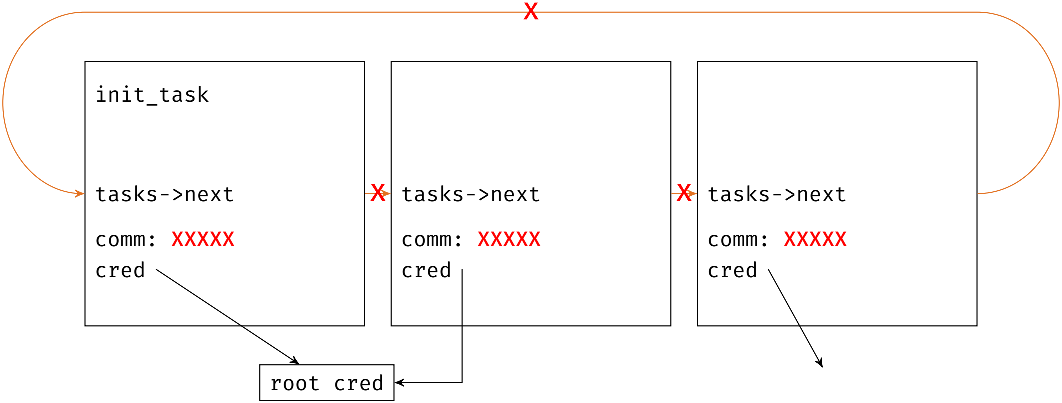

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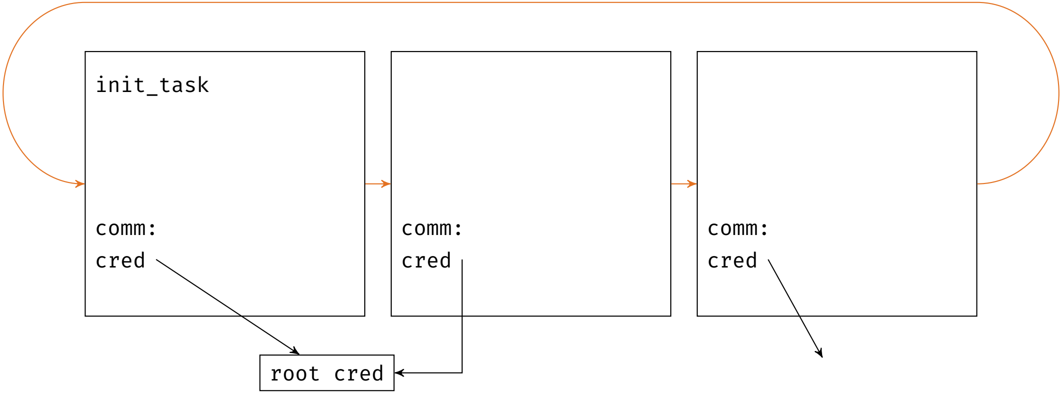
- first process in list contains well-known string (FG 1).
- Encrypt Pointers and Strings in process information objects
  - Store Encryption Key as immediate value in the compiled machine code.



Evaluation

Effectiveness against Offset Revealing Instruction based Analysis

	Base	RandCompile (no bogus)	RandCompile (-printk, -memref)	RandCompile (-printk)	RandCompile (full)
List Modules	✓	✓	✓	✓	✓
Members reconstructed	2	2	2	2	2
Task Listing	✓	✗	✗	✗	✗
Members reconstructed	6	5	5	4	4
List Files	✓	✗	✗	✗	✗
Members reconstructed	16	15	8	7	7
Dmesg Log	✓	✓	✓	✓	✗

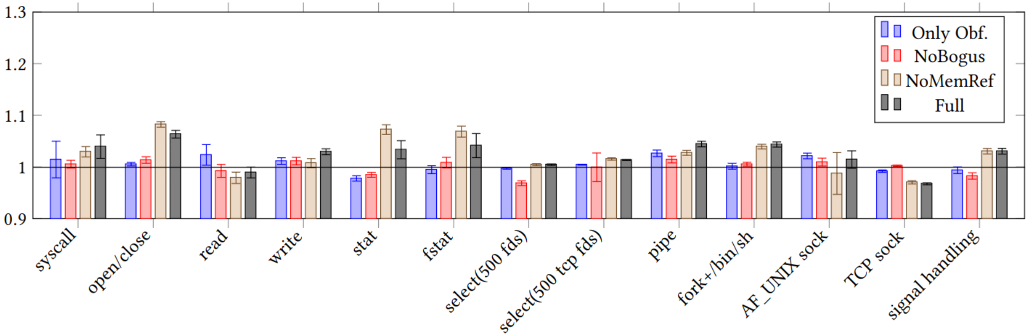
- We perform the core analysis of KATANA with and without RandCompile.
  - Already a single fault during reconstruction causes a fault!

Effectiveness against Kernel Runtime Data Analysis

- Encryption of the string `"swapper/0"` (FG-1) is most effective.
  - Stops LogicMem, Trustzone Rootkit, and HyperLink from operating
  - Fossil analysis performance is degraded. It depends on the analysts queries.
- Pointer Encryption
  - Degrades analysis opportunities of LogicMem, Trustzone Rootkit, and HyperLink further
  - Further degrades attack possibilities of Fossil
  - Future Work: Encrypt also other kernel pointers

Performance

Results using the lmbench Microbenchmark (runtimes are normalized to 1):



Performance

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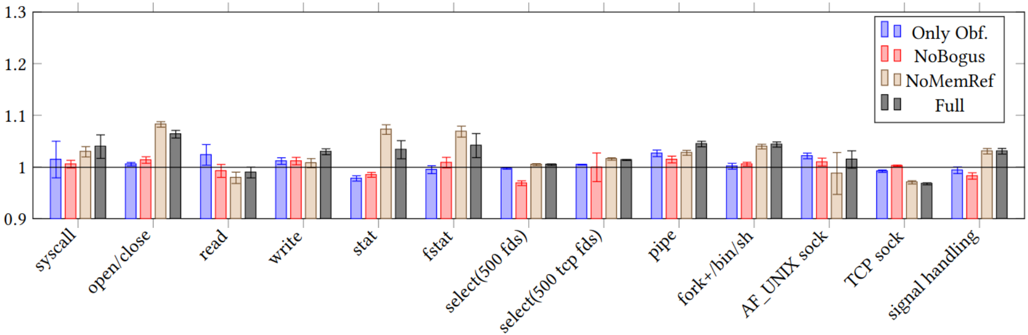
- Less than 1-3 percent overhead on average



Discussion

- Are you applying only sound transformations?
  - Yes. RandCompile does not change the semantic/core functionality of the Linux kernel.
- Does not confidential computing (CC) (like AMD-SEV) mitigate this problem?
  - RandCompile complements protection of CC approaches. I.e. AMD-SEV expects a Linux kernel to not trust his drivers.
- Can this be used as a binary exploitation defense?
  - Yes. In combination with Control Flow Integrity protections, it makes abusing existing kernel functions in ROP chains harder.
- Is it a problem that the defenses are applied at compile time?
  - Partially. Applying them during runtime would allow for more widespread use. Applying them at compile time adds diversity to the binary layout.

Conclusion

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- RandCompile is an obfuscation tool for the Linux Kernel to harden it various memory forensic tools.
- It is effective against modern forensic analysis tools.
- It completes and extends the Structure Layout Randomization, a mainlined Linux kernel feature.

We have source code!