バイナリ書き換えを用いたシステムコールフック機構

第 159 回 システムソフトウェアとオペレーティング・システム研究会
2023 年 5 月 16 日

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[1] IIJ 技術研究所
[2] 法政大学

About this Work

- zpoline is a system call hook mechanism for x86-64 CPUs
- We made this for transparently applying user-space OS subsystems to existing applications
- The source code of zpoline has been publicly available at https://github.com/yasukata/zpoline since October 2021

USENIX ATC 2023 で発表予定の内容です

https://www.usenix.org/conference/atc23/presentation/yasukata

https://github.com/yasukata/presentation/tree/gh-pages/2023/05/ipsj-sigos159

System Call

- System calls are the primary interface for user-space programs to communicate with OS kernels

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Kernel-space OS subsystem

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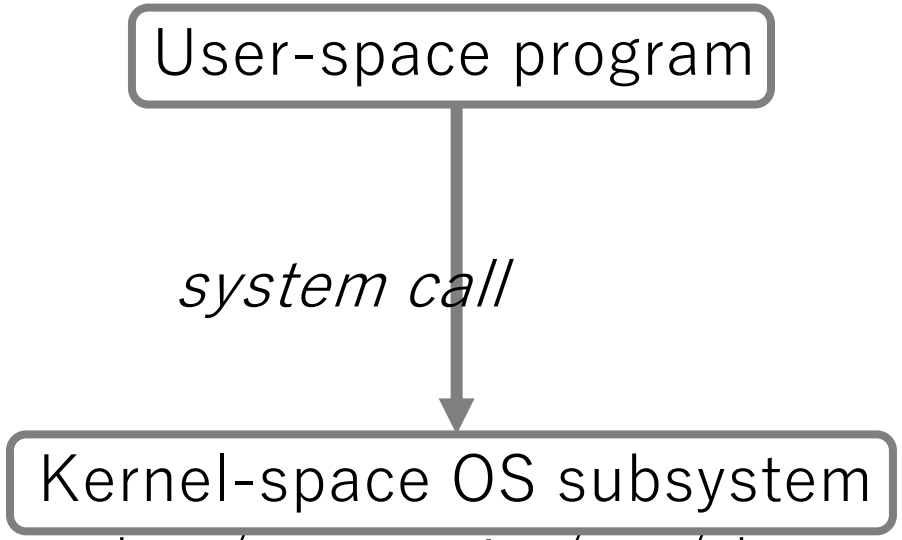

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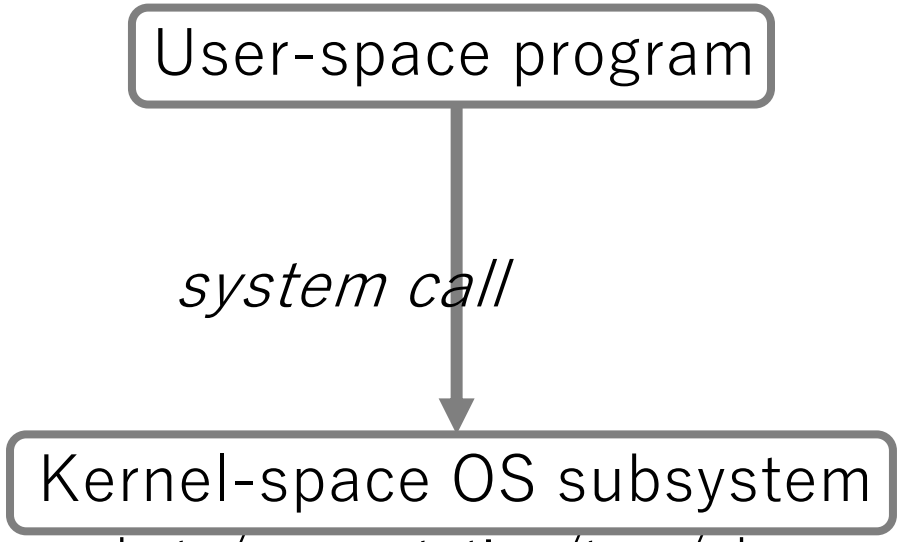

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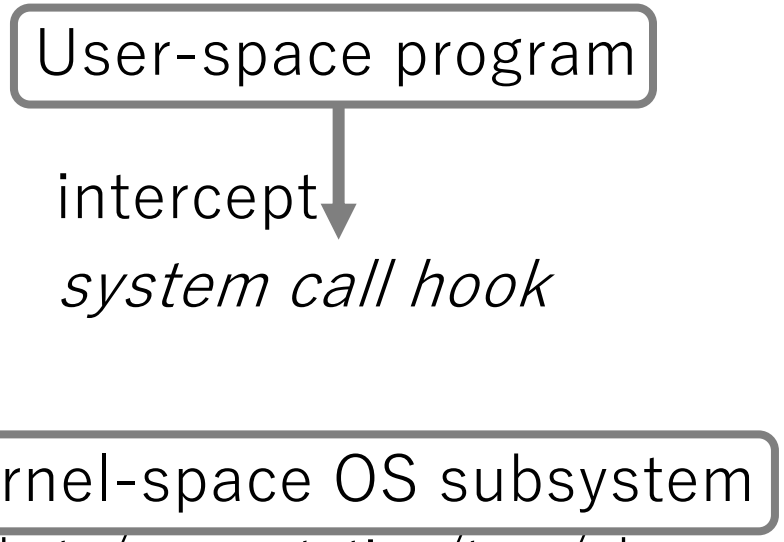

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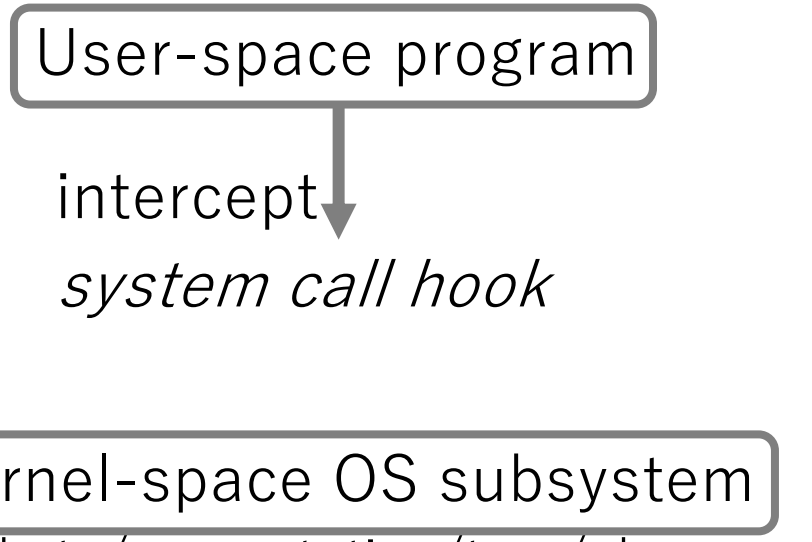

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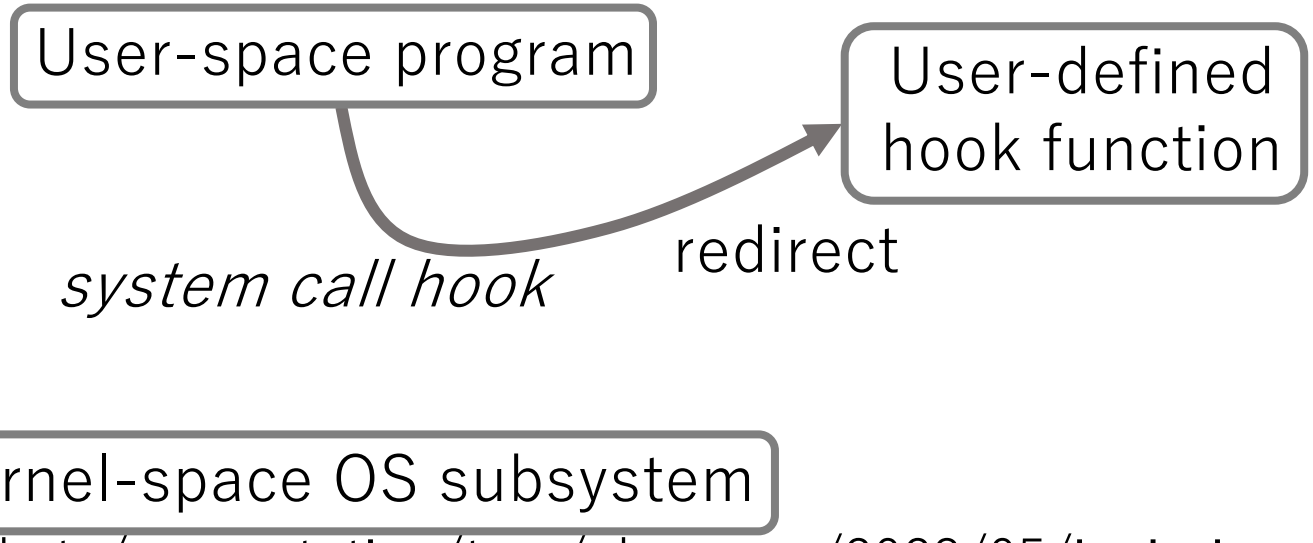

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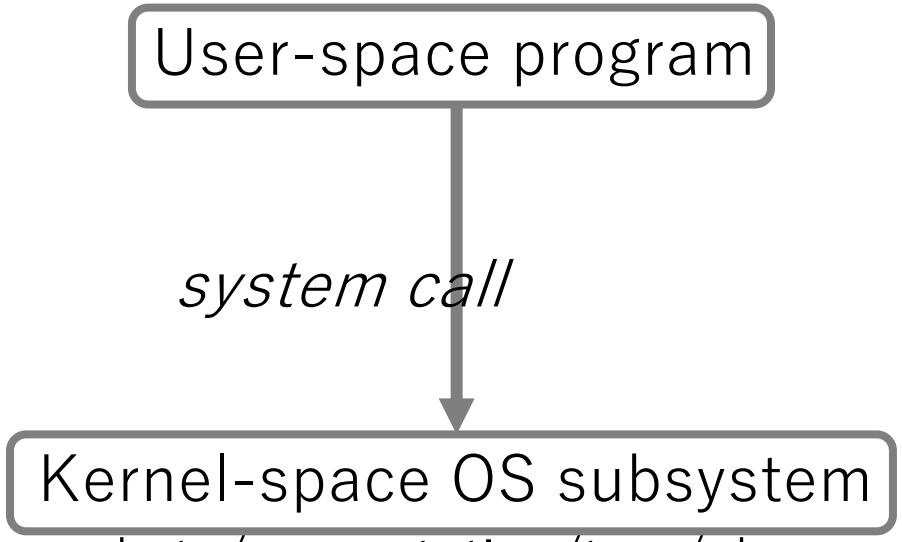

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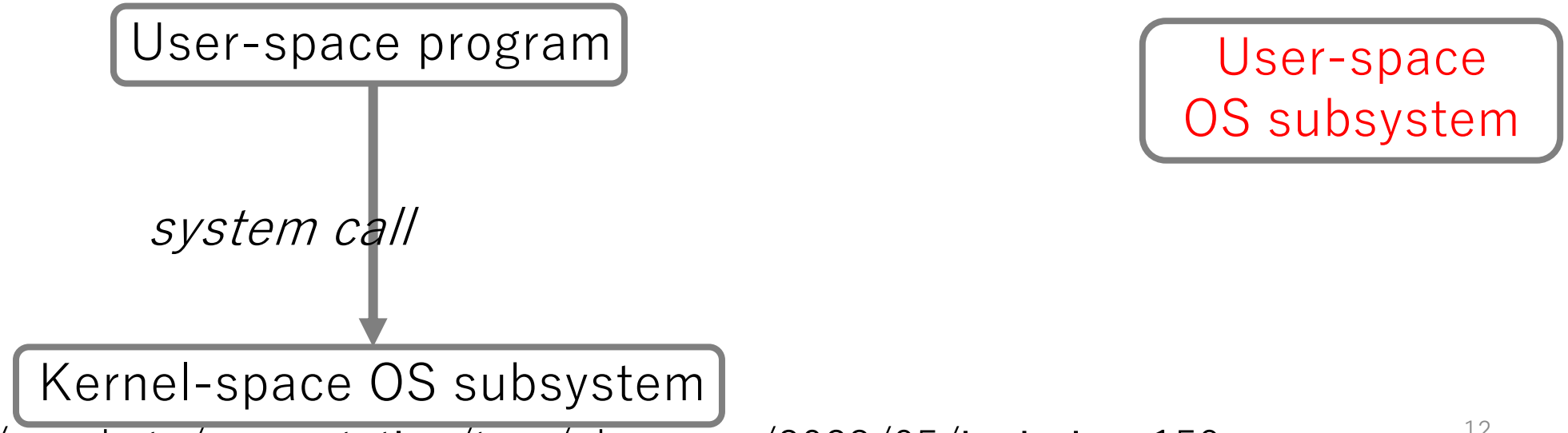

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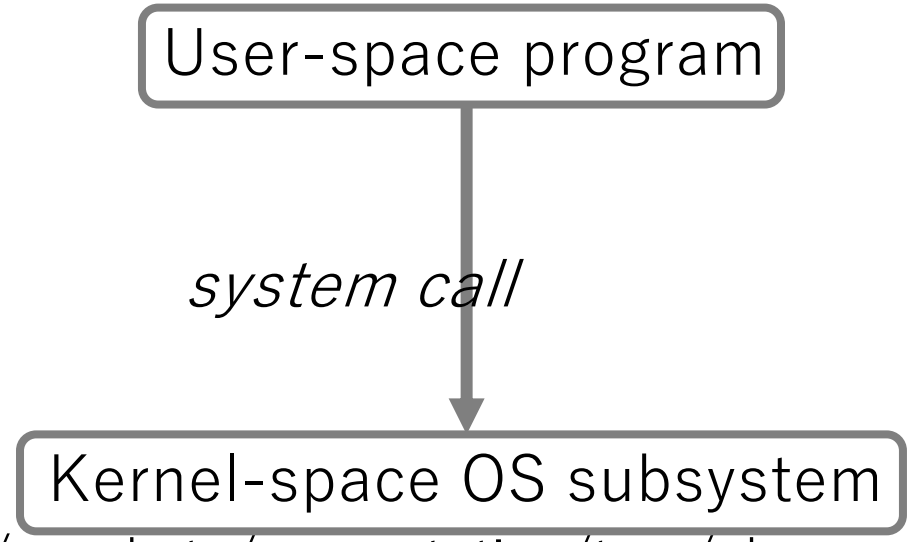

User-space
OS subsystem

Highly performant

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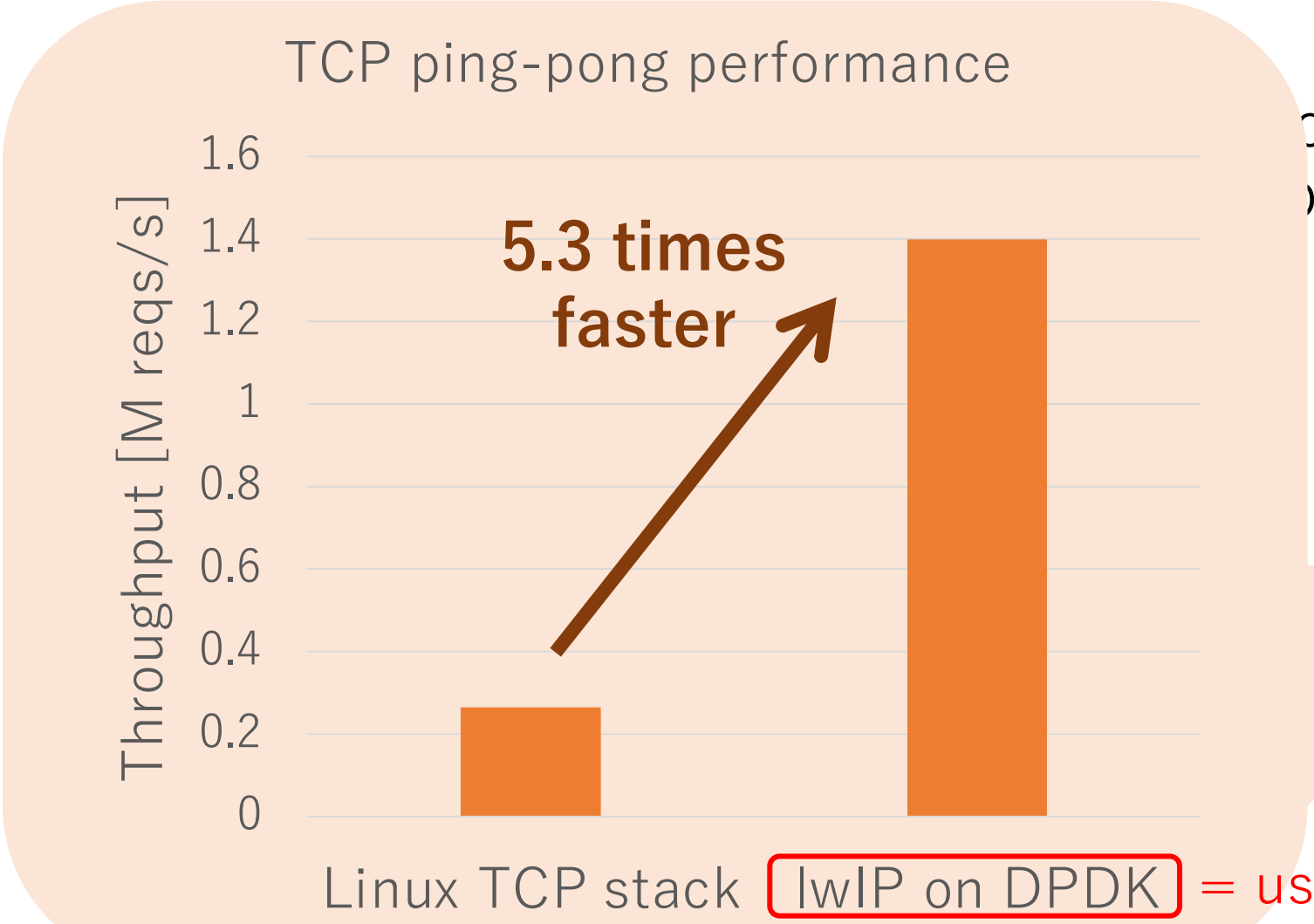

= user-space network stack

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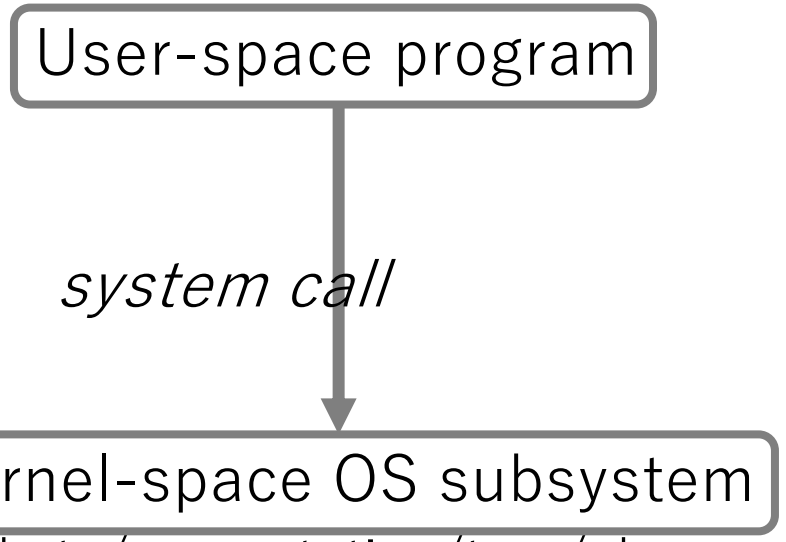

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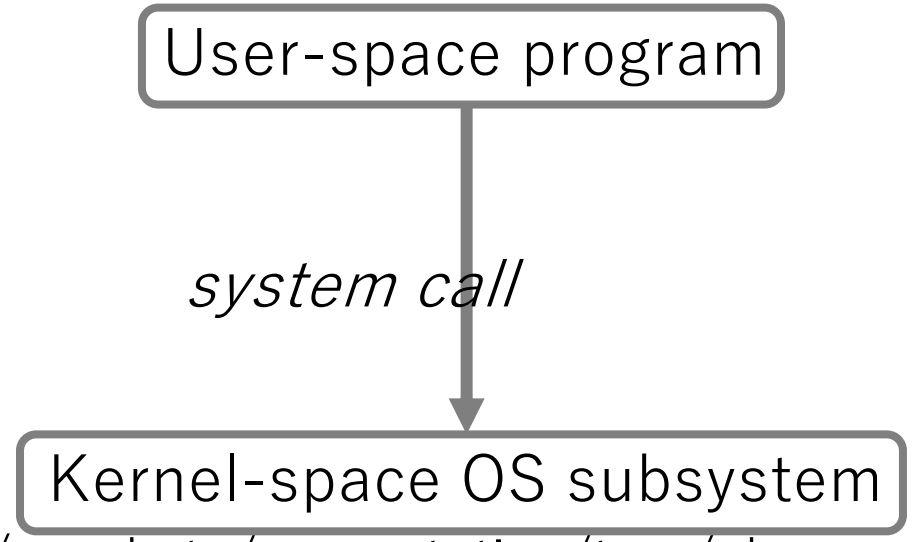

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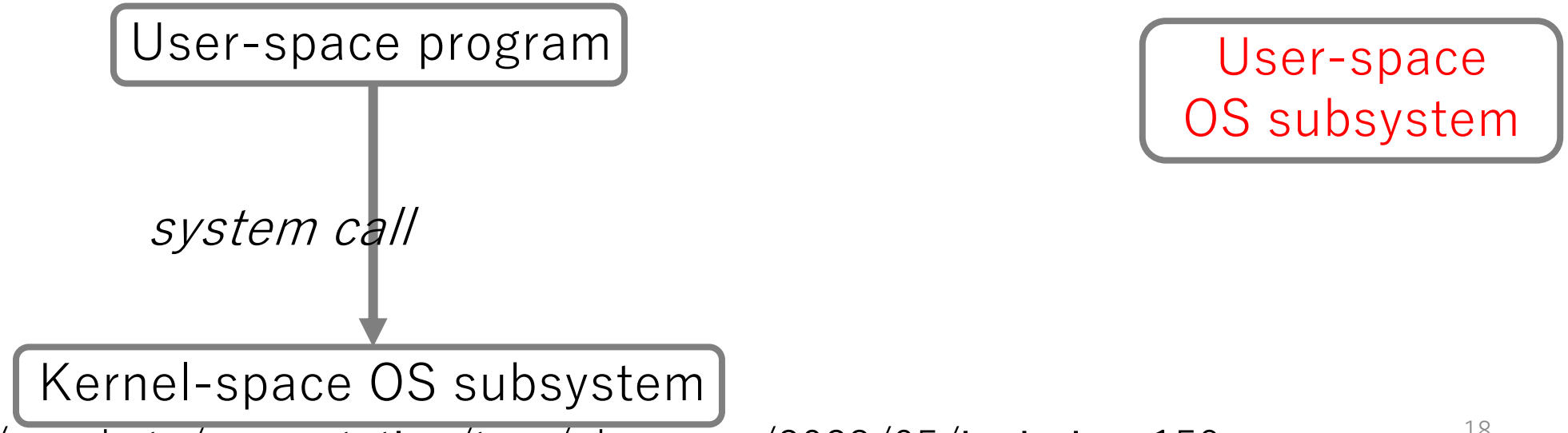

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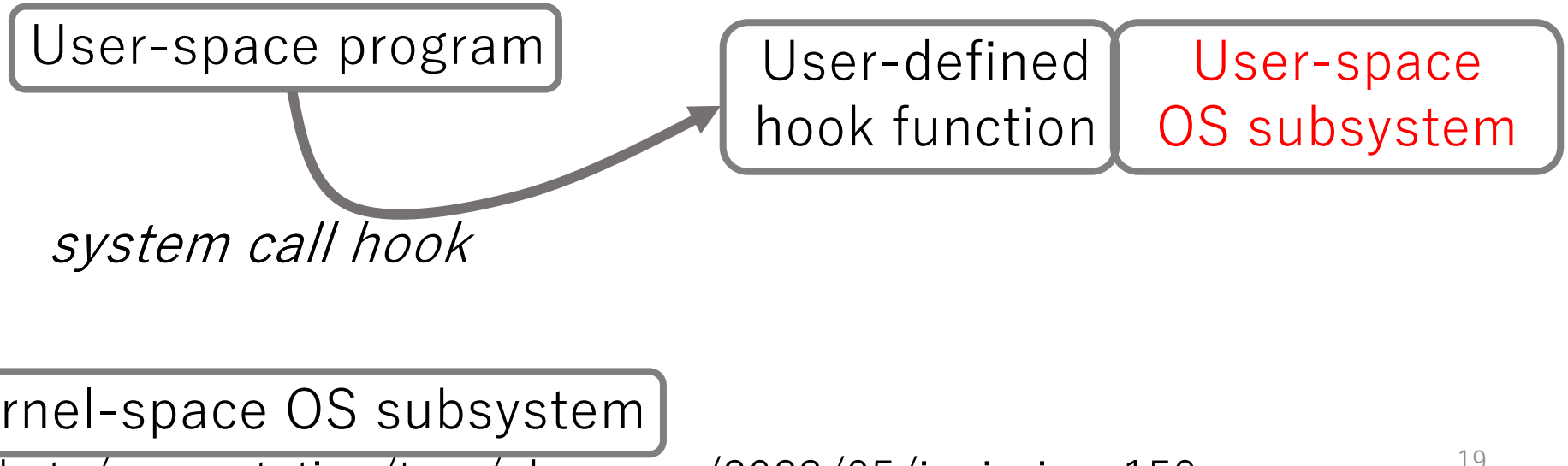

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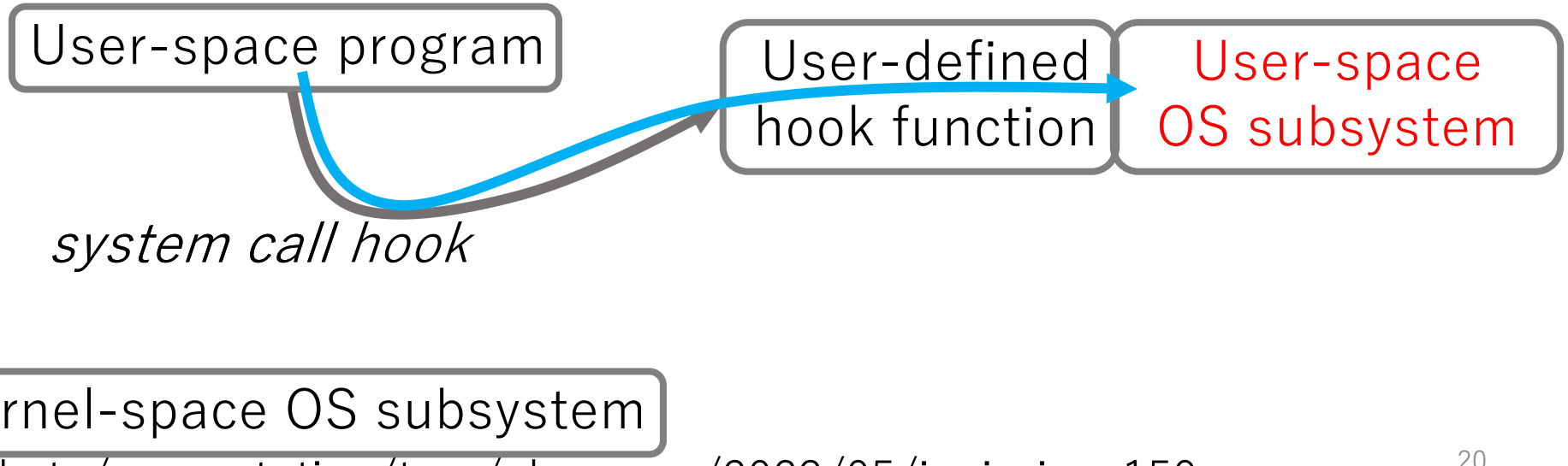

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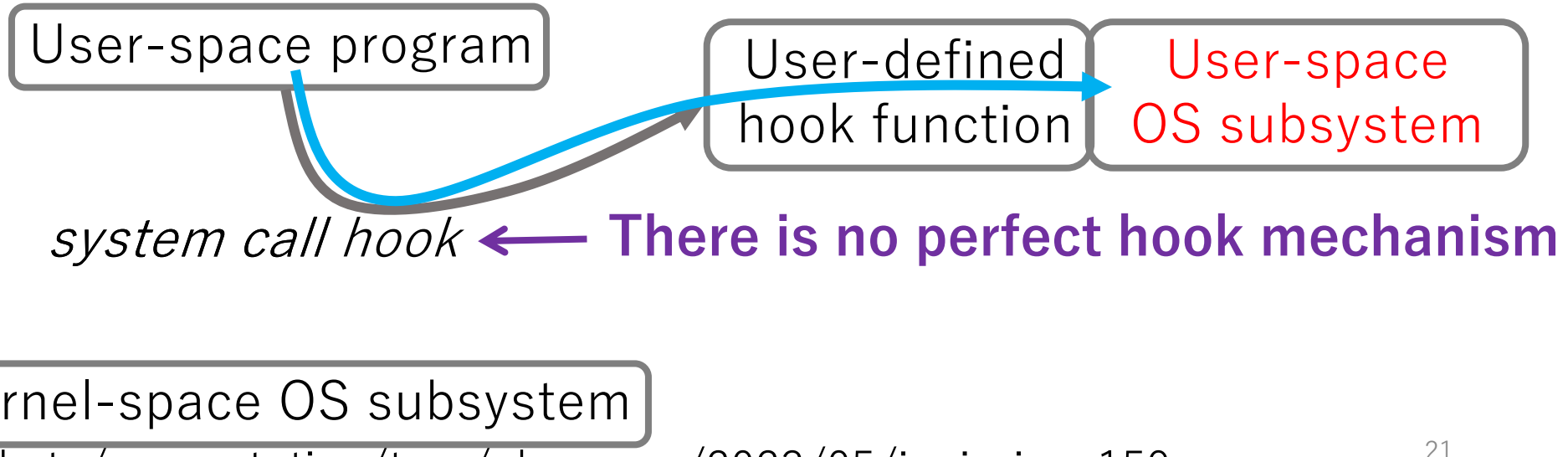

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- ptrace
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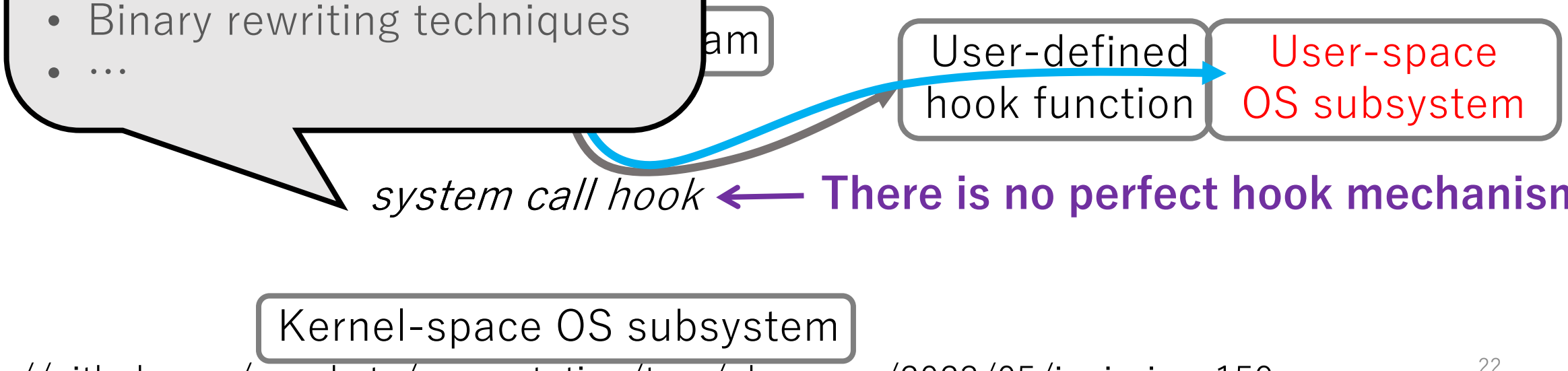

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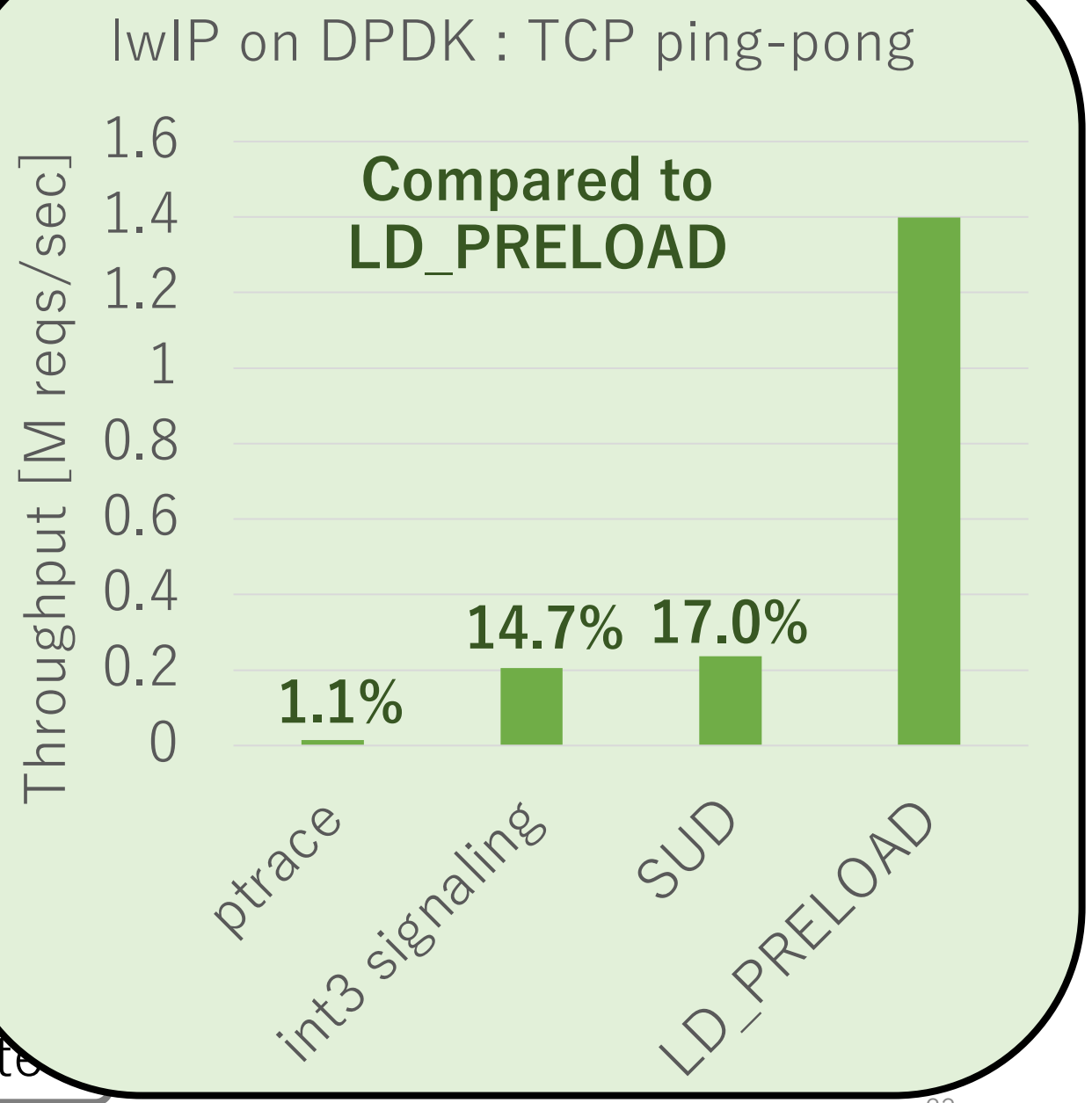

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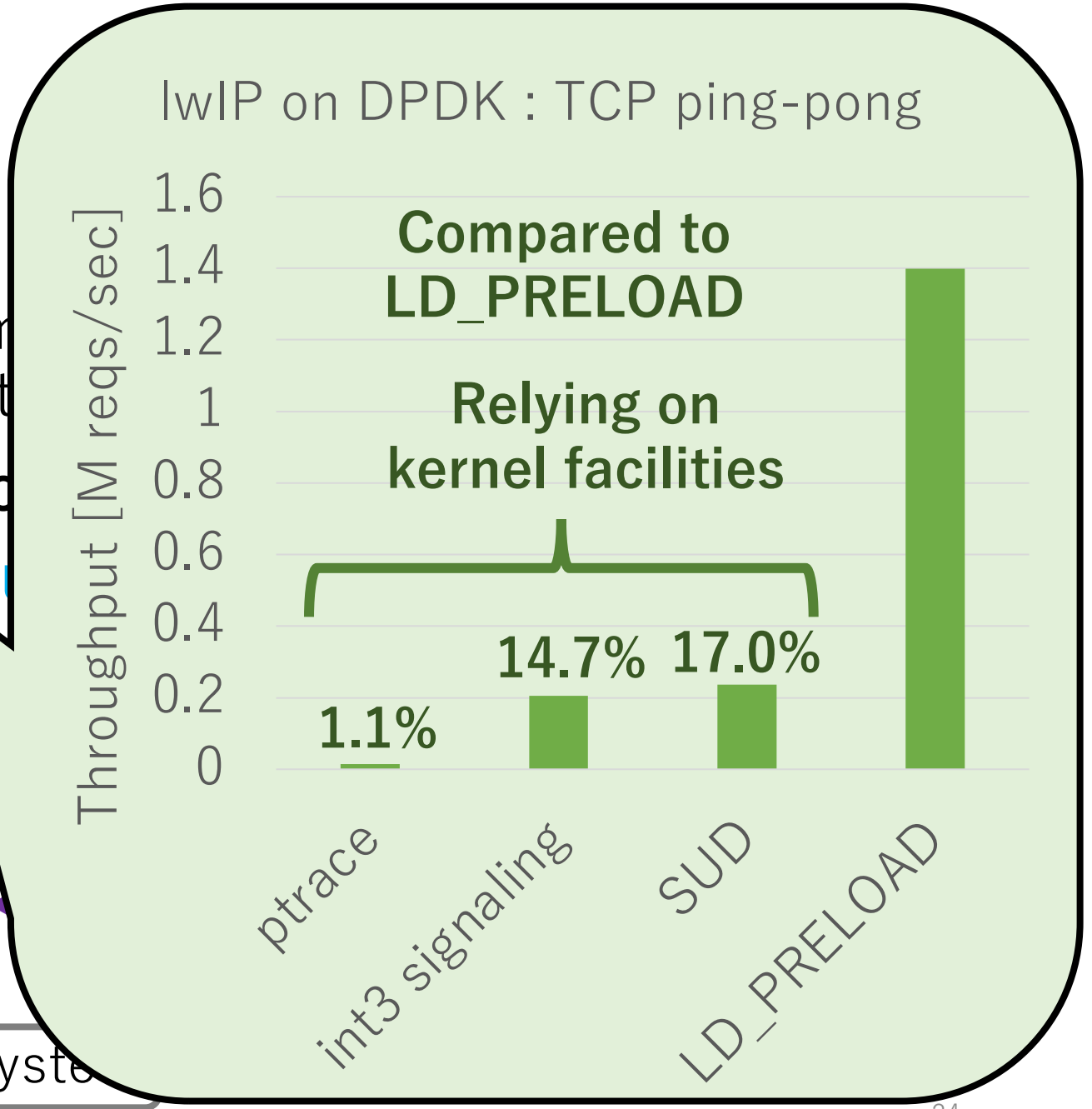

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Prob

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}
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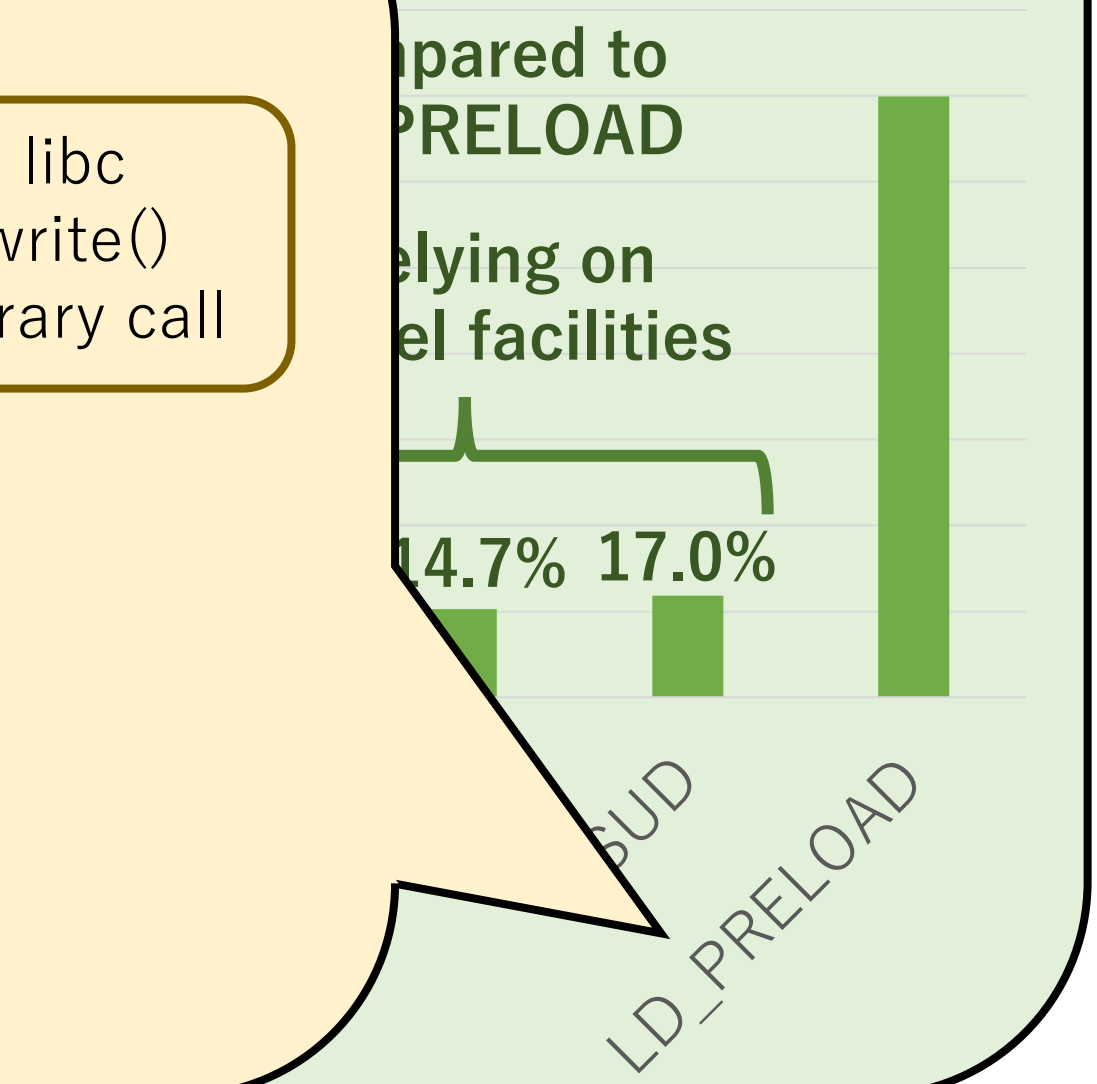
libc
write()
library call

K : TCP ping-pong



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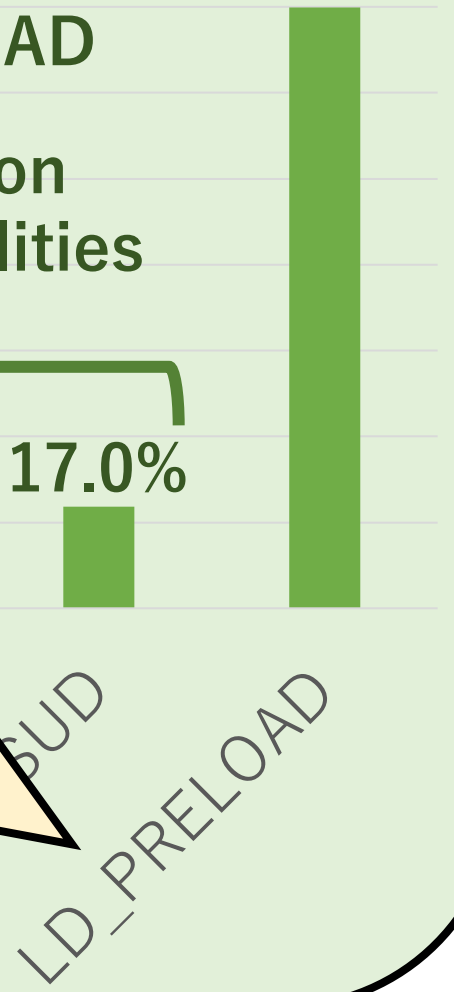

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function call replacement

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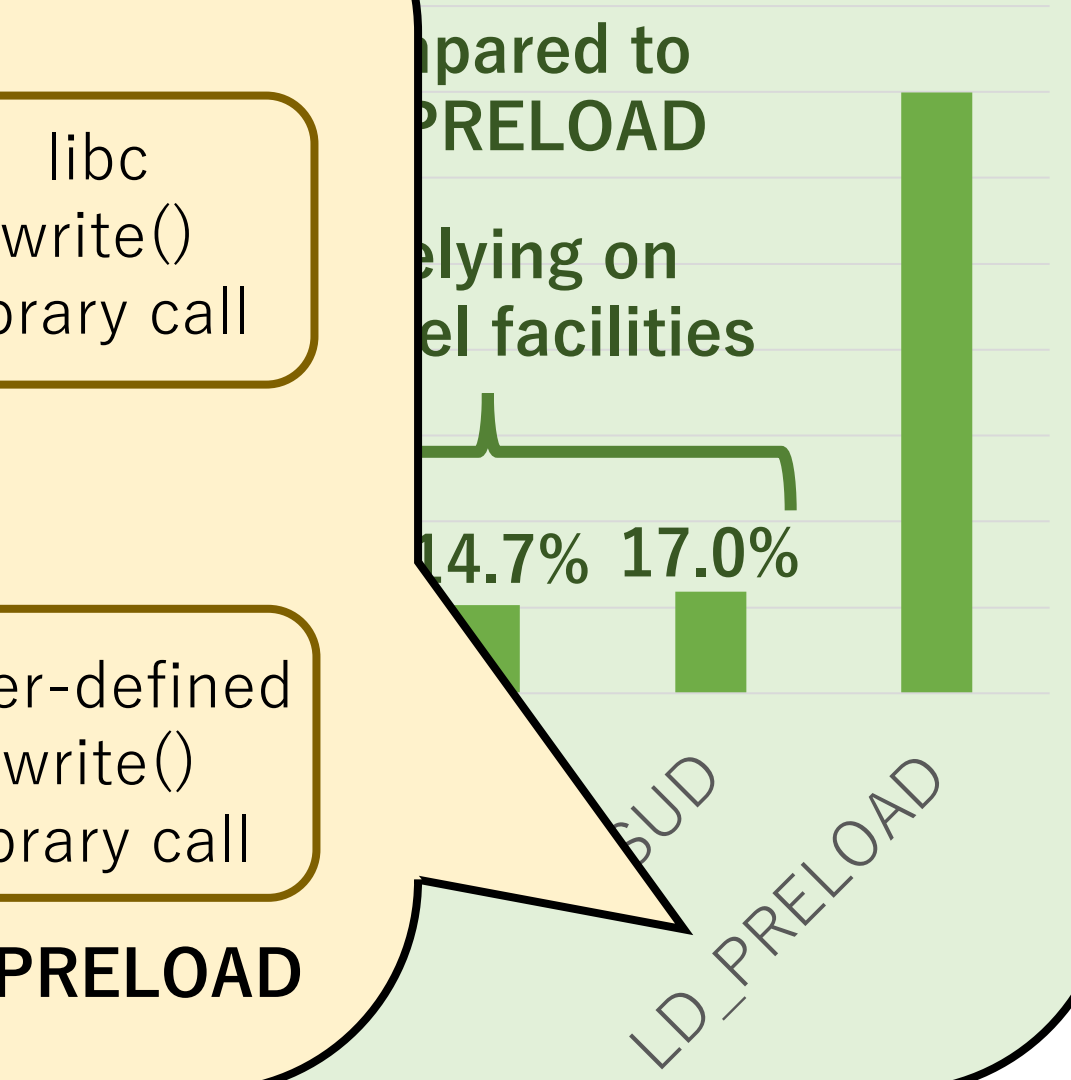

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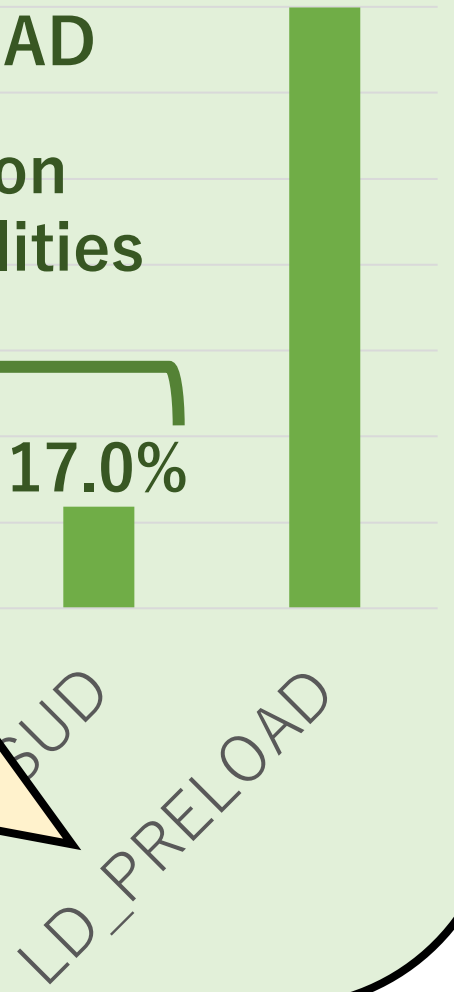

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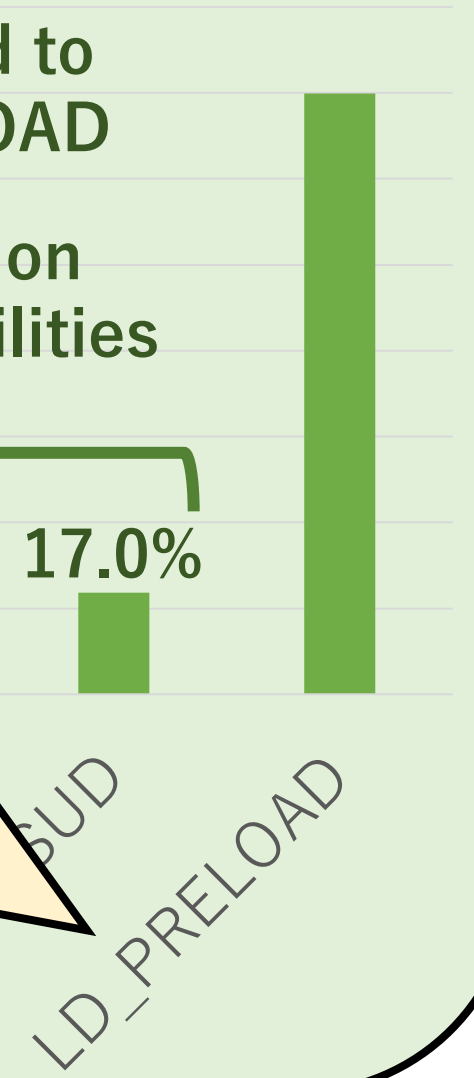

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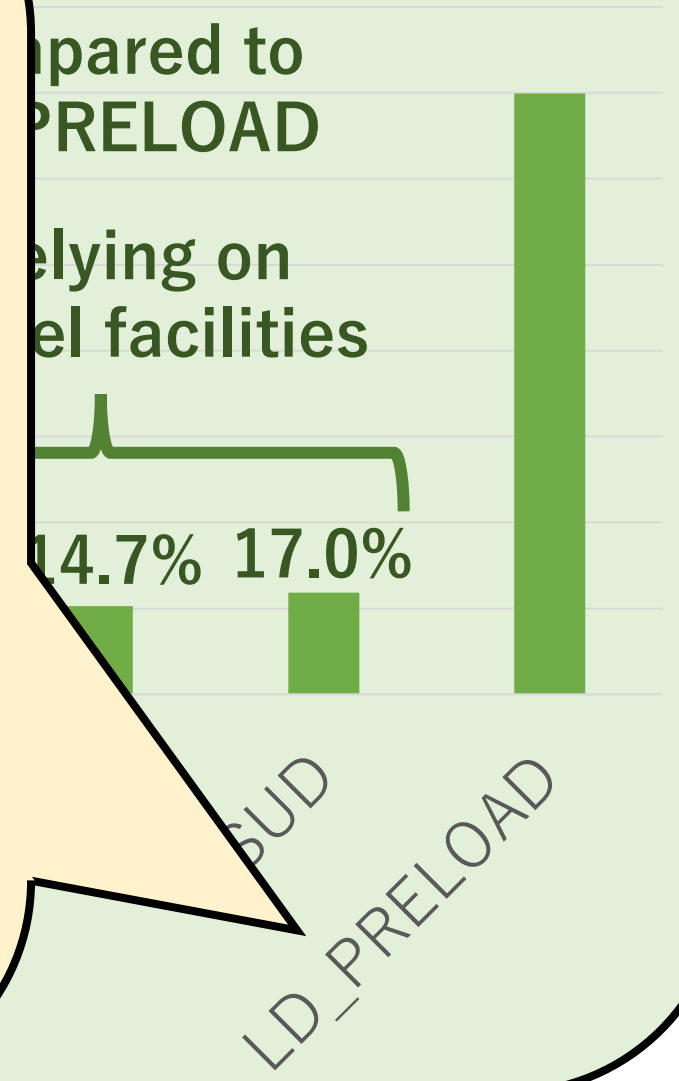

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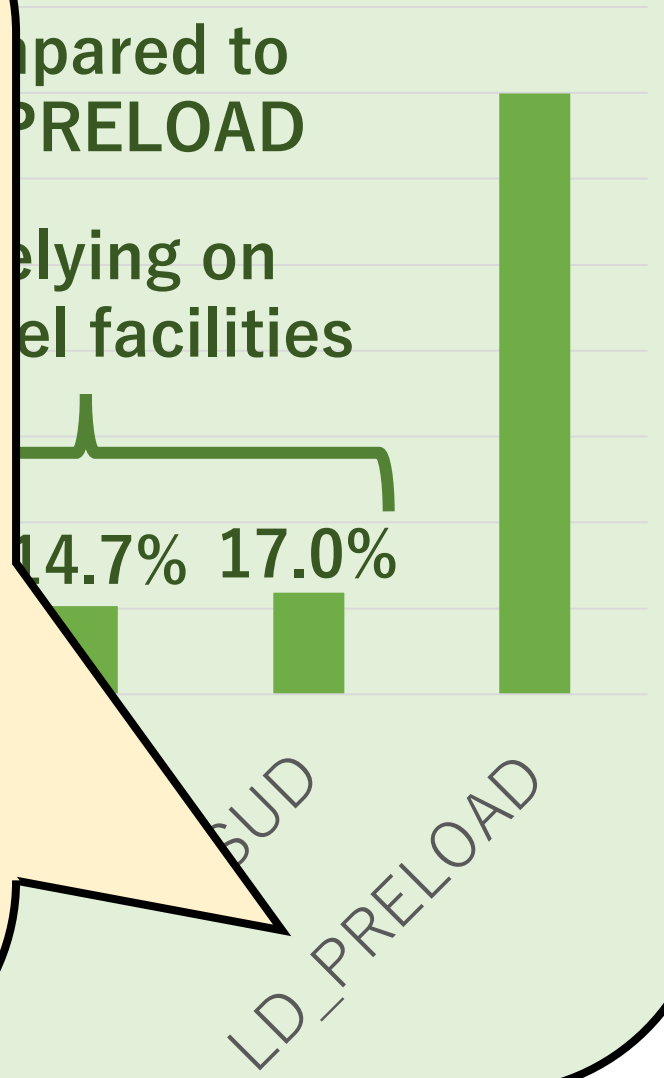

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Hook is not applied

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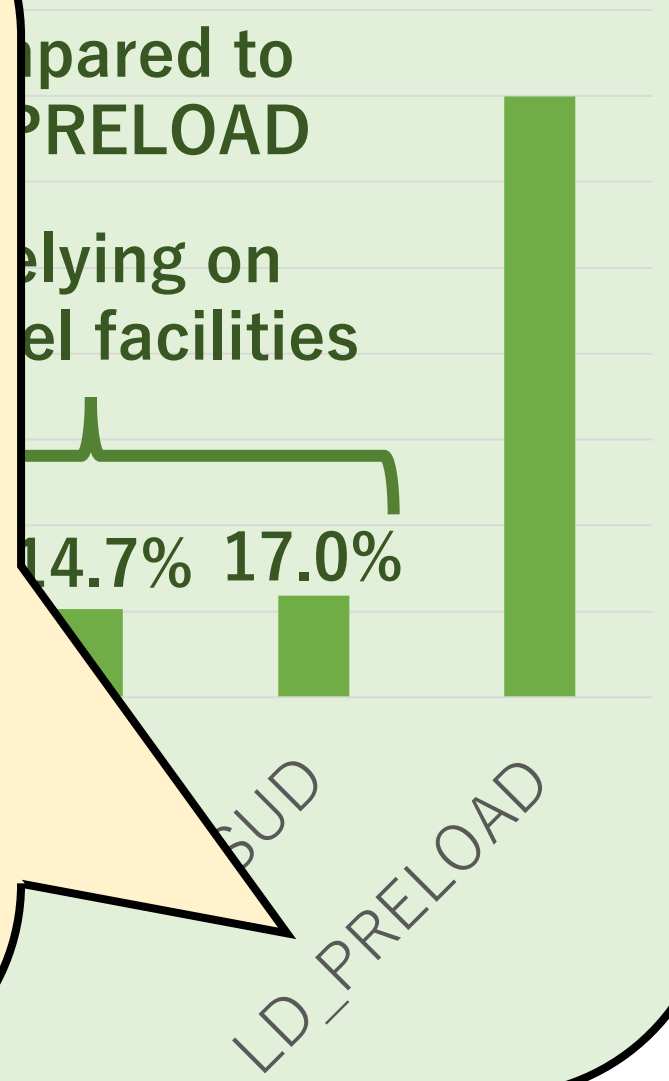

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because names are different

User-defined
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library call

Hook is not applied

LD_PRELOAD

K : TCP ping-pong

pared to
PRELOAD

lying on
el facilities

14.7% 17.0%

SUD

LD_PRELOAD

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We see this case in glibc often

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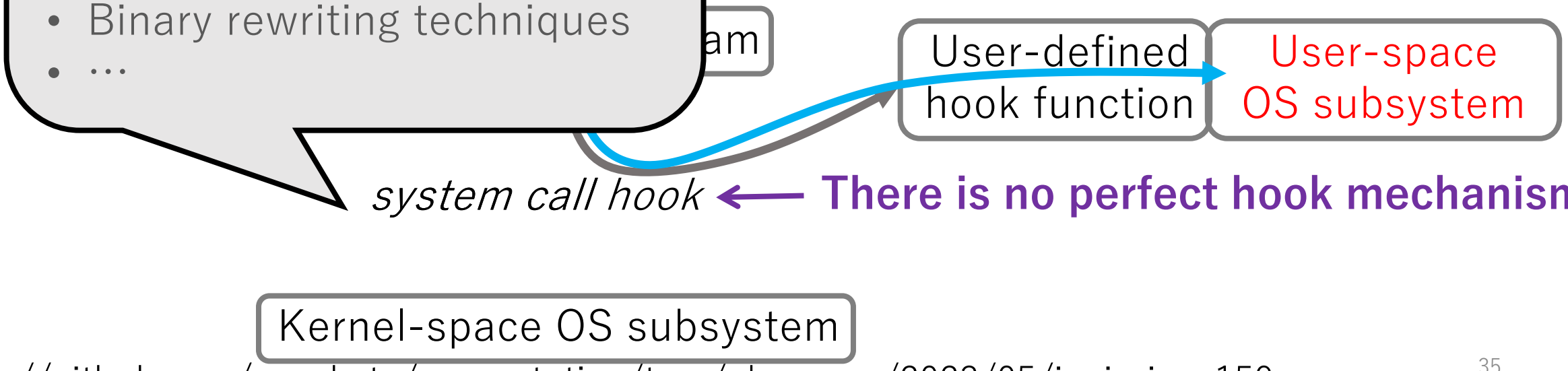

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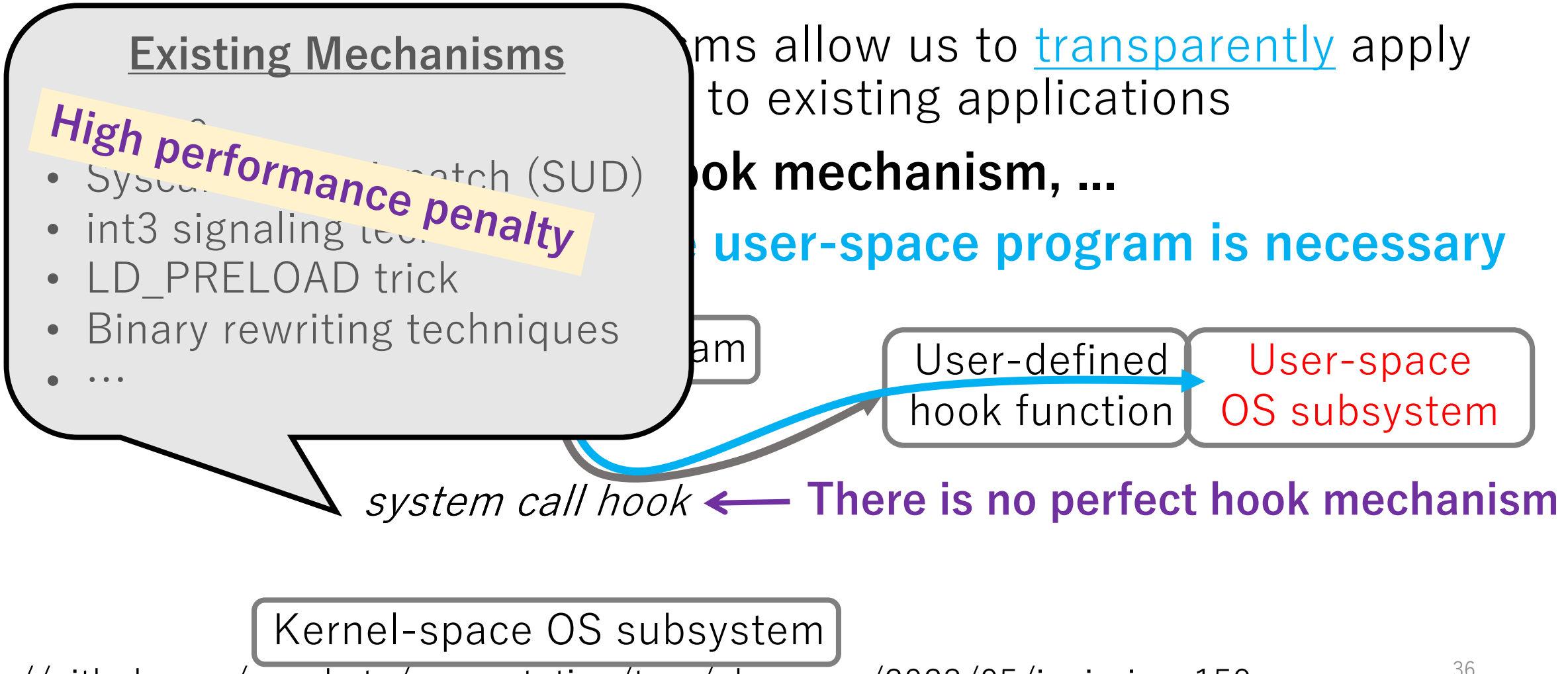

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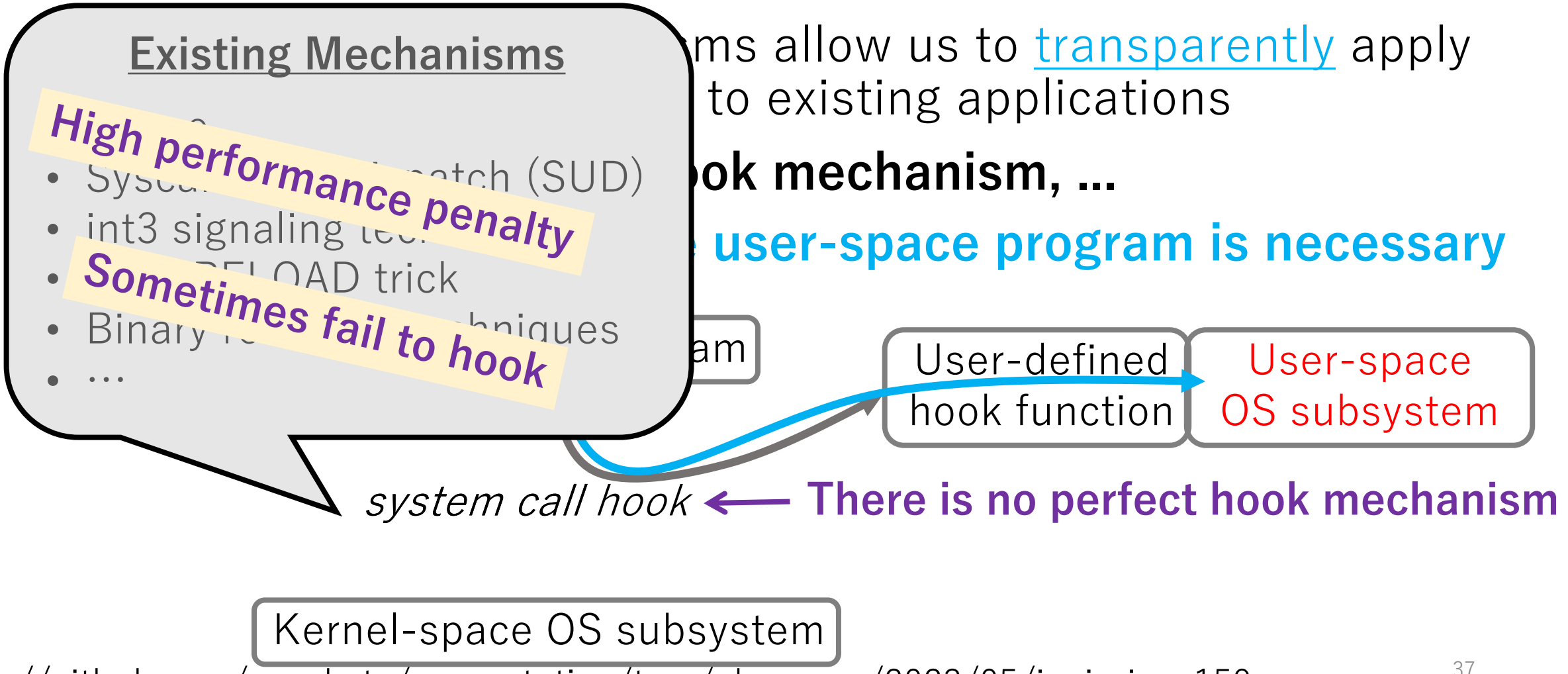

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Problem ➡ Applicability of user-space OS subsystems has been limited regardless of their benefits

Existing Mechanisms

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- int3 signaling tec…
- …ELOAD trick
- Binary re… …hniques
- …

High performance penalty

Sometimes fail to hook

…ms allow us to transparently apply … to existing applications

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… user-space program is necessary

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Contribution

- zpoline employs binary rewriting and offers 6 advantages
  1. Low hook overhead
  2. Exhaustive hooking
  3. No breakage of user-space program logic
  4. No kernel change and no additional kernel module are necessary
  5. No source code of a user-space program is needed
  6. It can be used for emulating system calls

- None of existing mechanisms achieve them simultaneously

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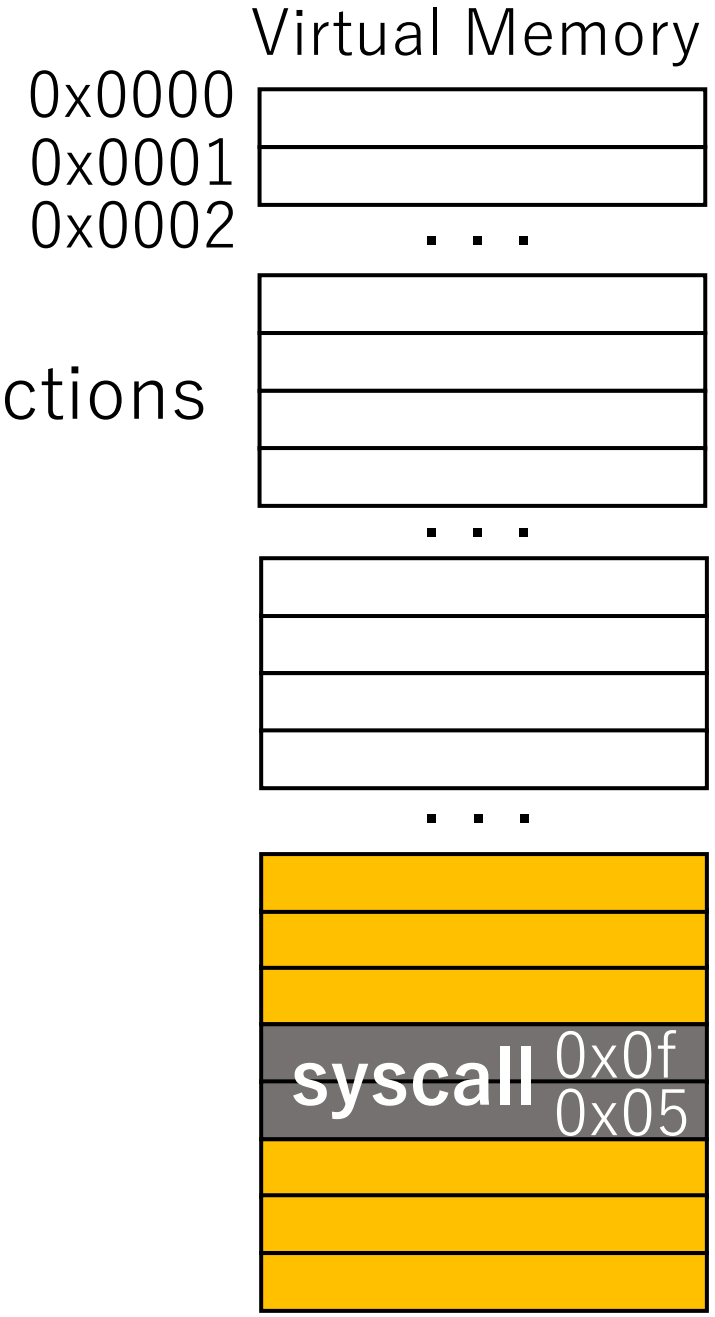
Binary Rewriting Approach

- On x86-64 CPUs, syscall and sysenter instructions trigger a system call
  - syscall: 0x0f 0x05, sysenter: 0x0f 0x34



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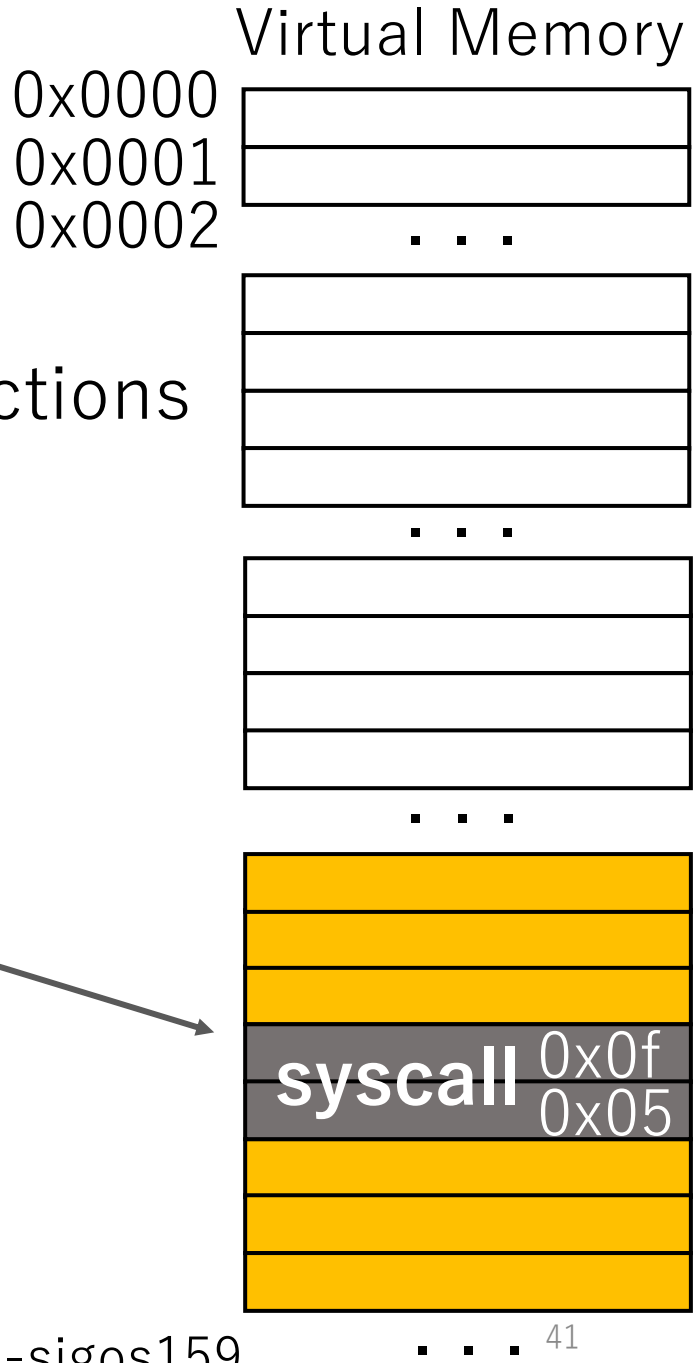

https://github.com/yasukata/presentation/tree/gh-pages/2023/05/ipsj-sigos159

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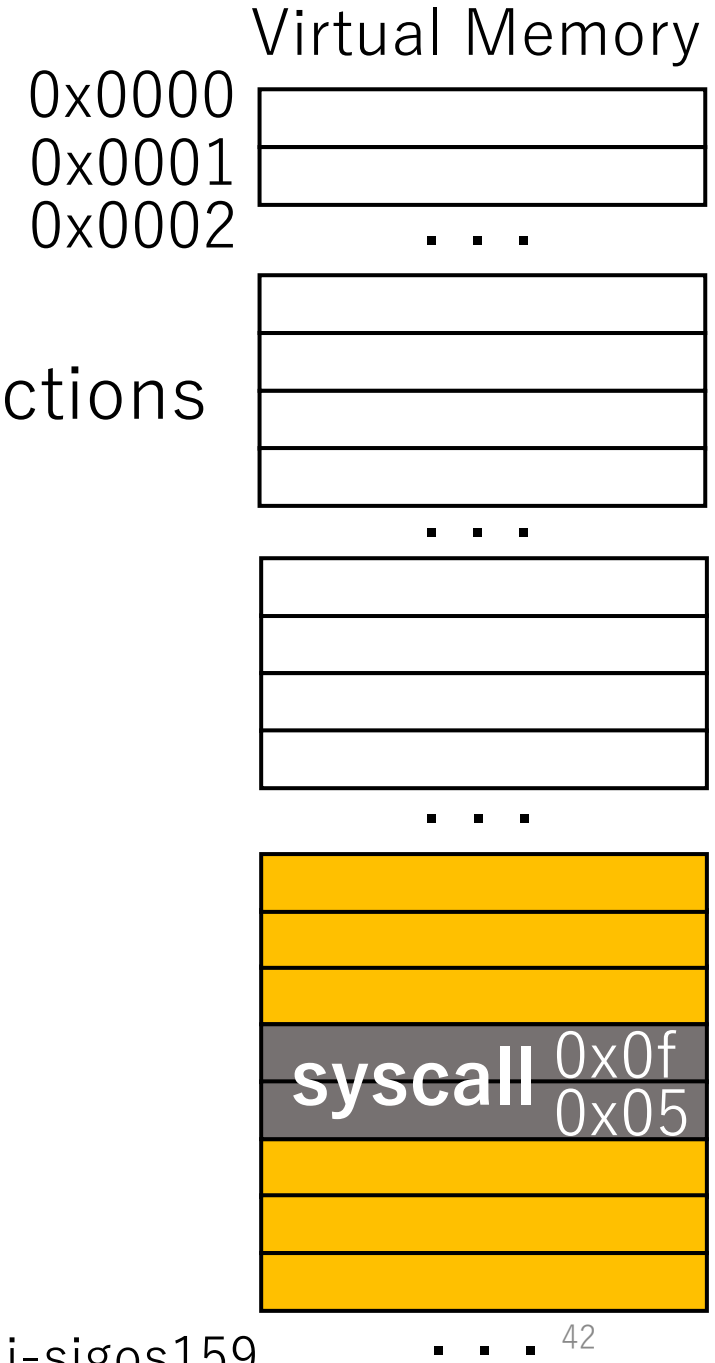

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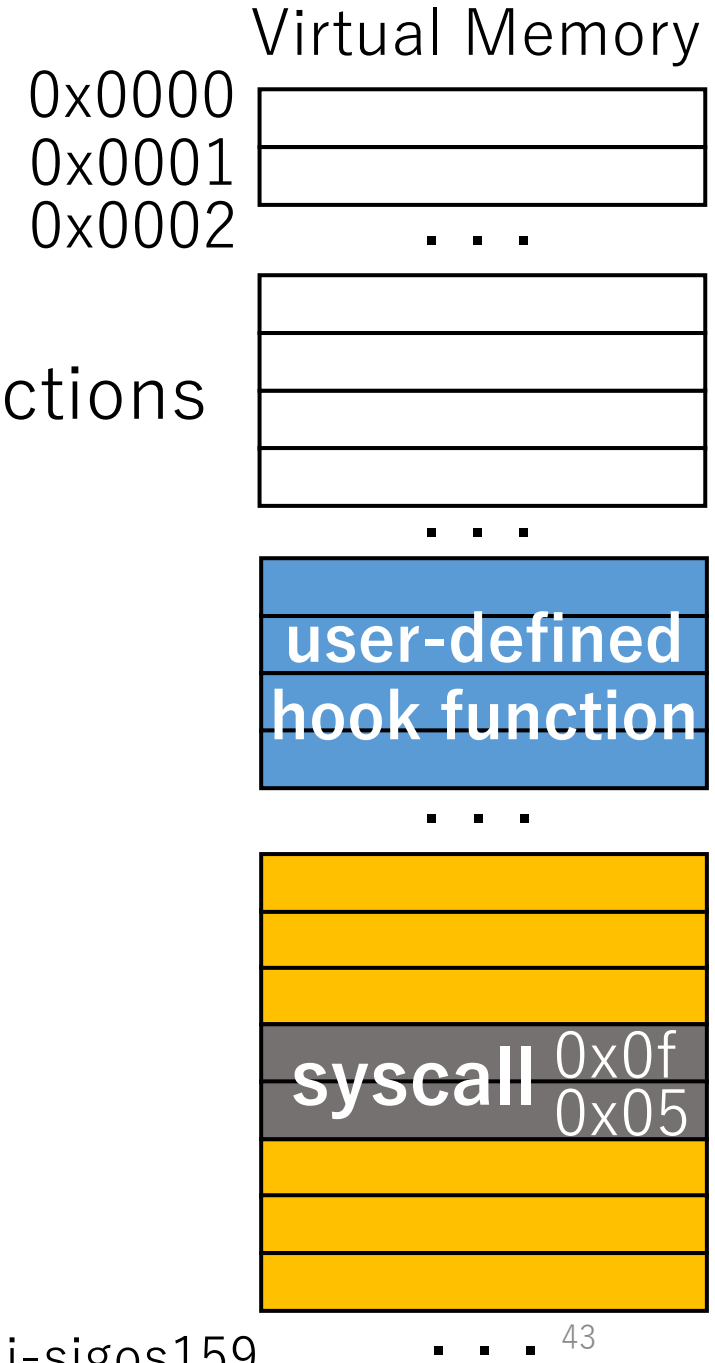

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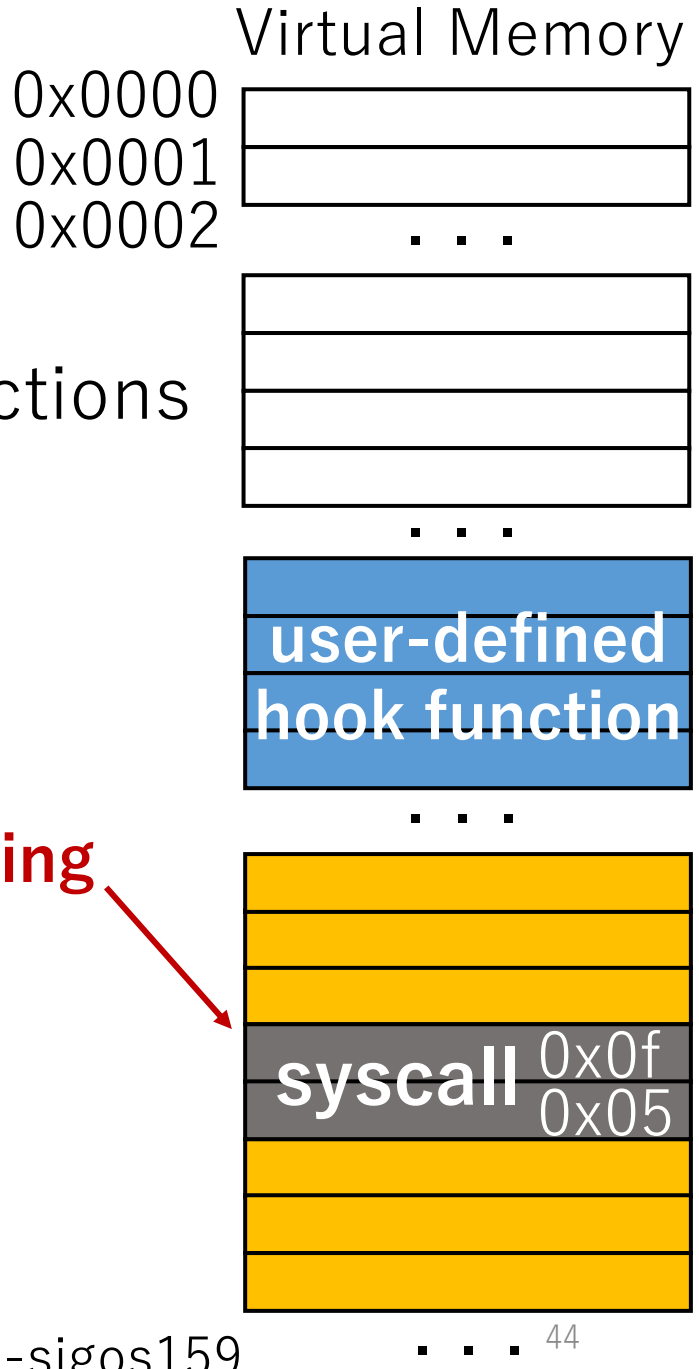

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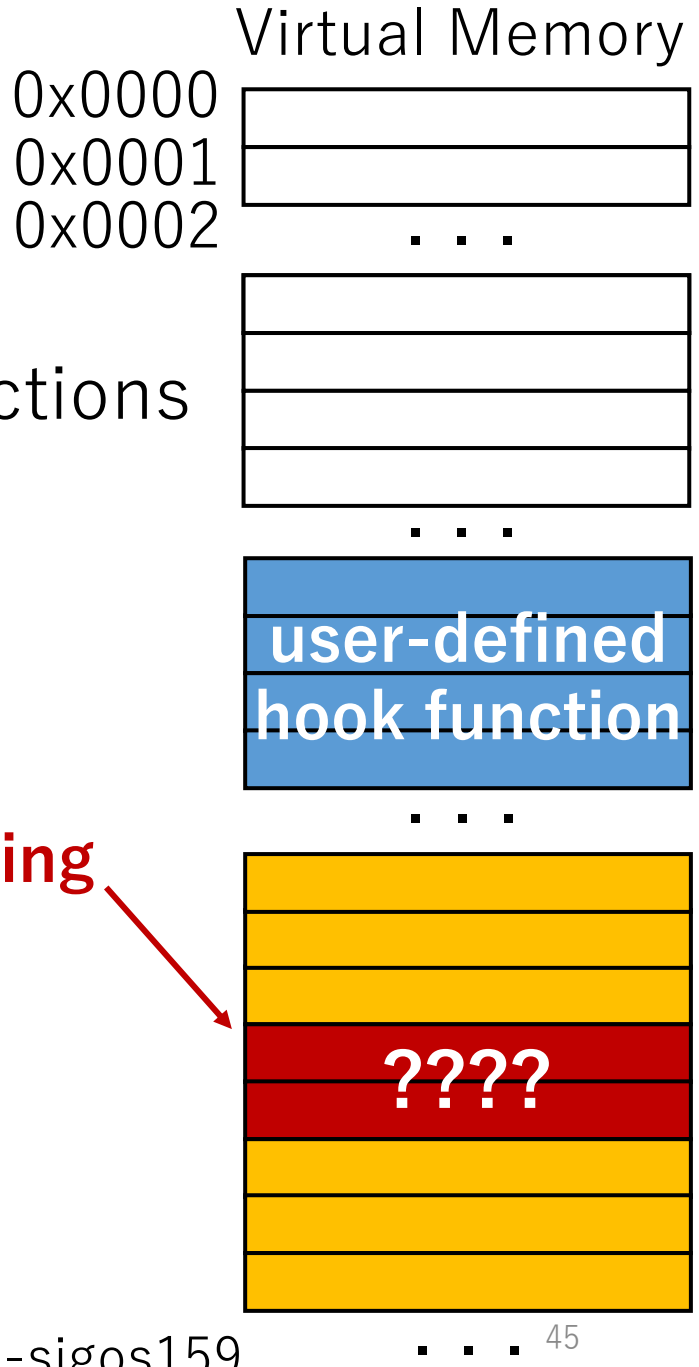

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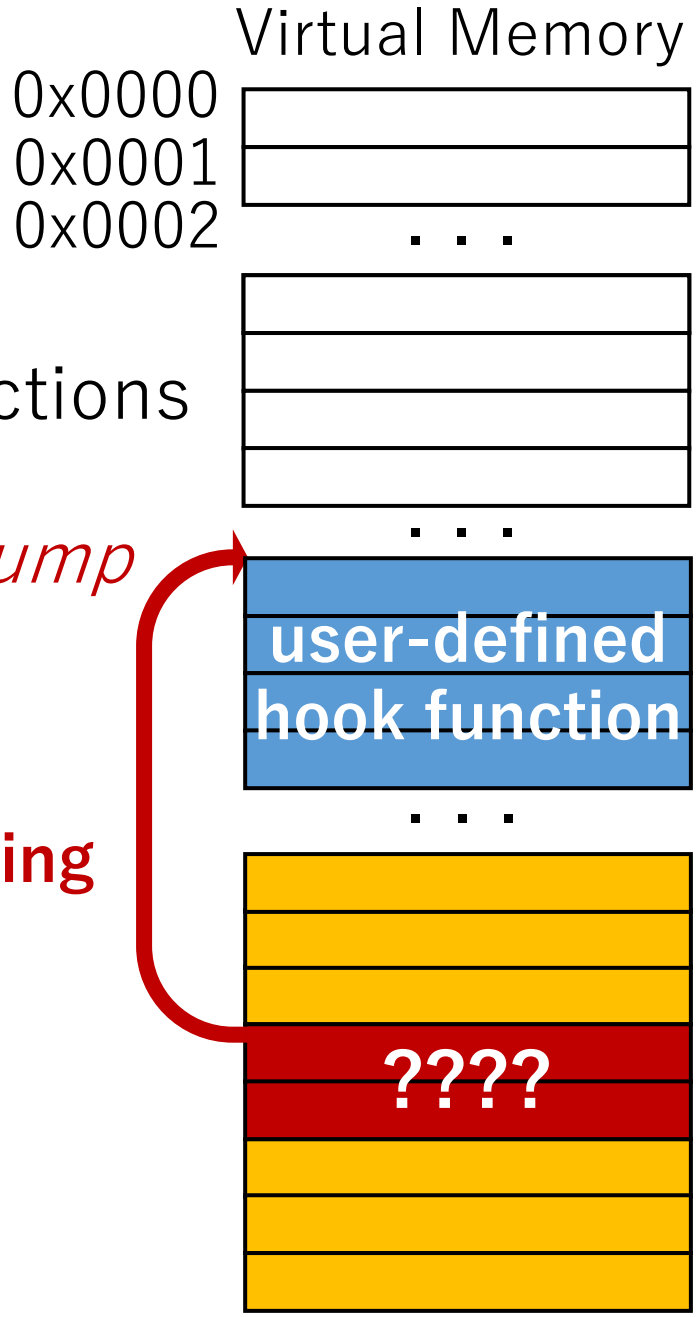

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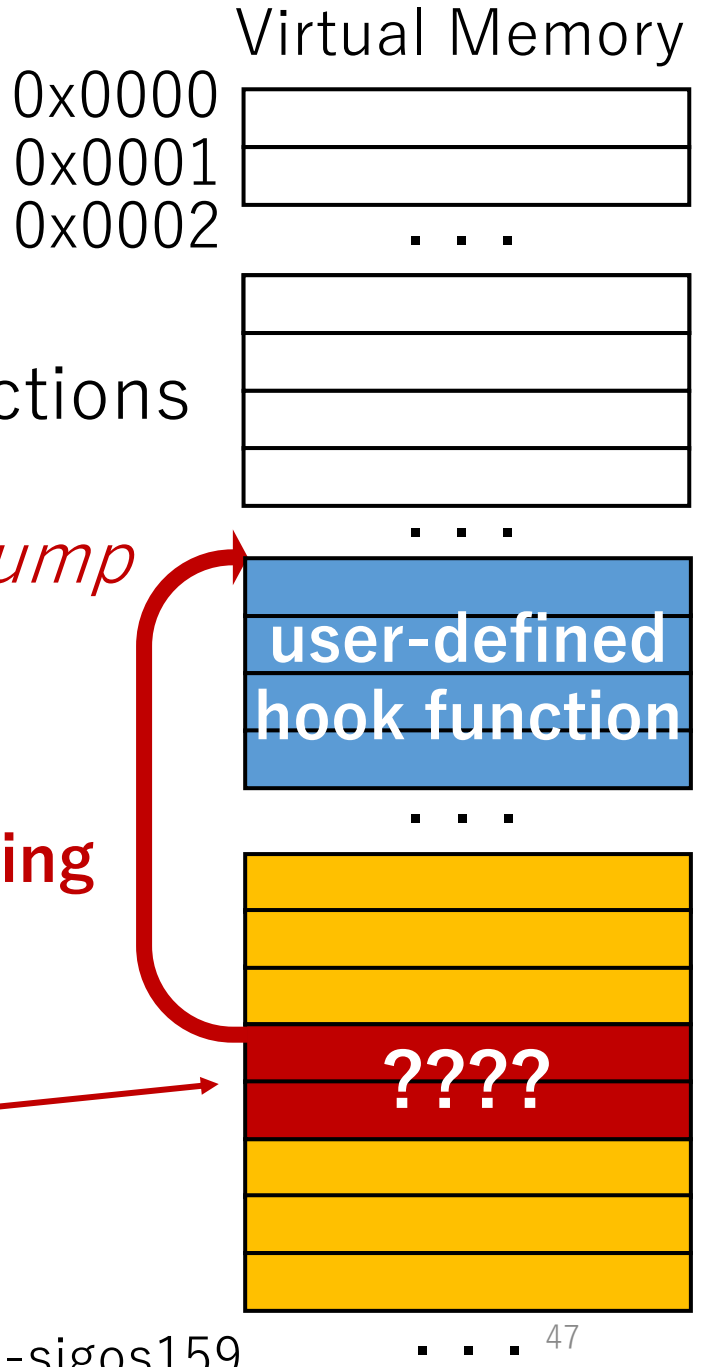
- **Question: what should we put here?**



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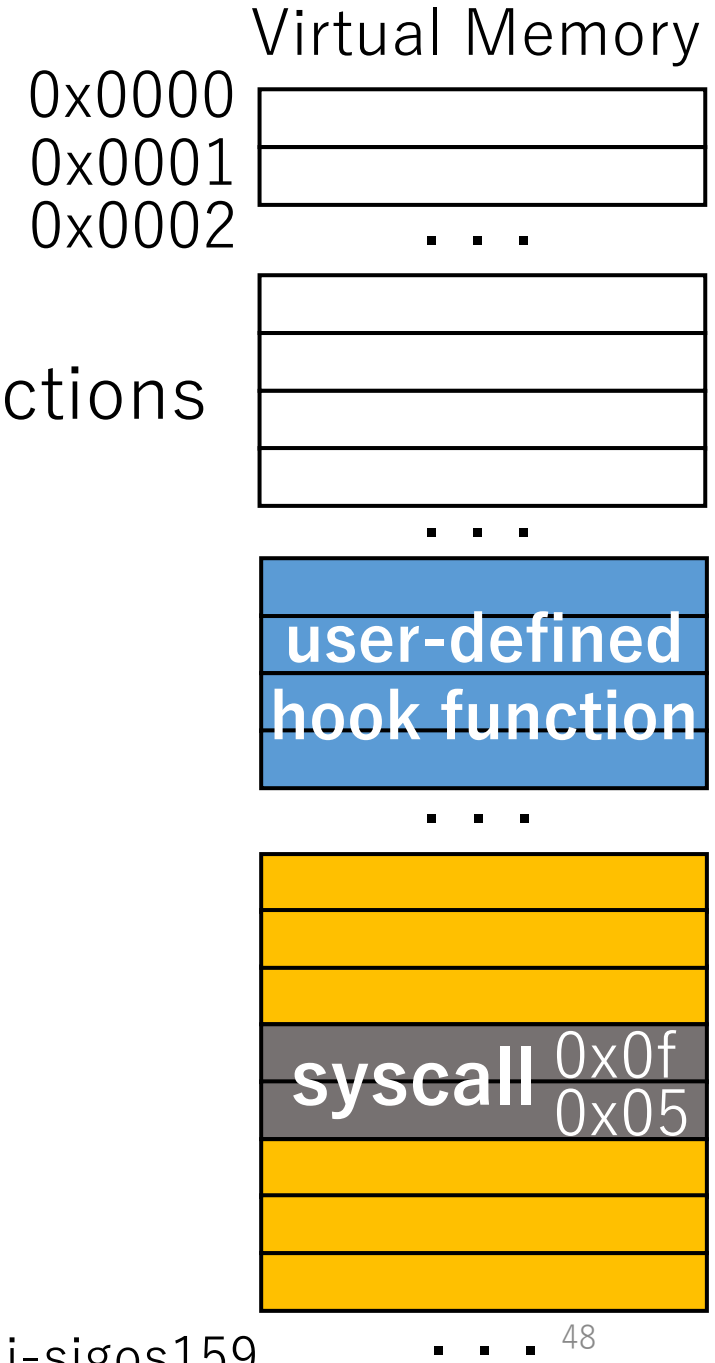

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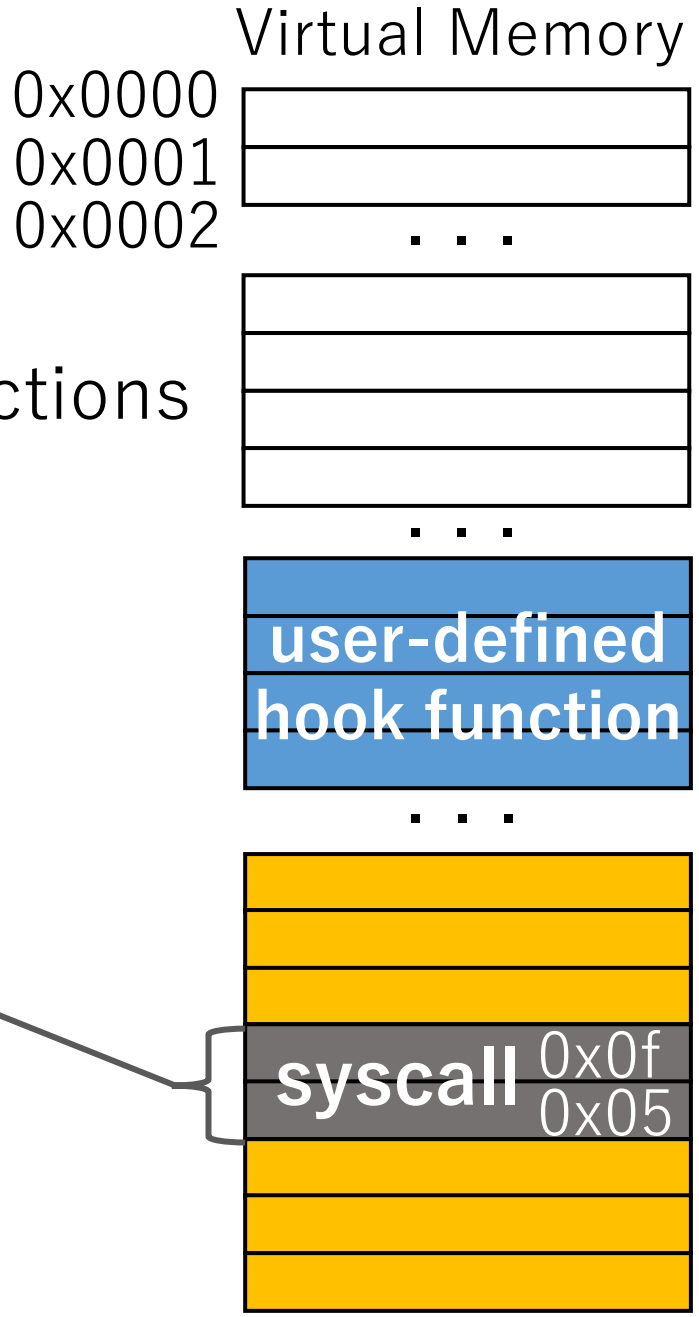

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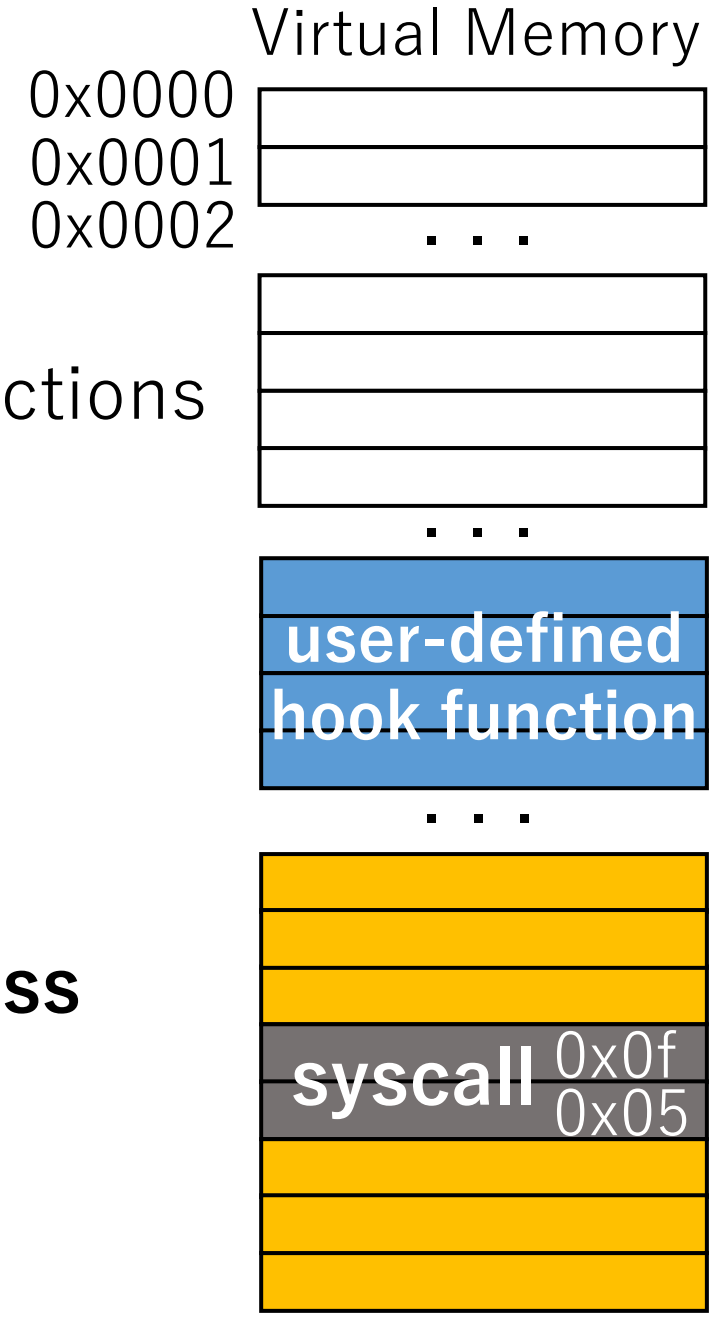

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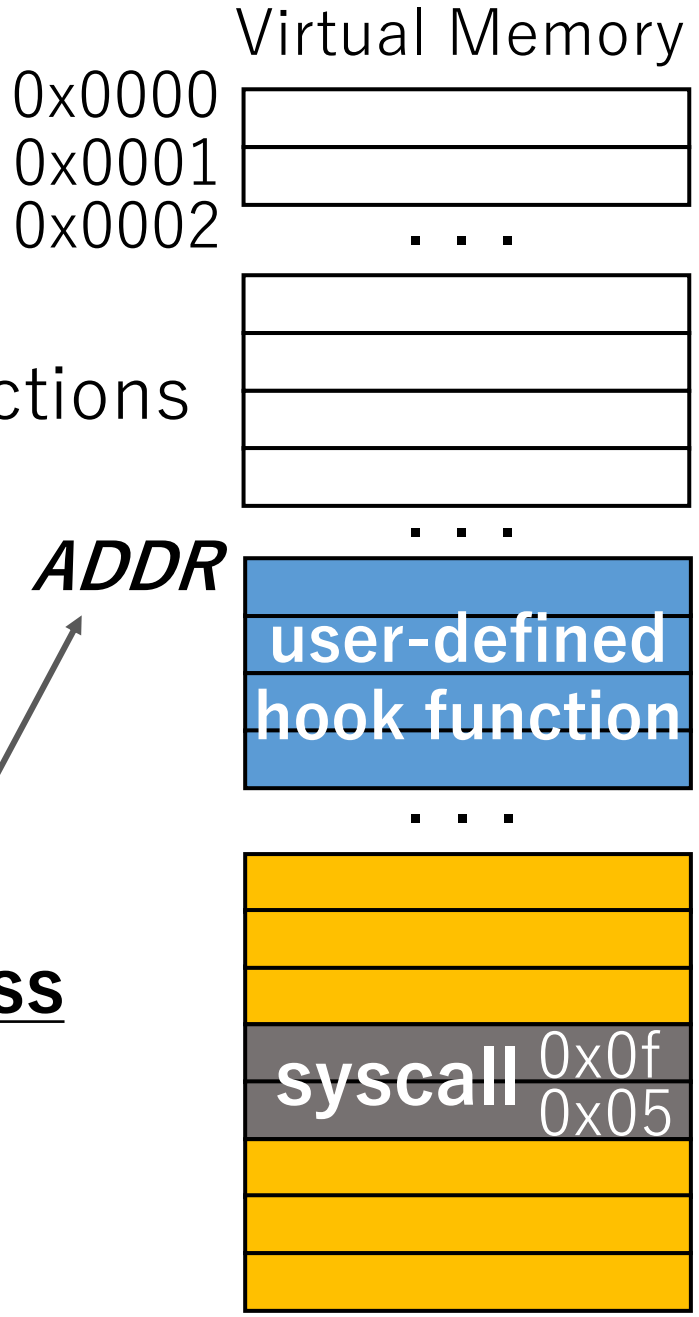

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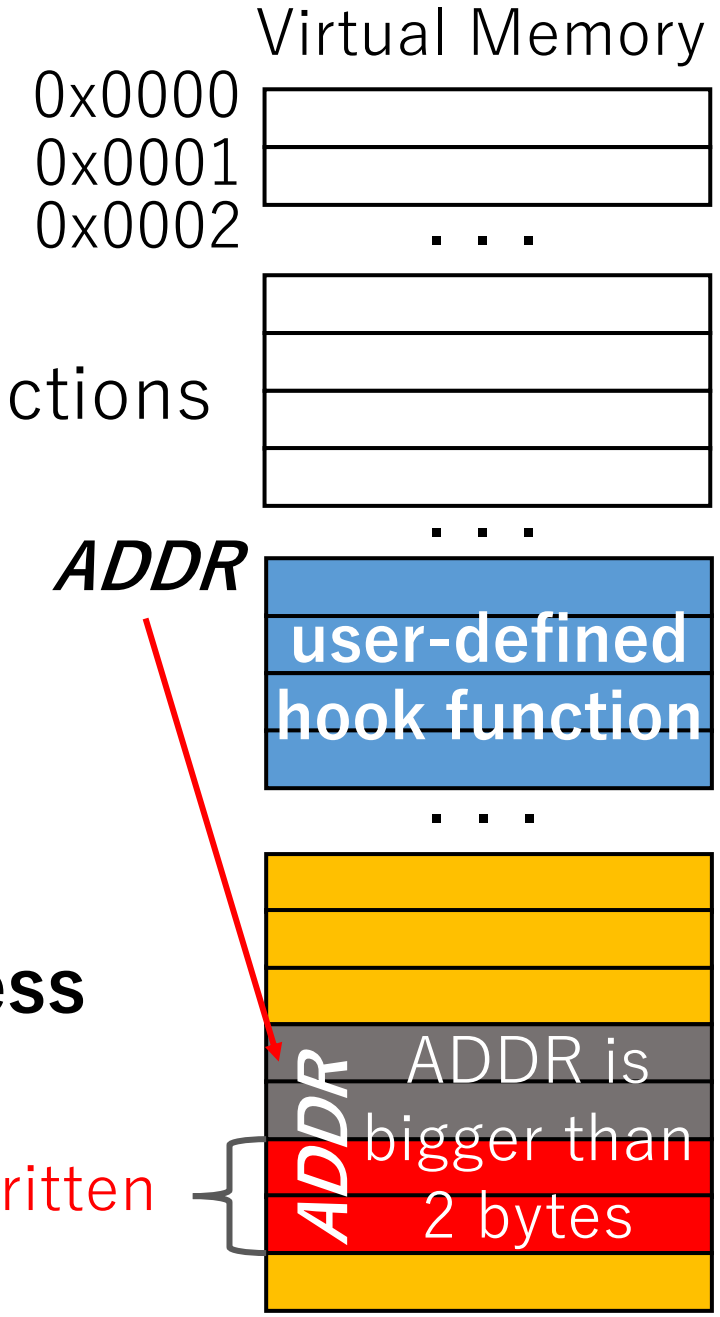

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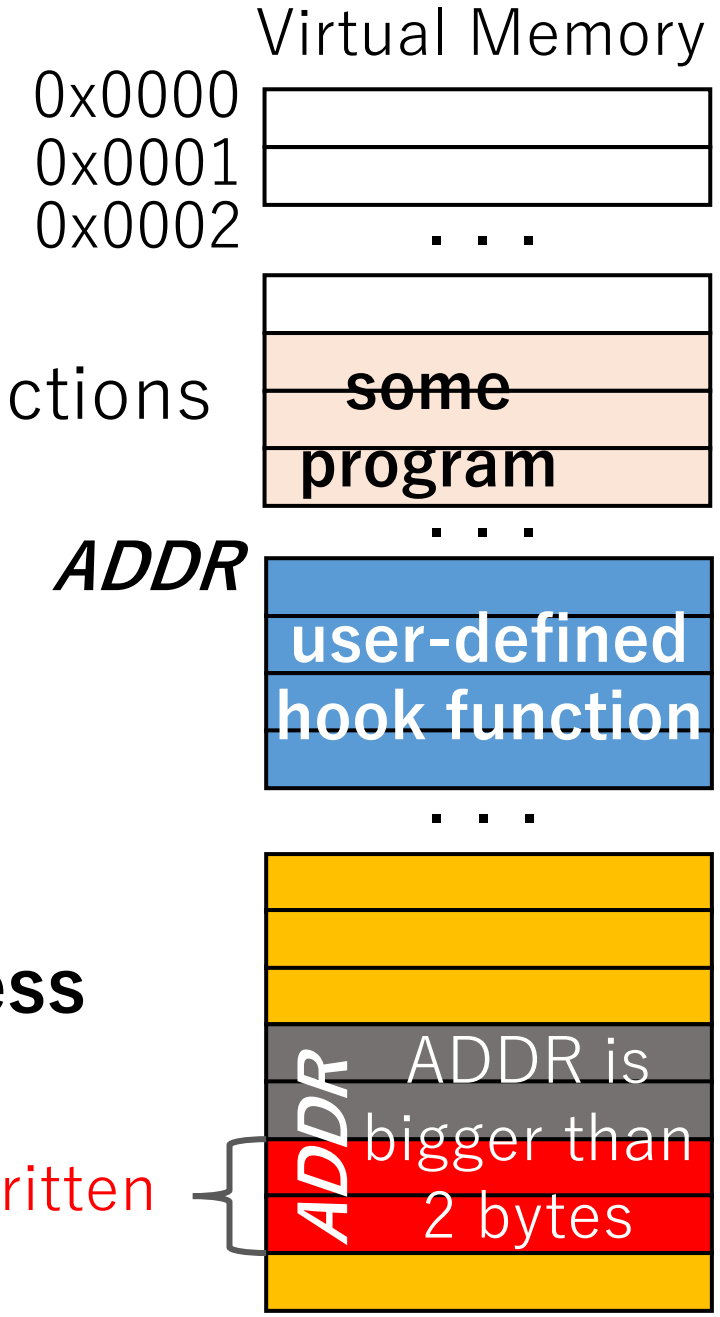

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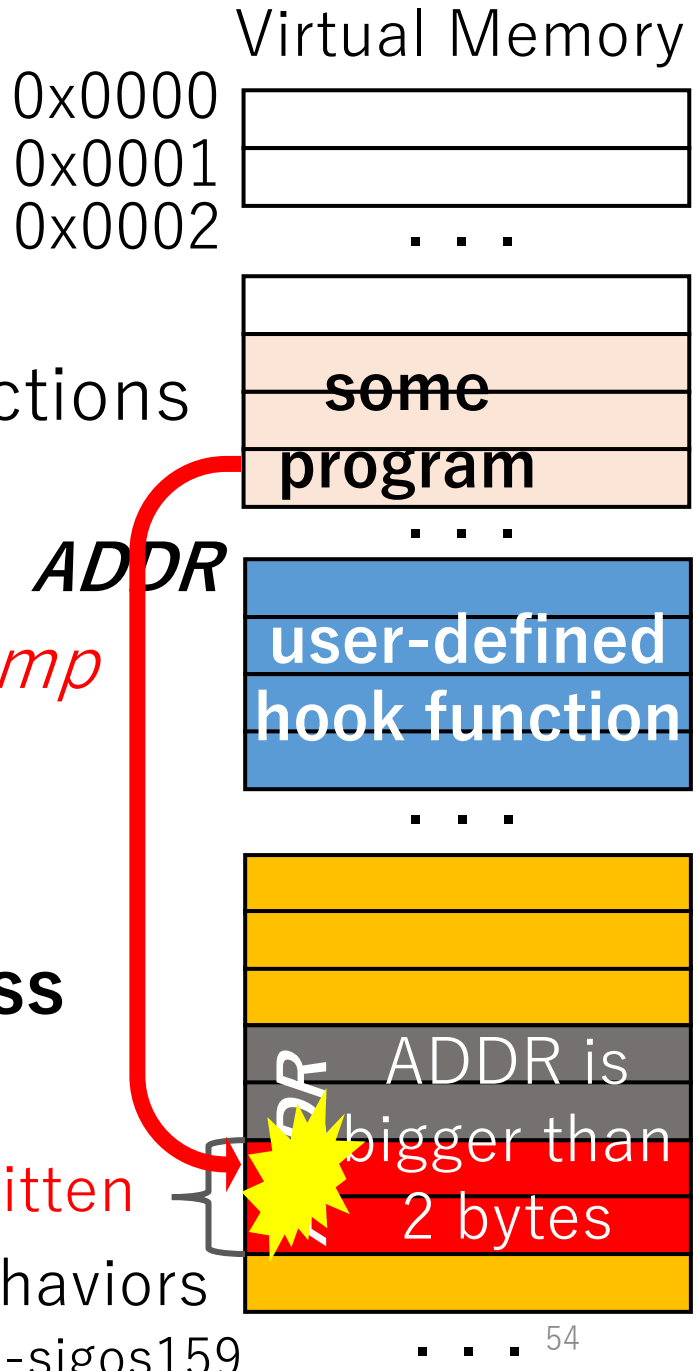

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Goal ➡ **jump to a function using only 2 bytes originally occupied by syscall/sysenter**

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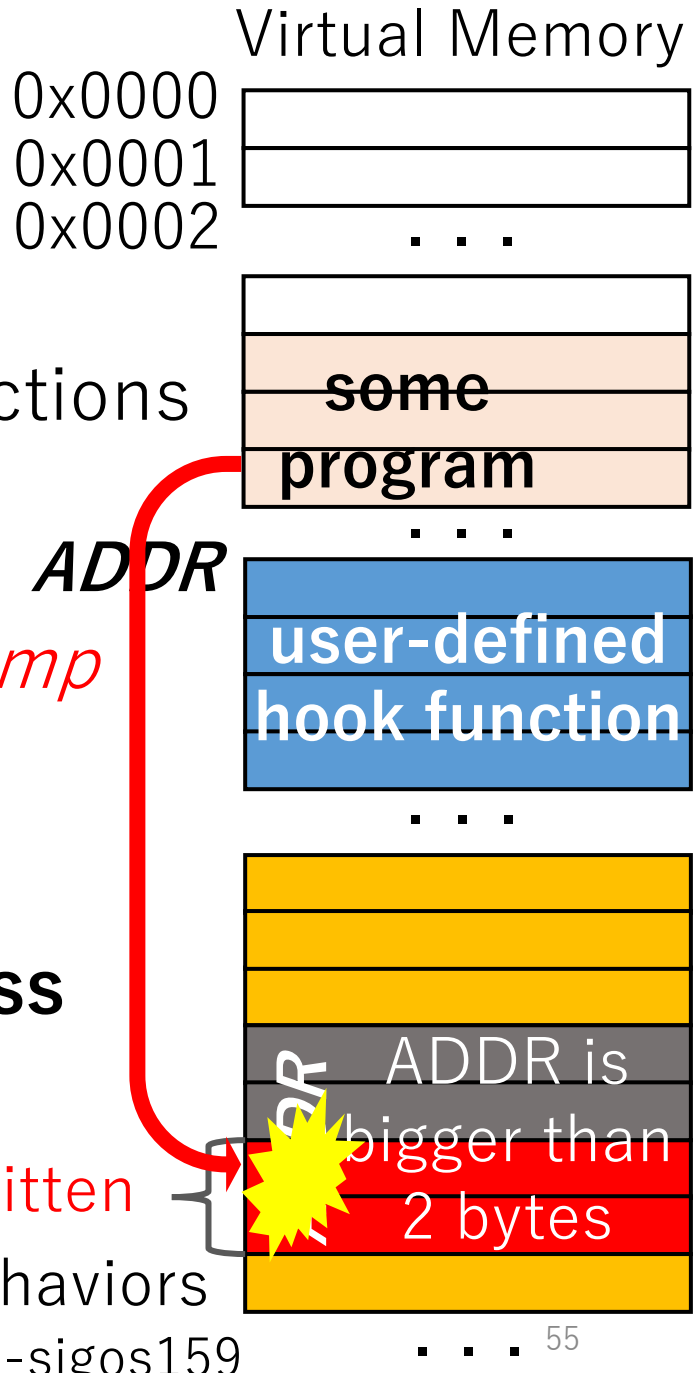

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Calling Convention

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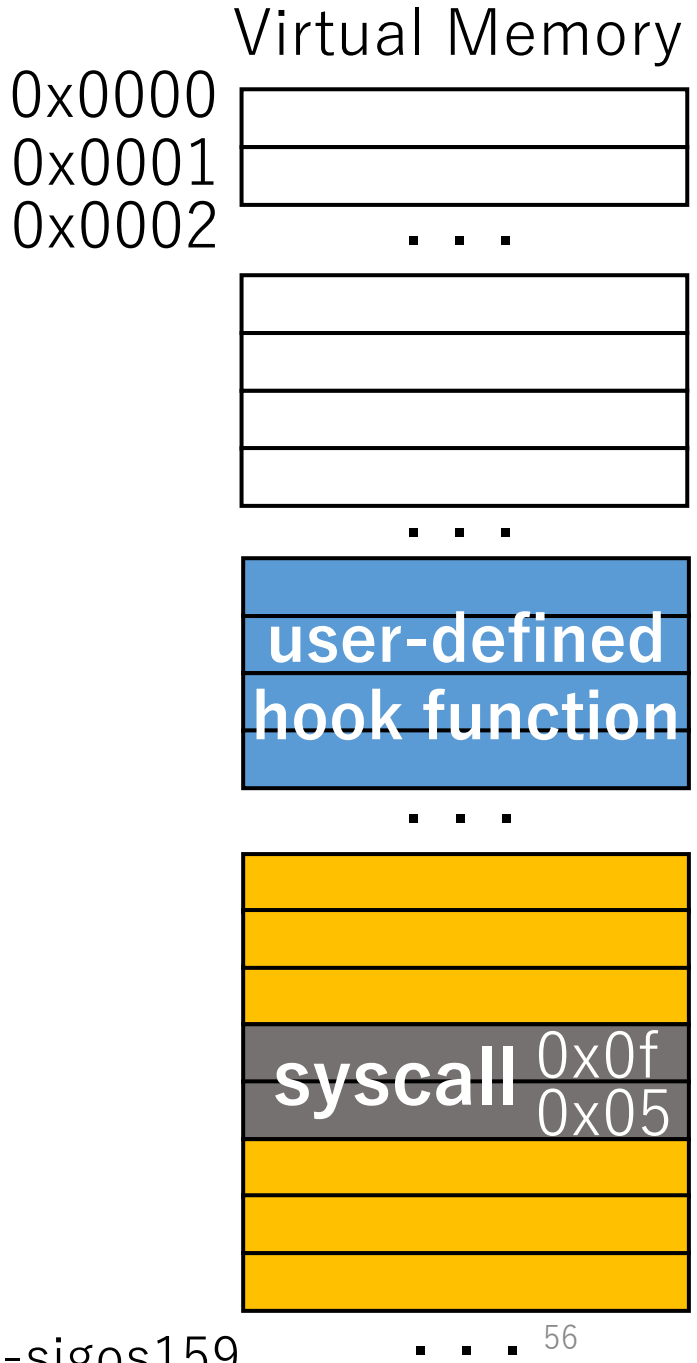

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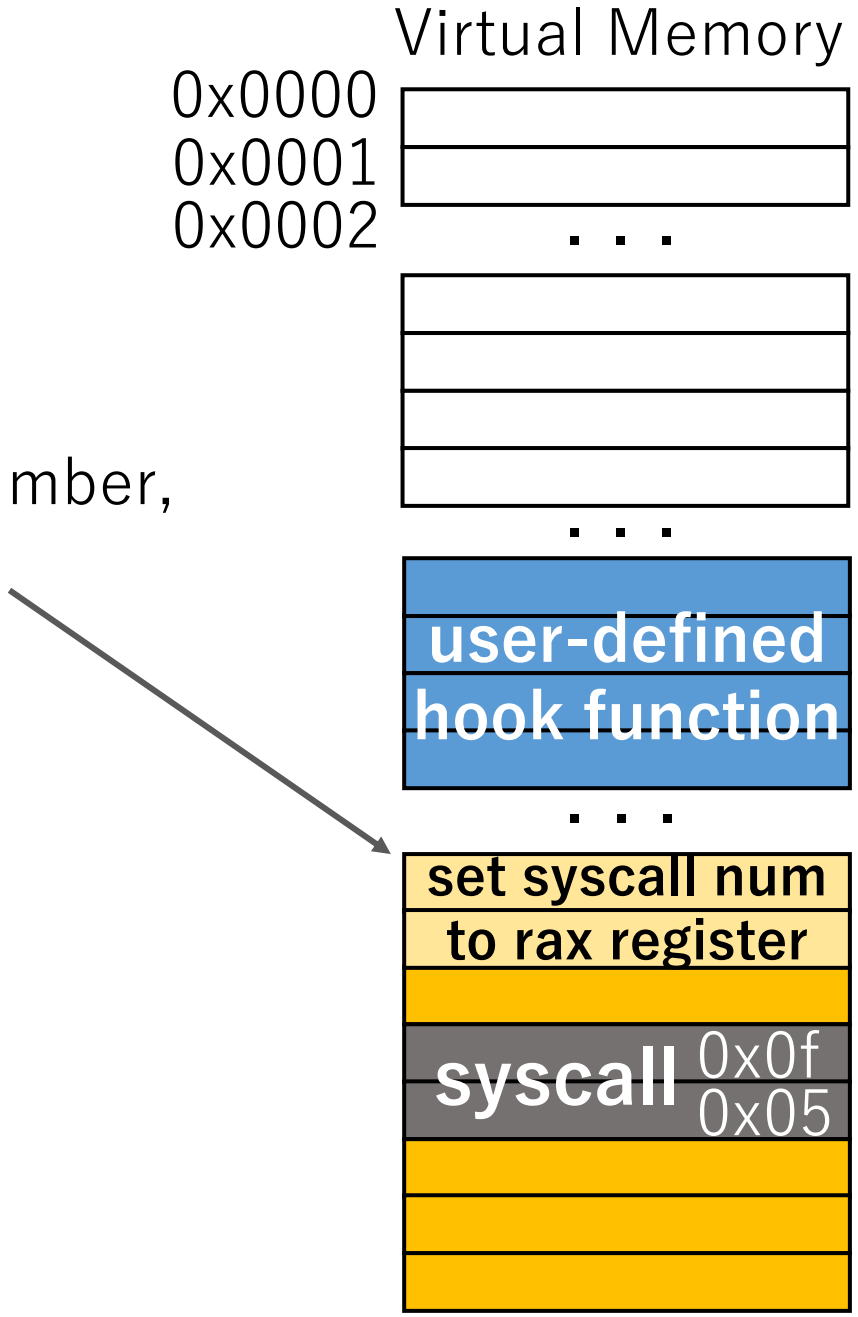

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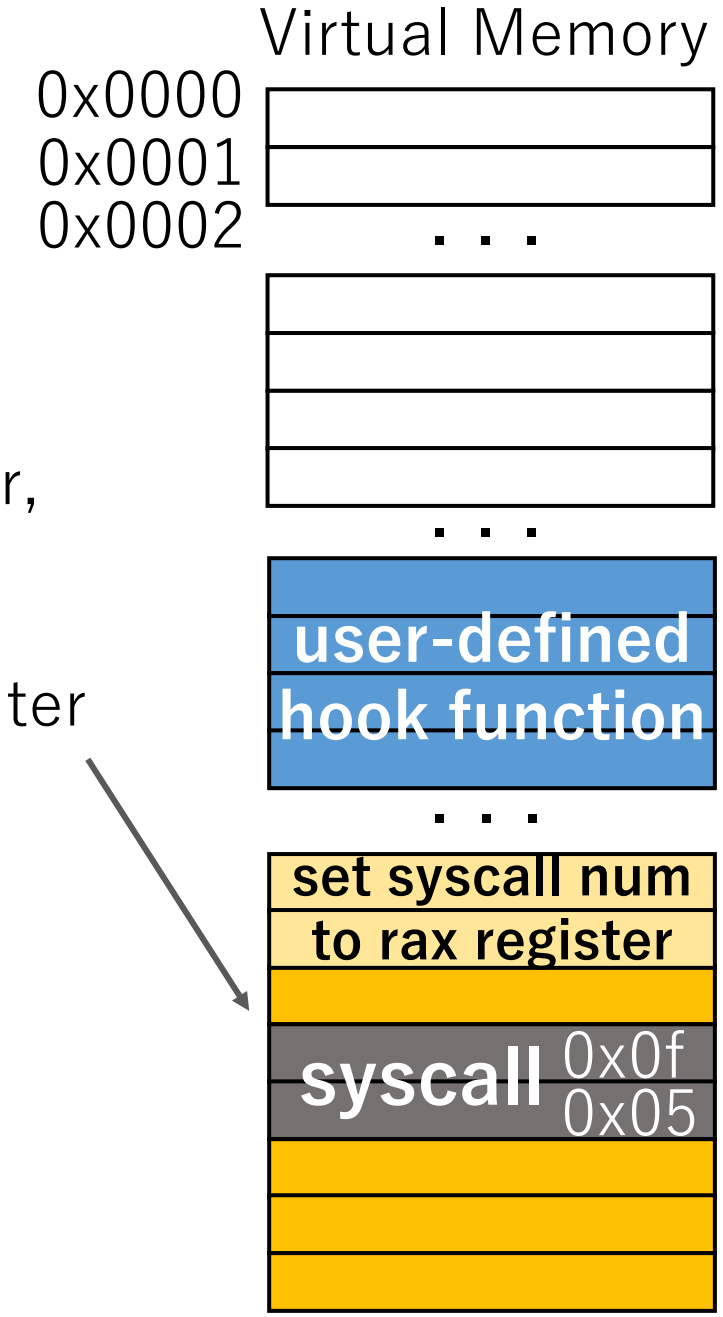

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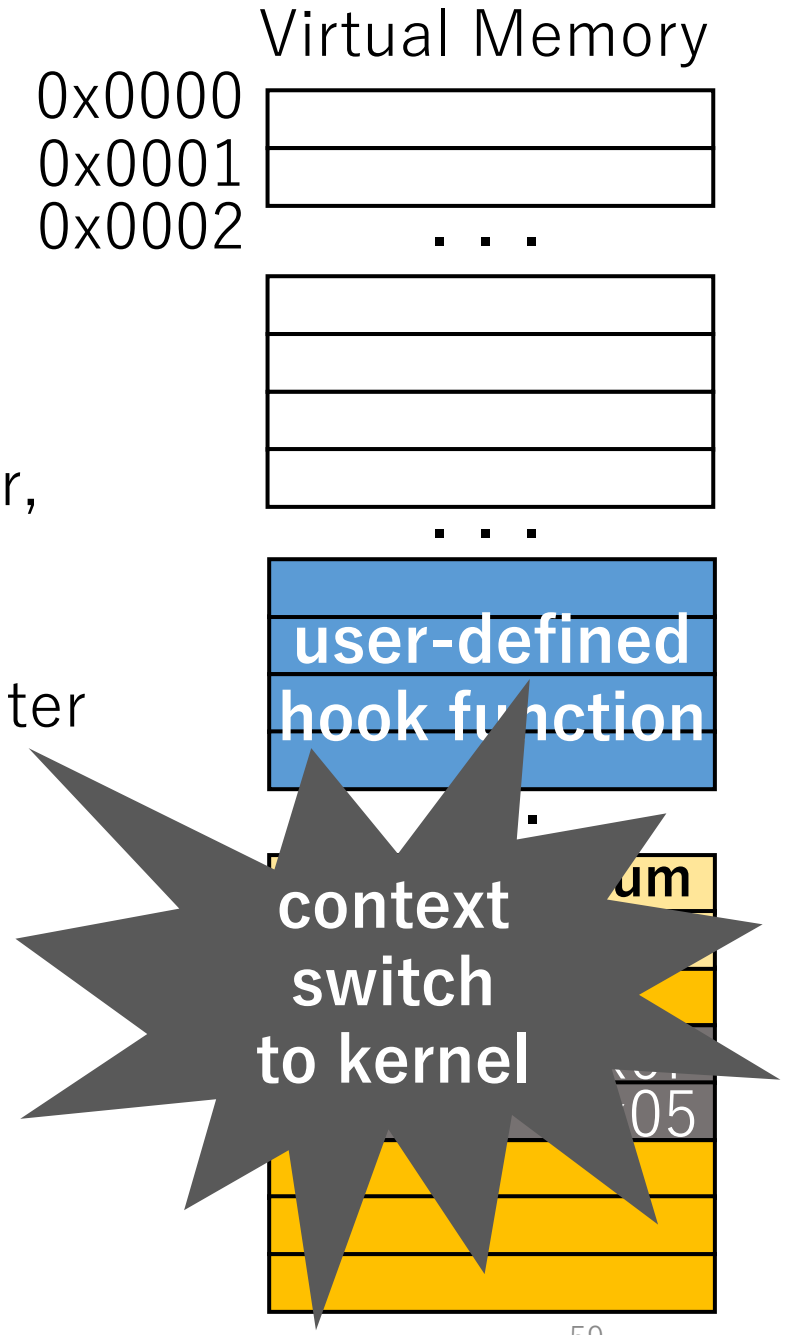

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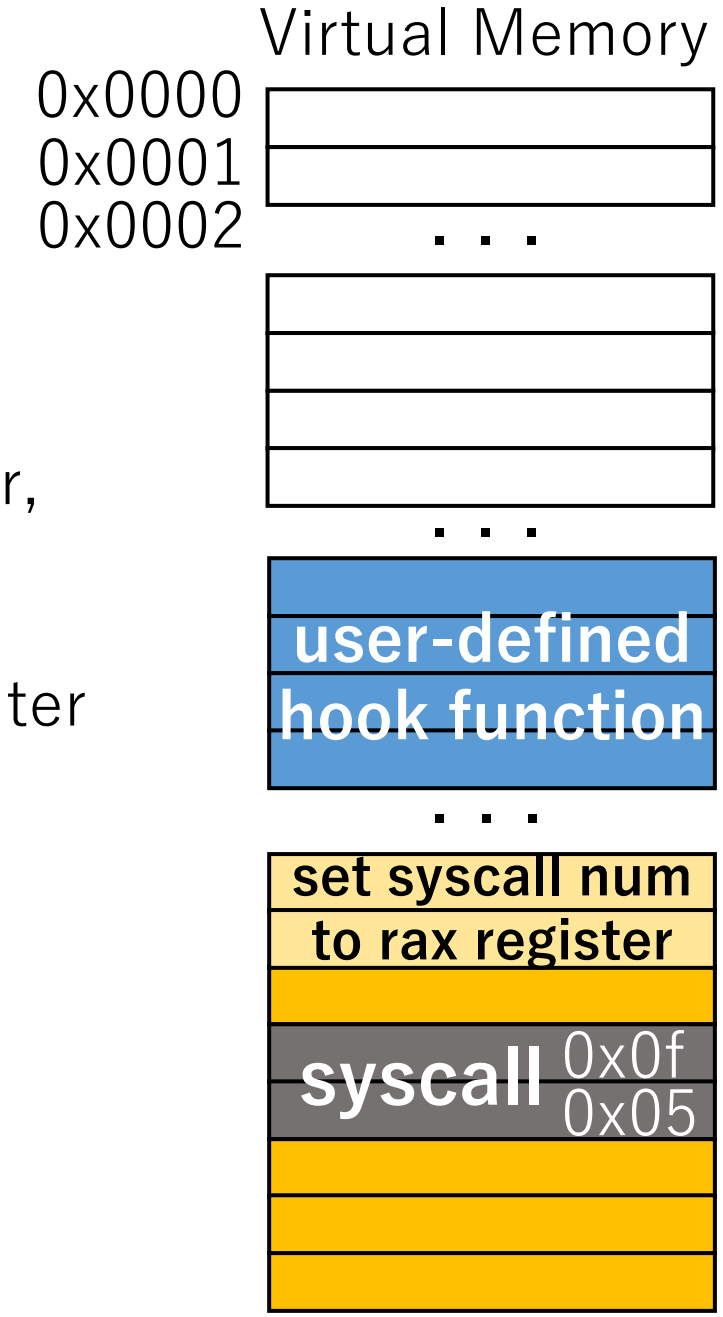

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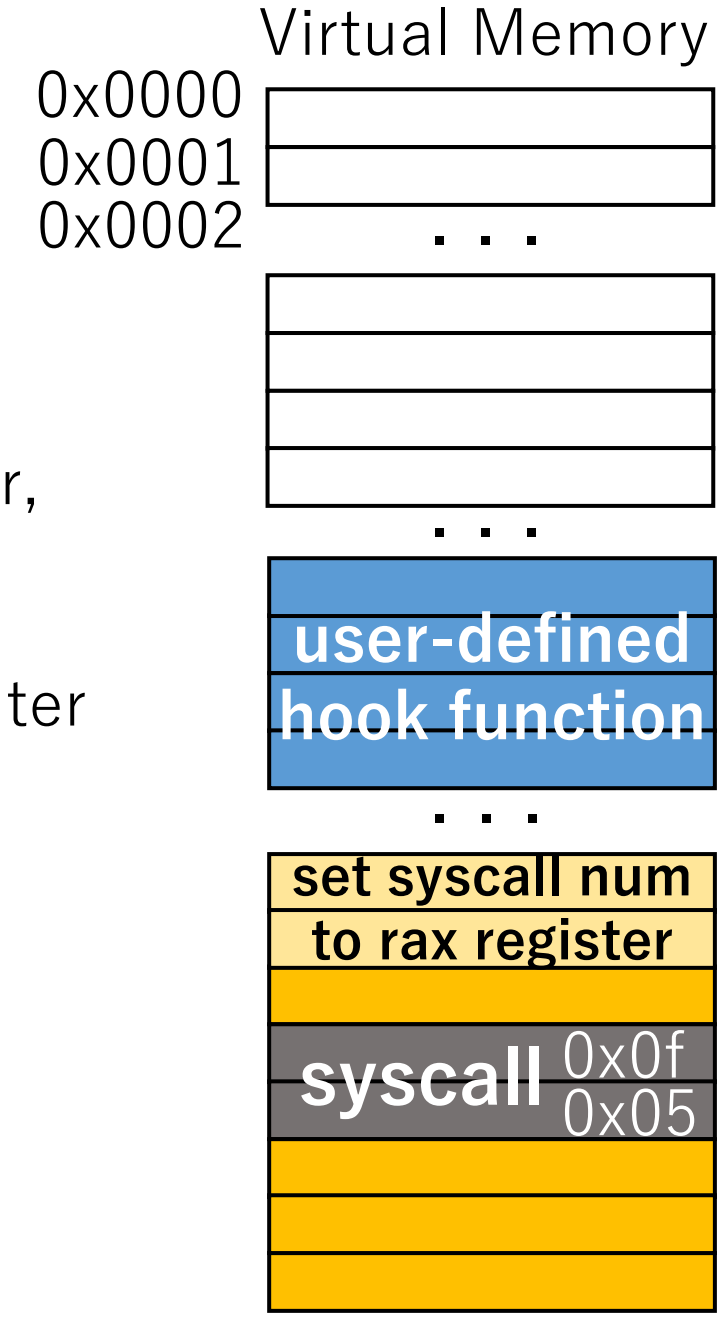

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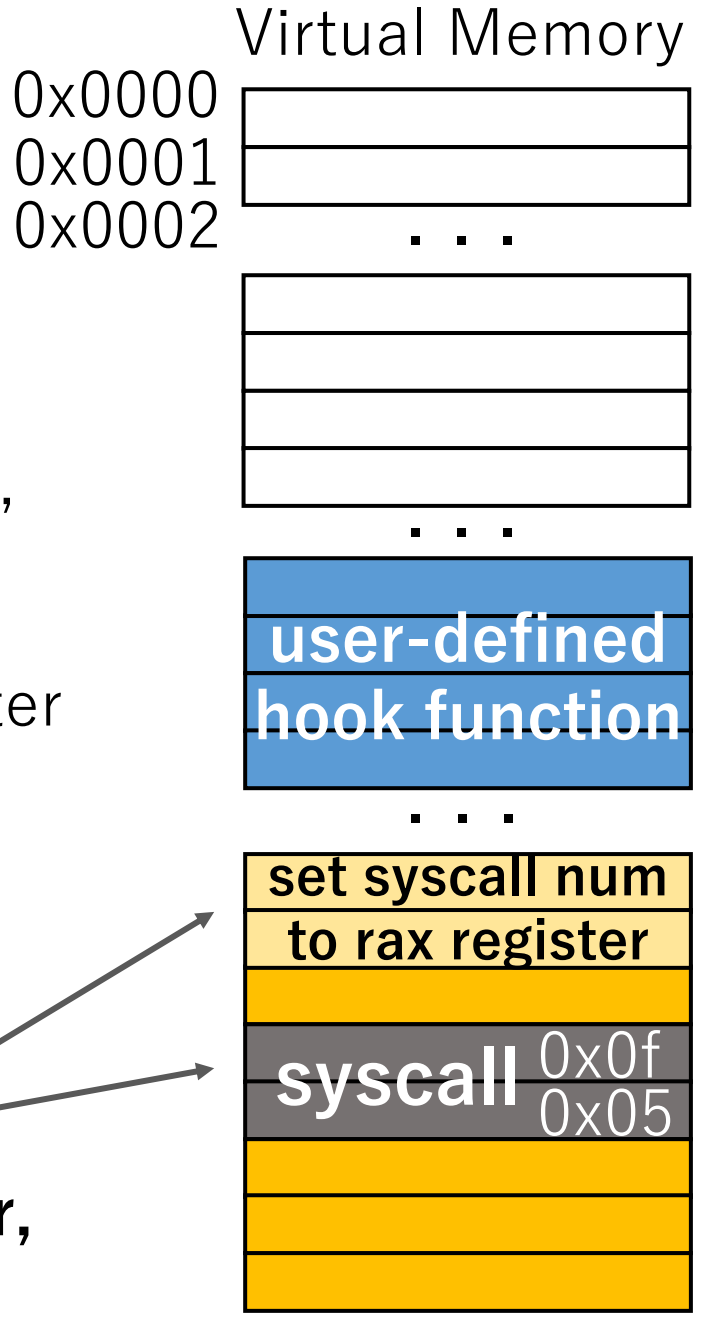

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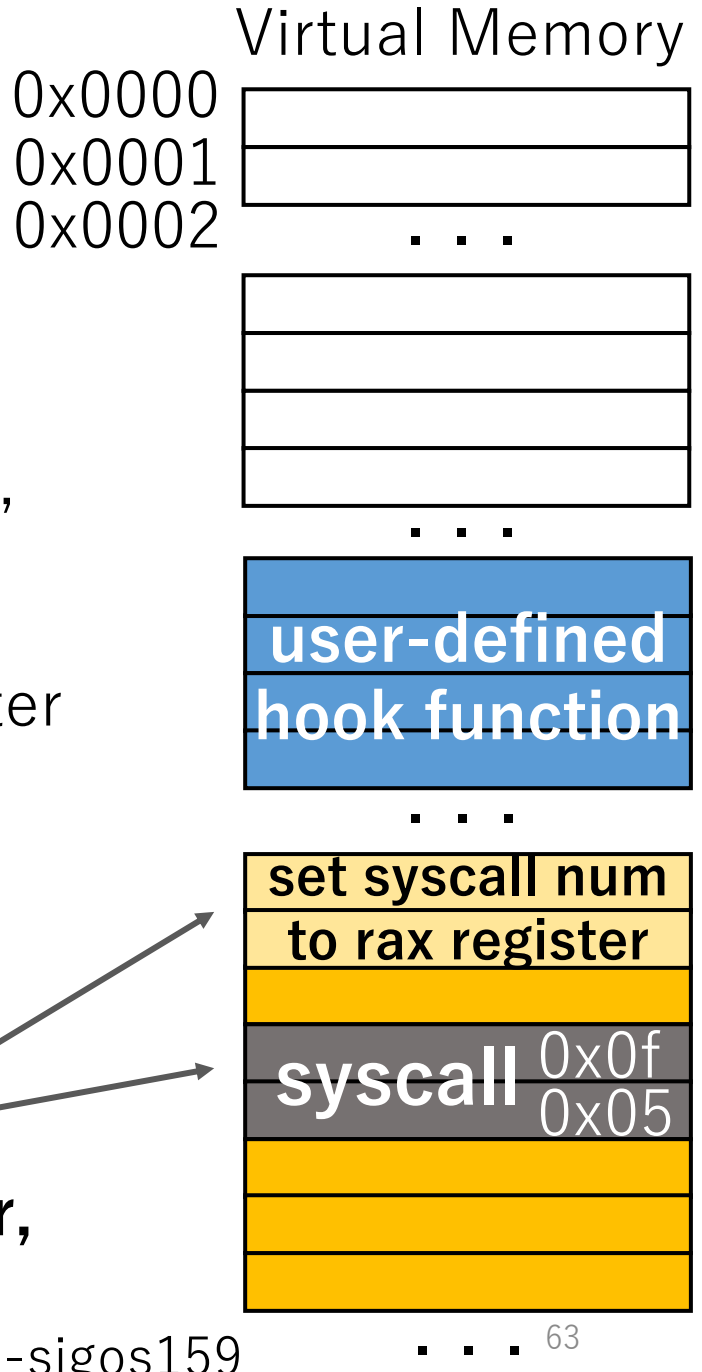

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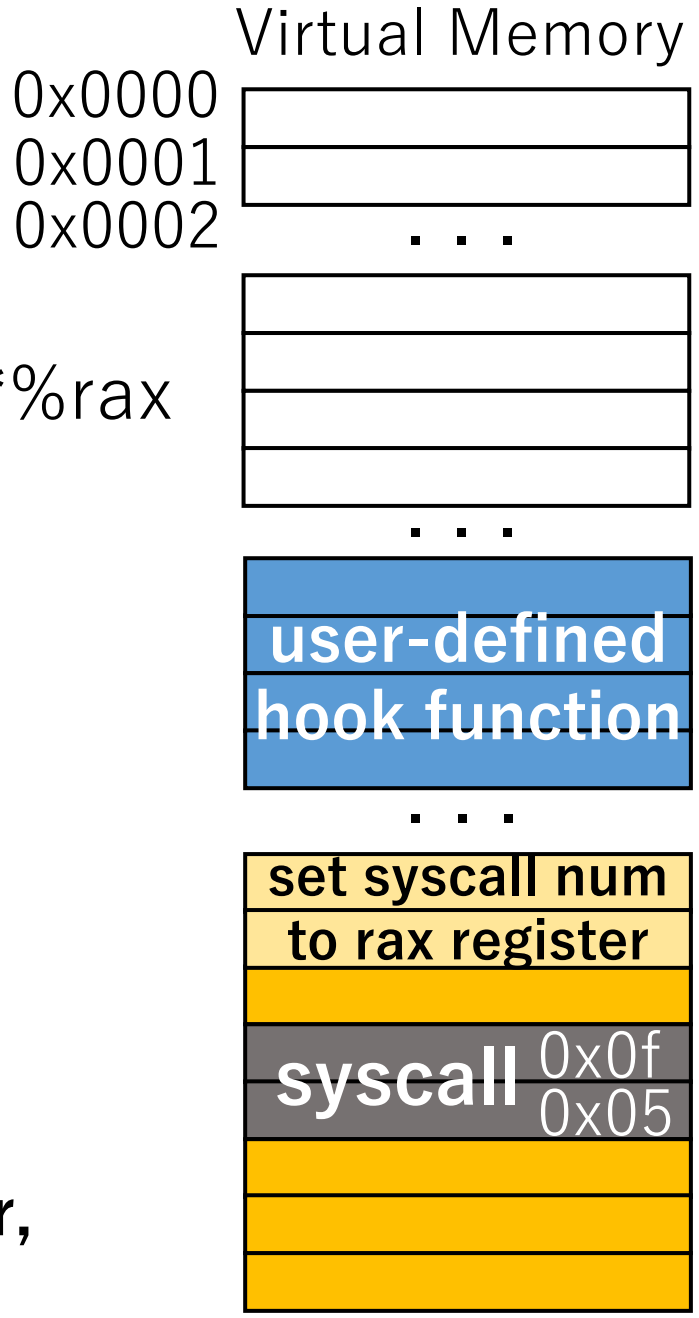

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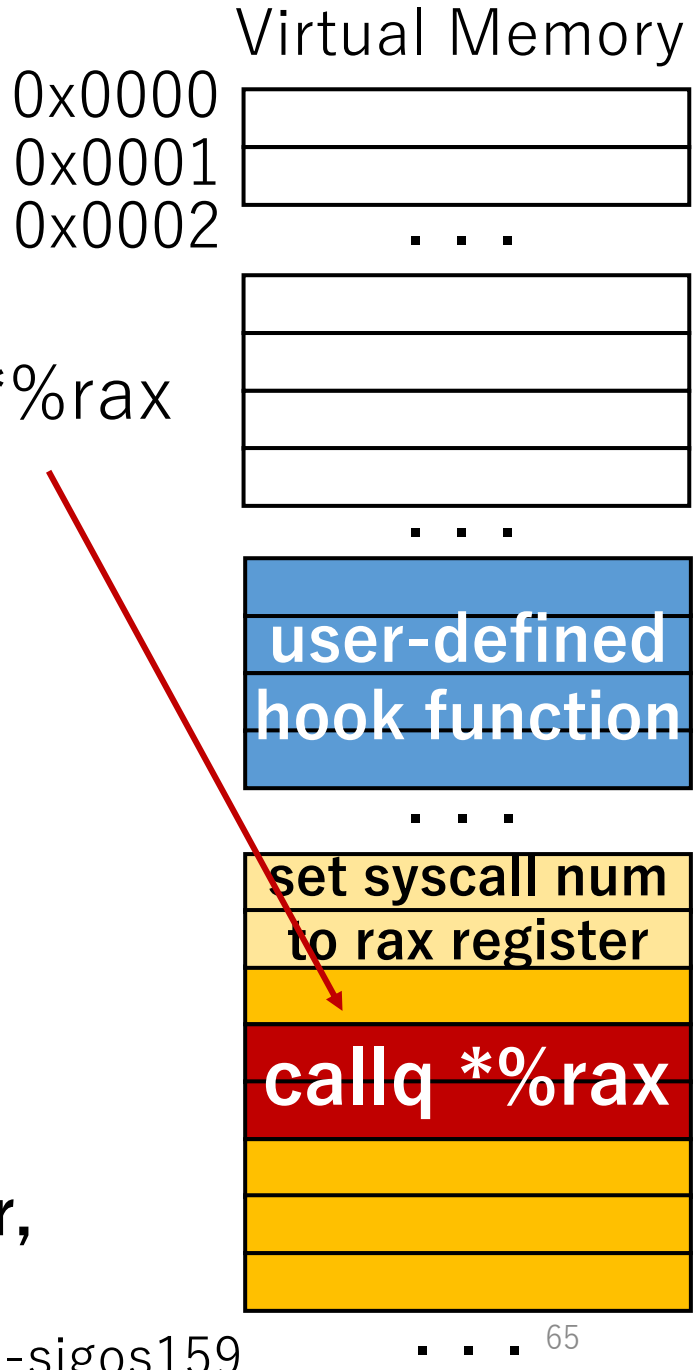

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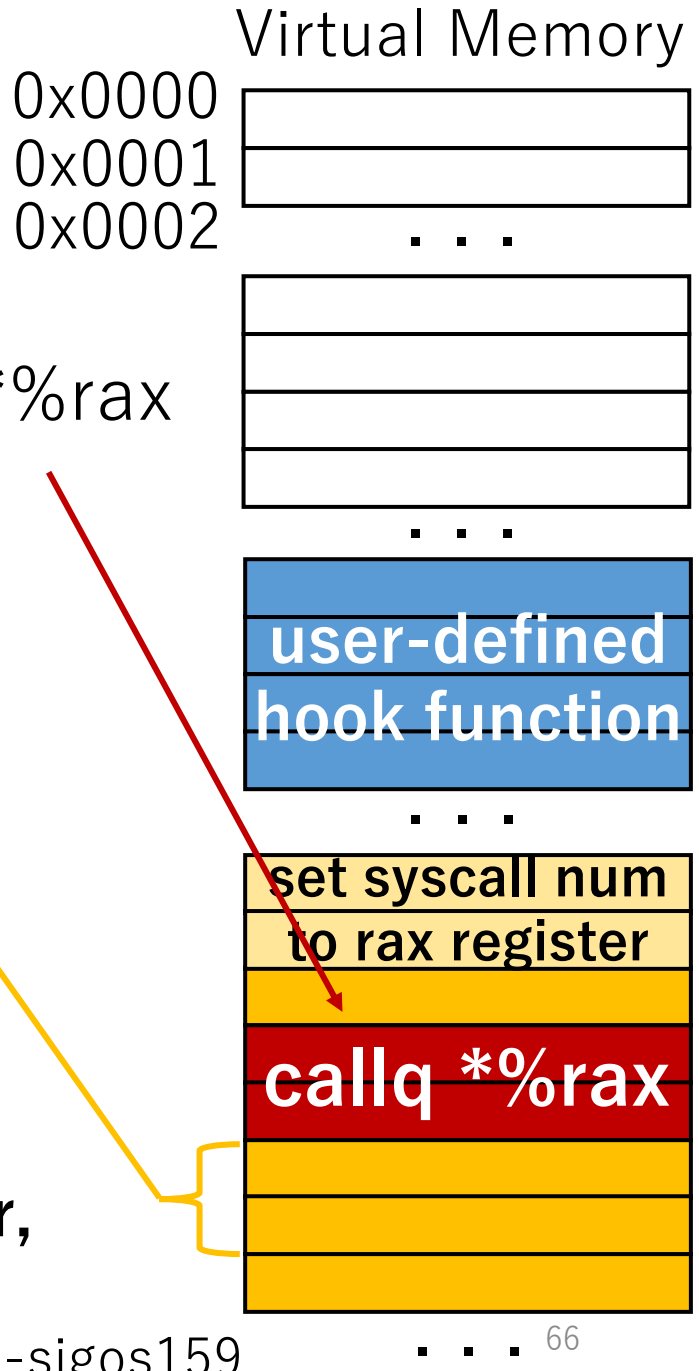

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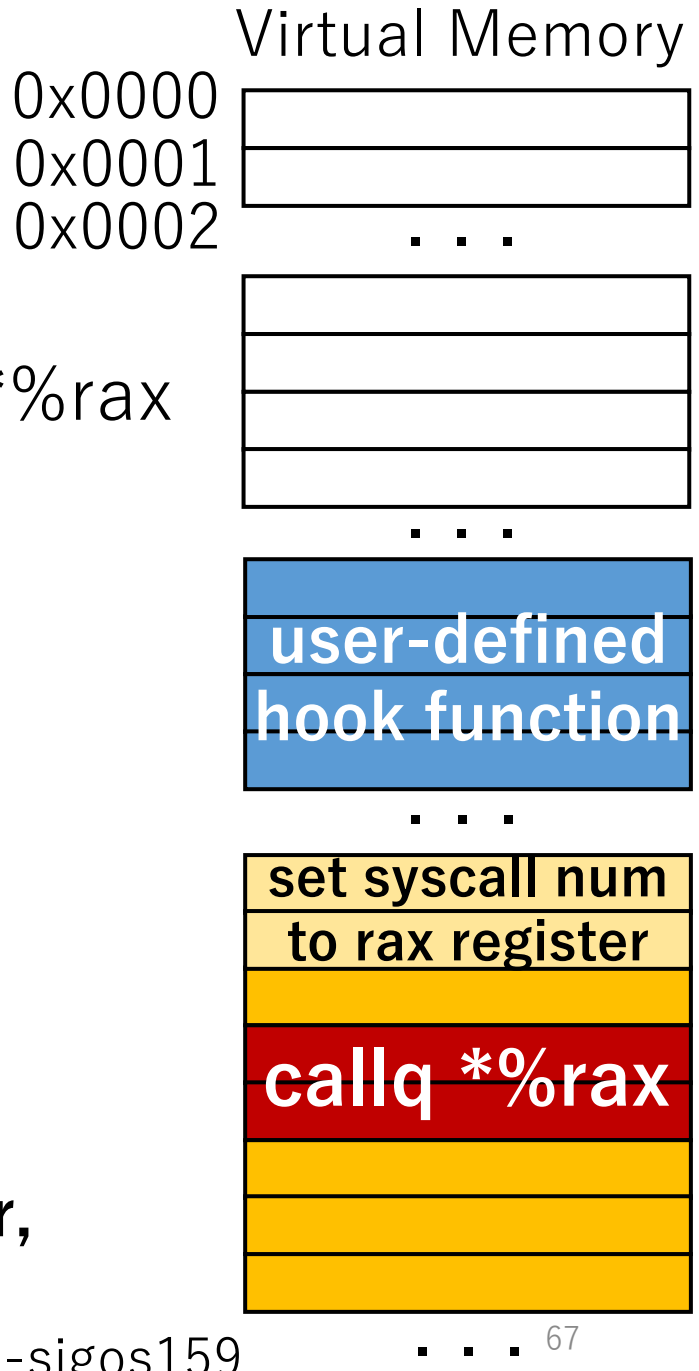

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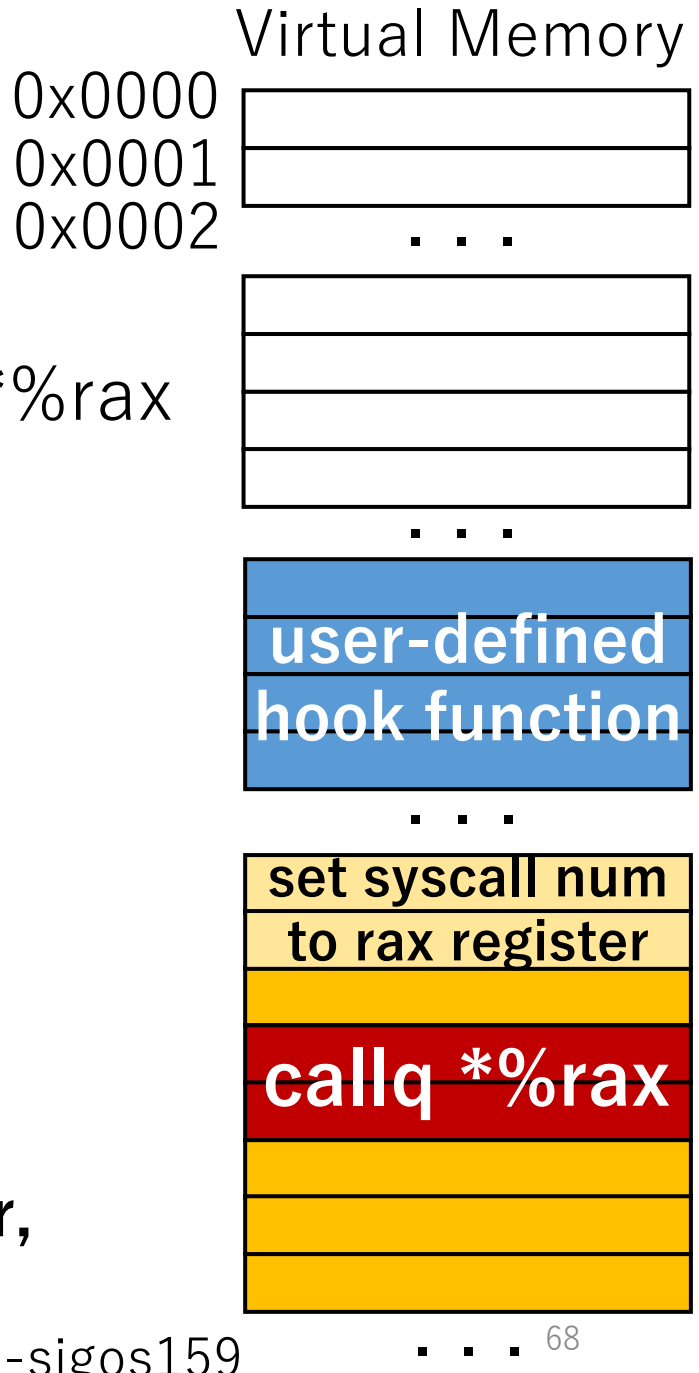

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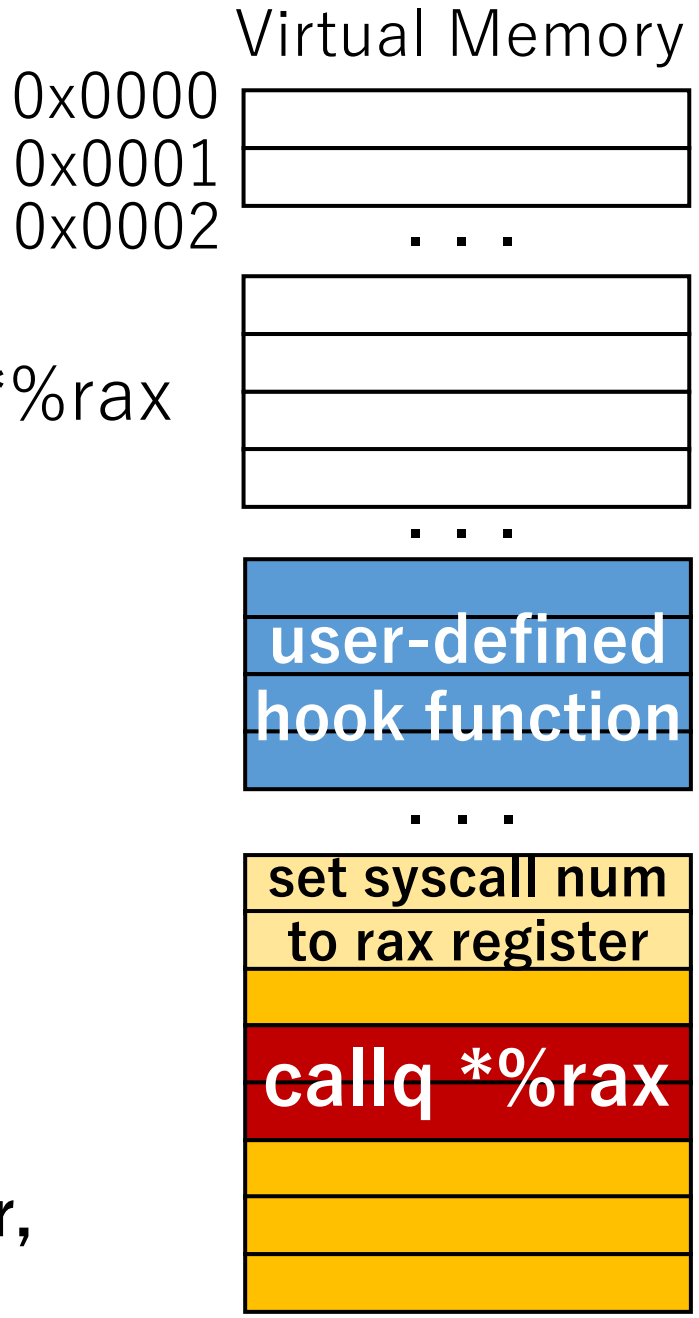

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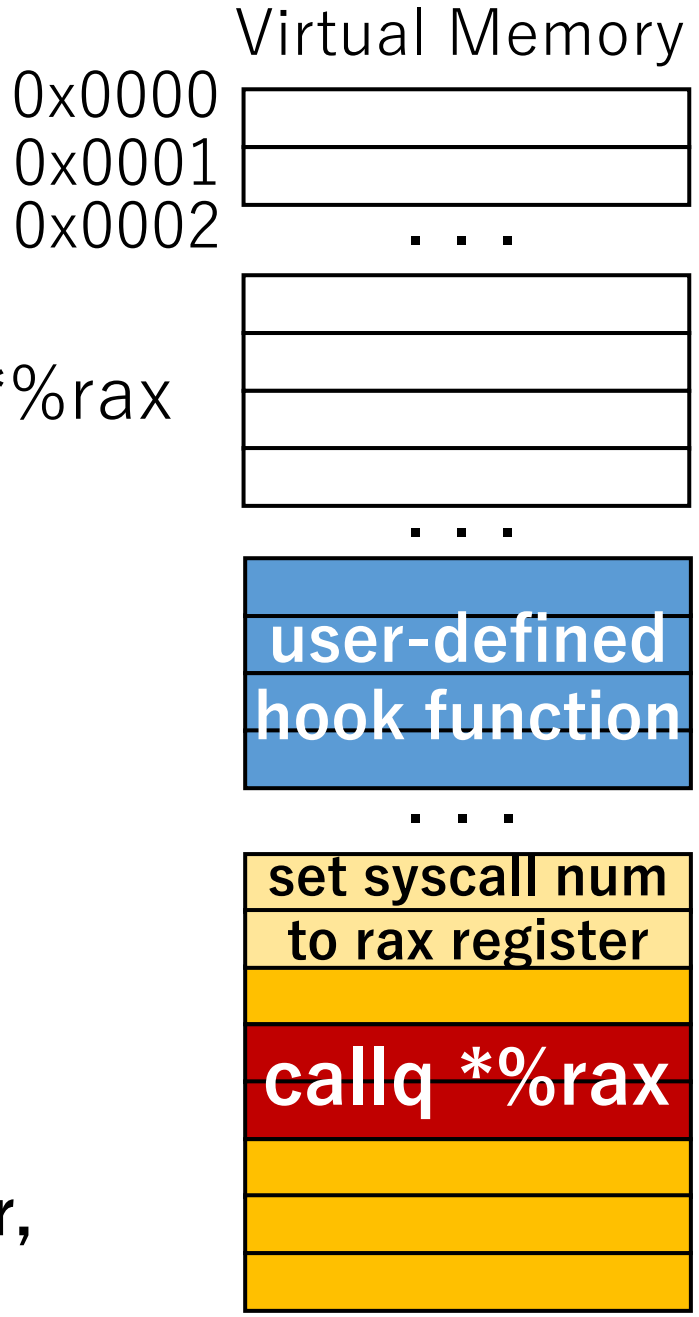

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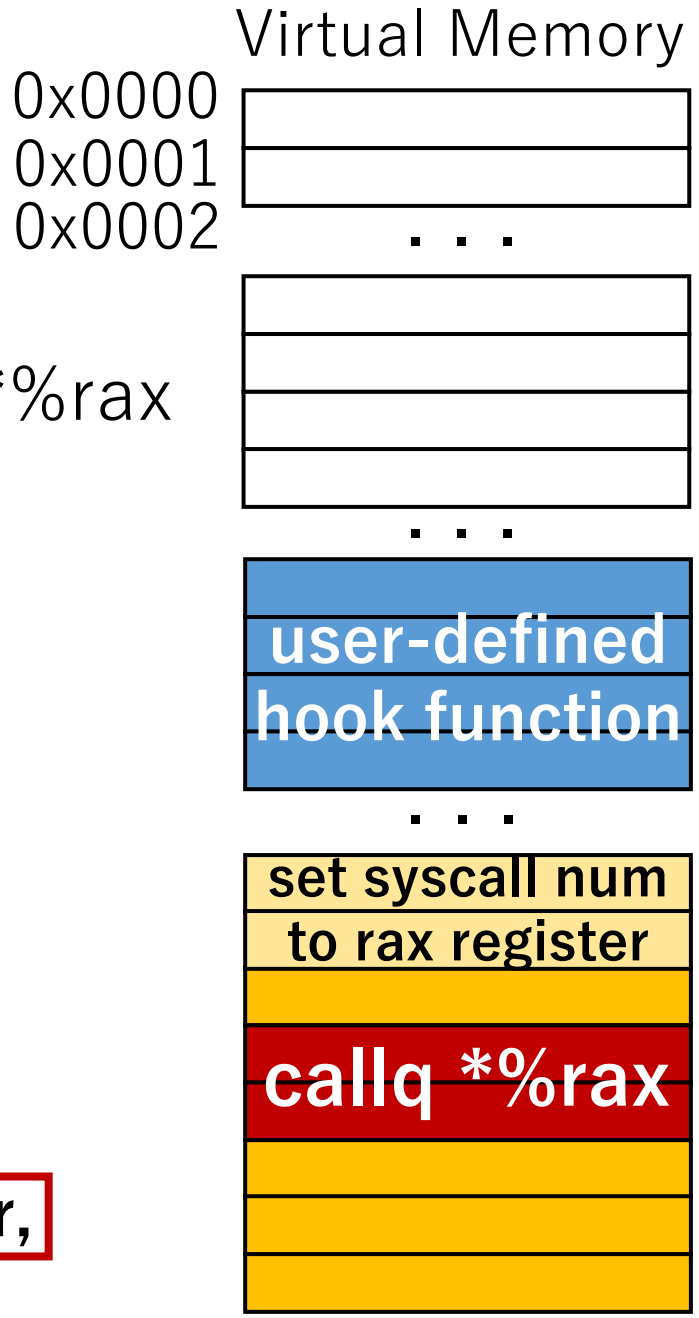

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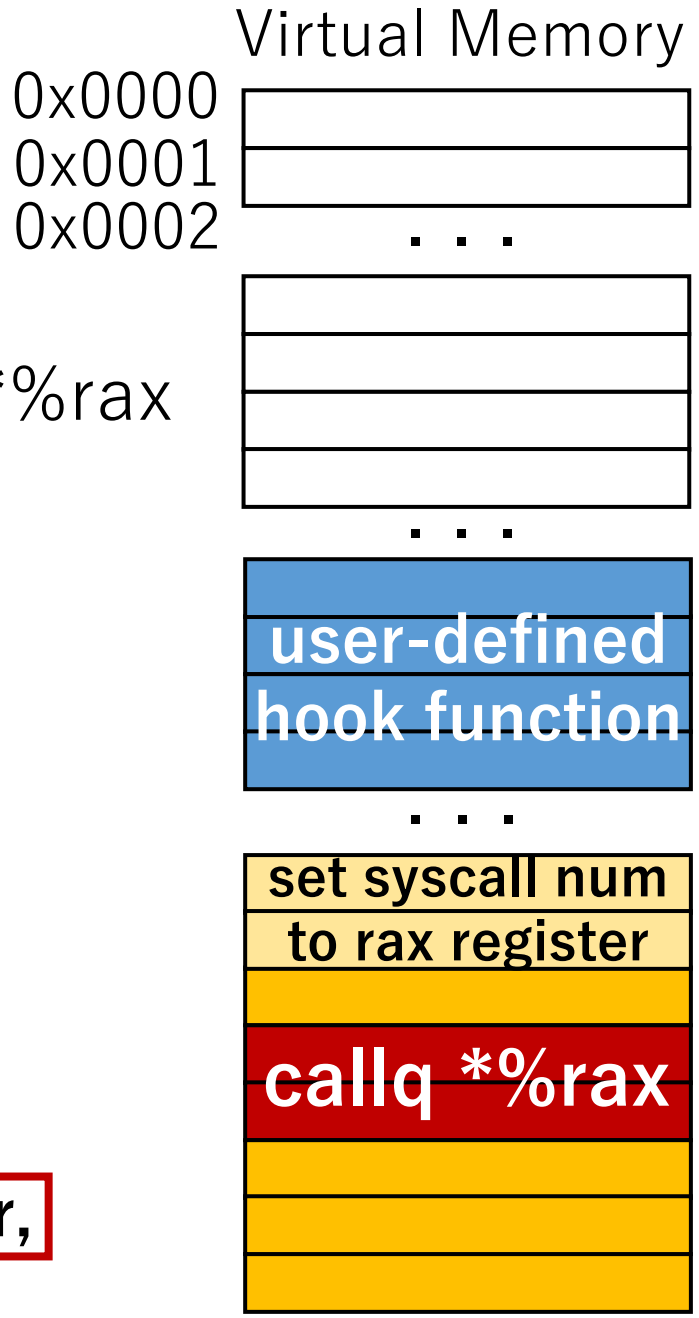

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https://github.com/yasukata/presentation/tree/gh-pages/2023/05/ipsj-sigos159

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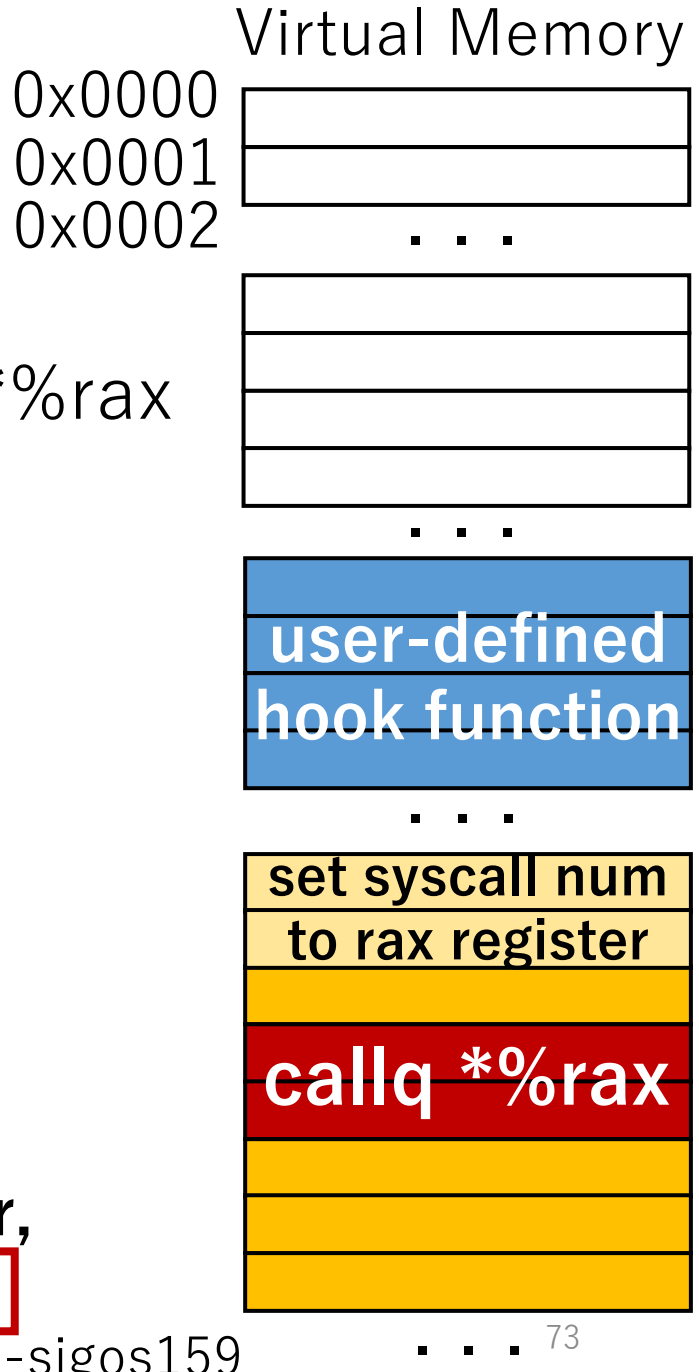

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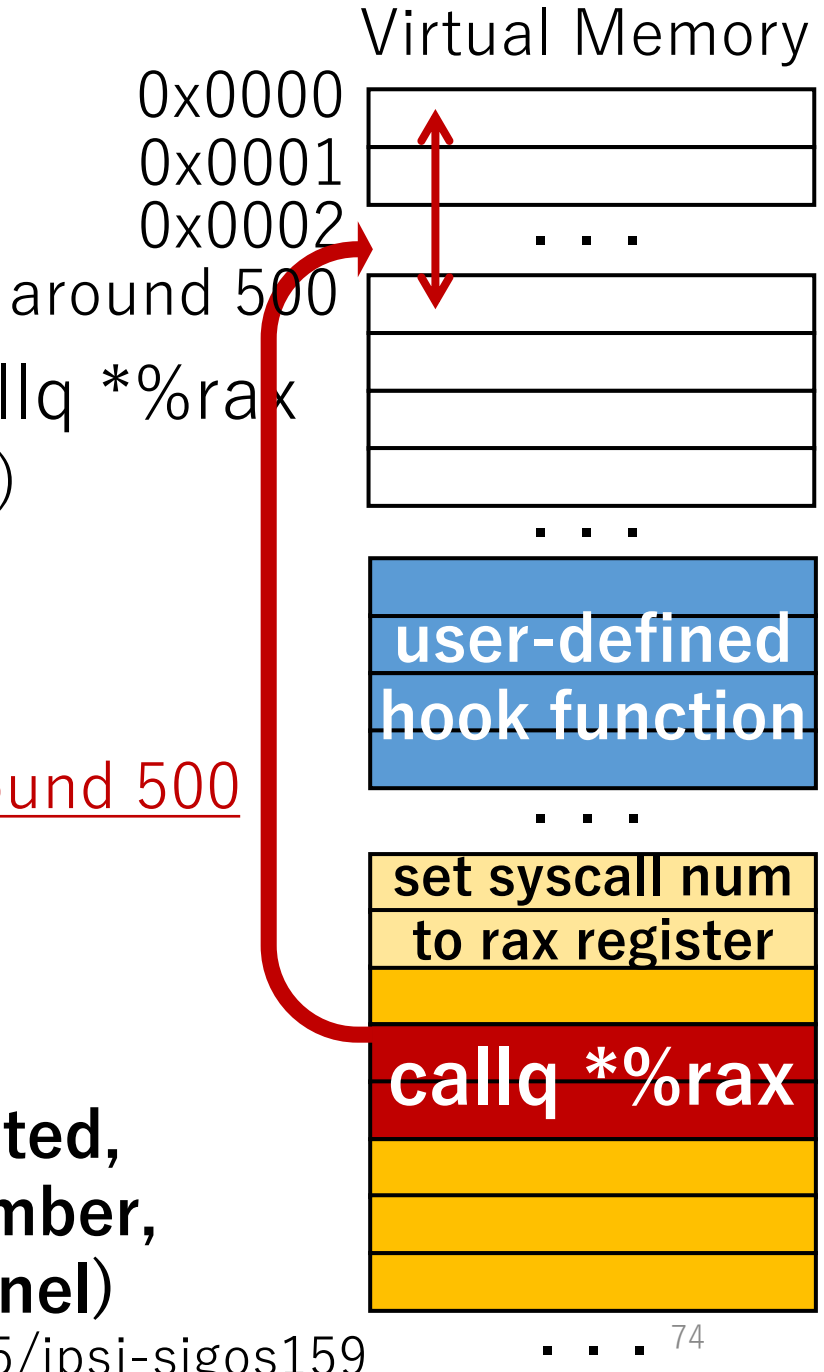

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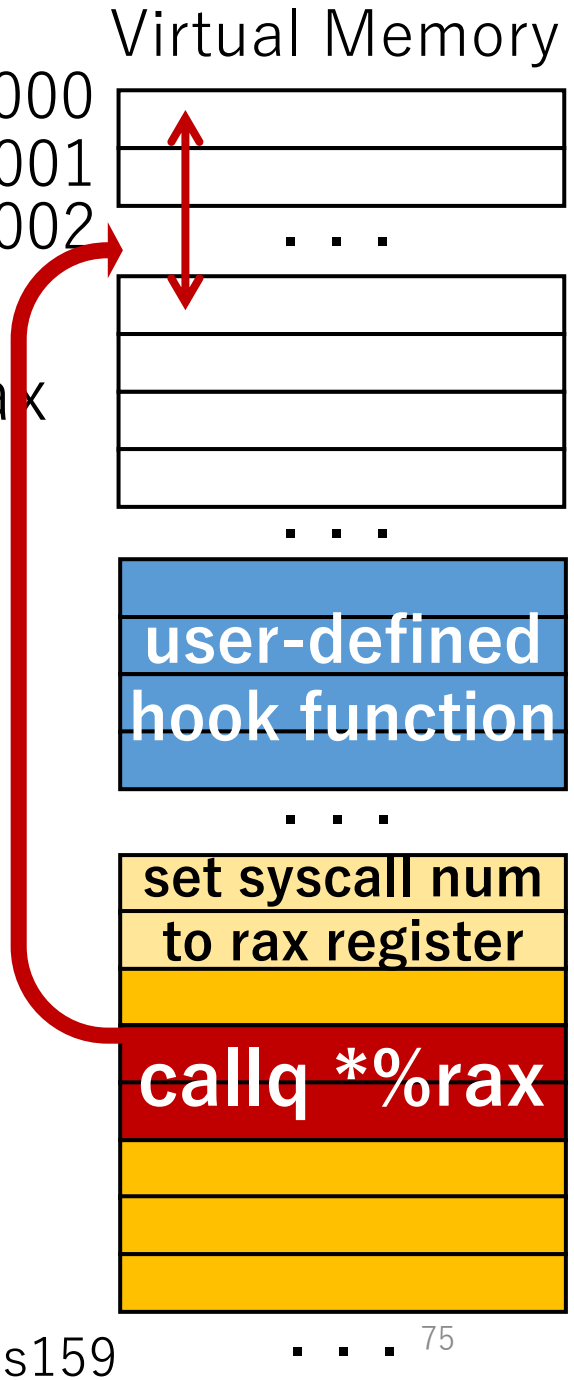

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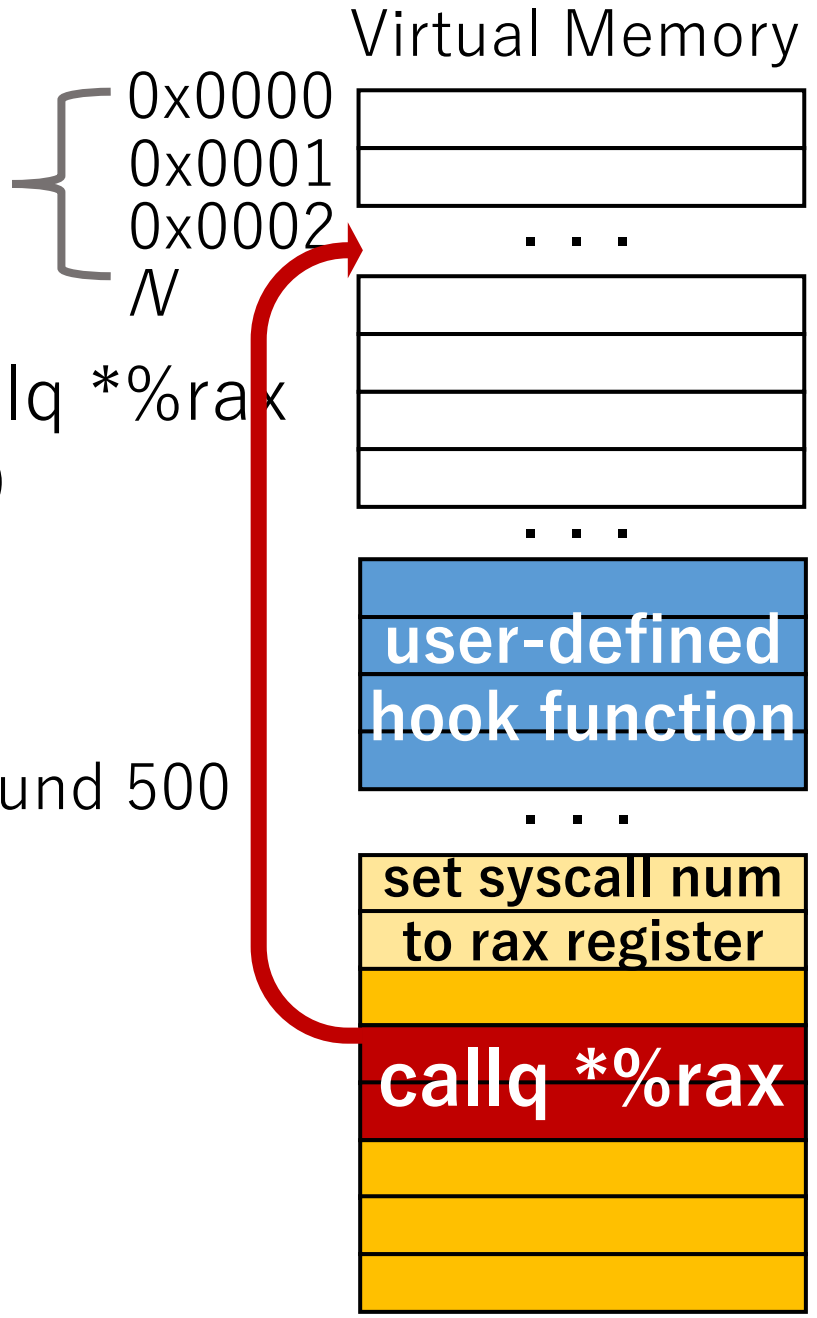

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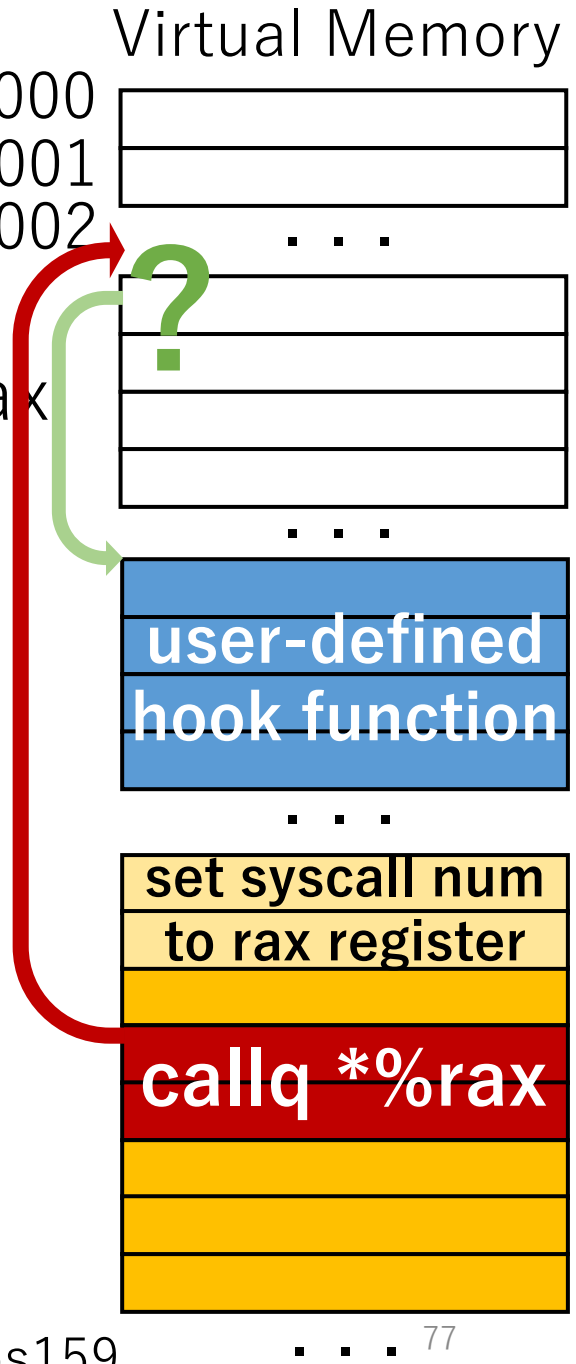

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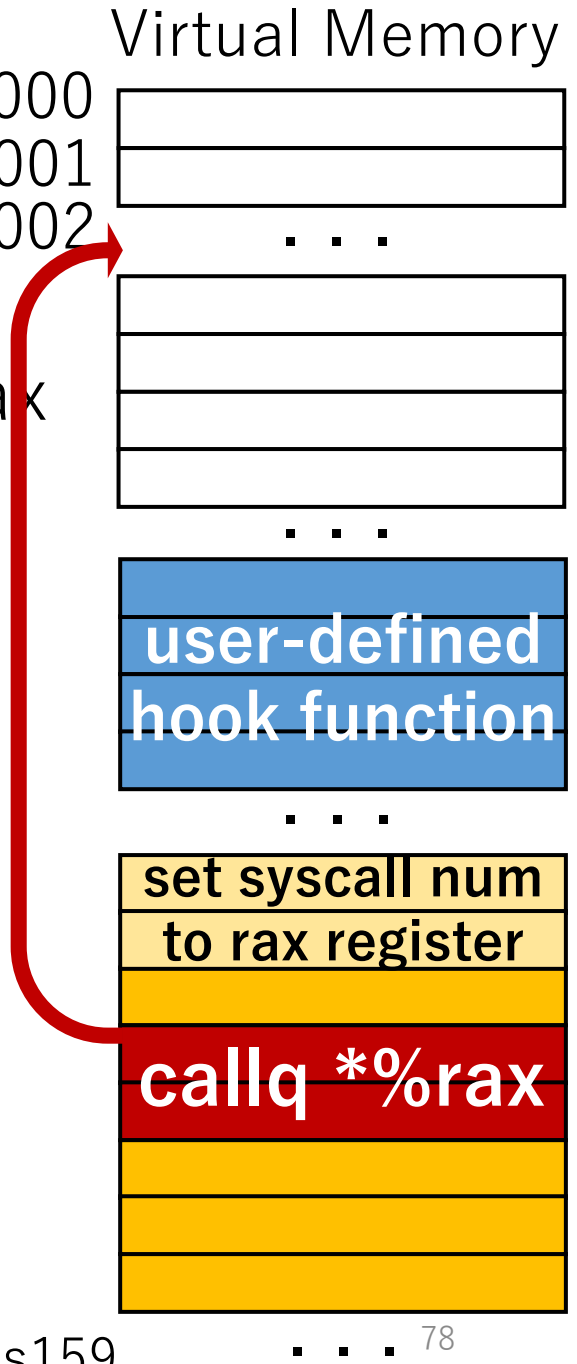

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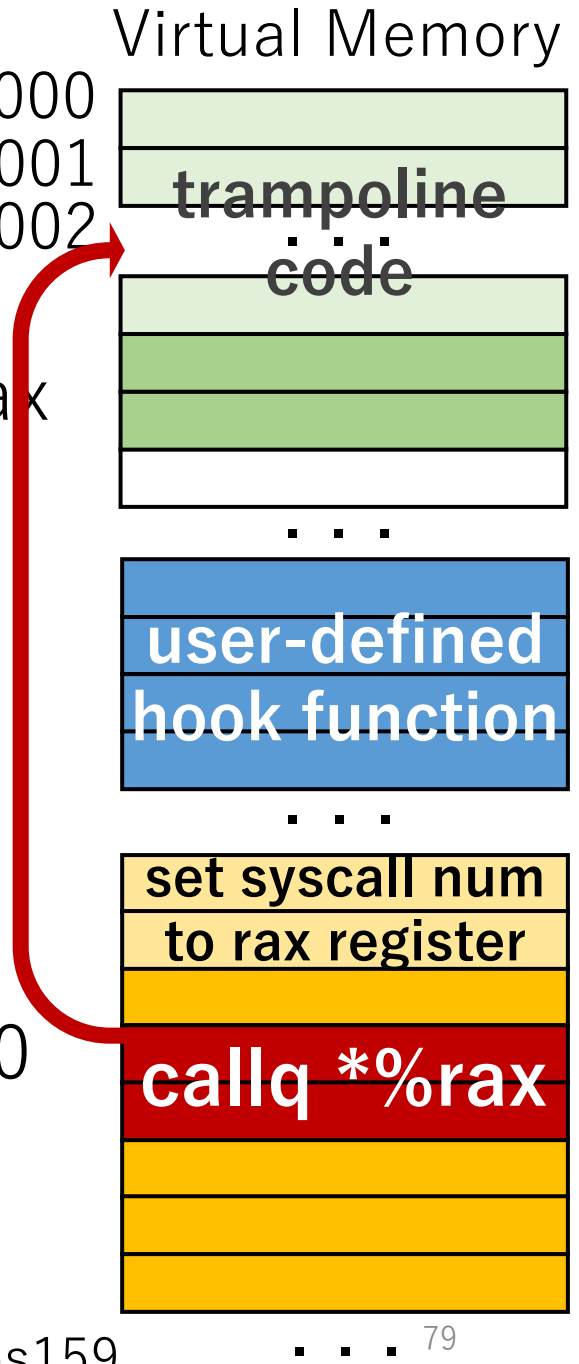

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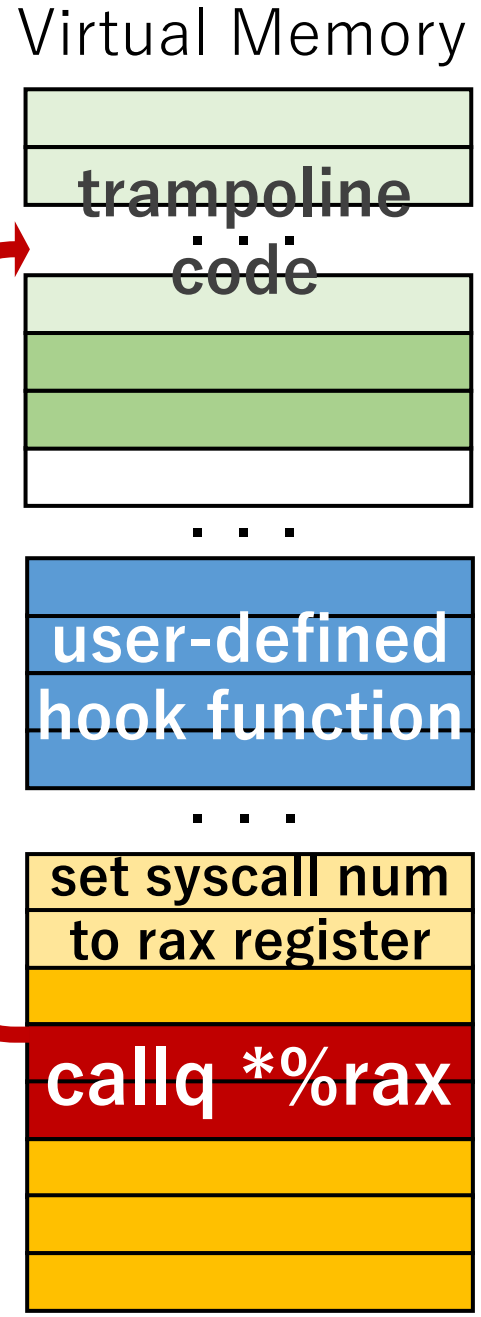

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Tram**poline** code at address 0 (**z**ero) ➔ **zpoline**

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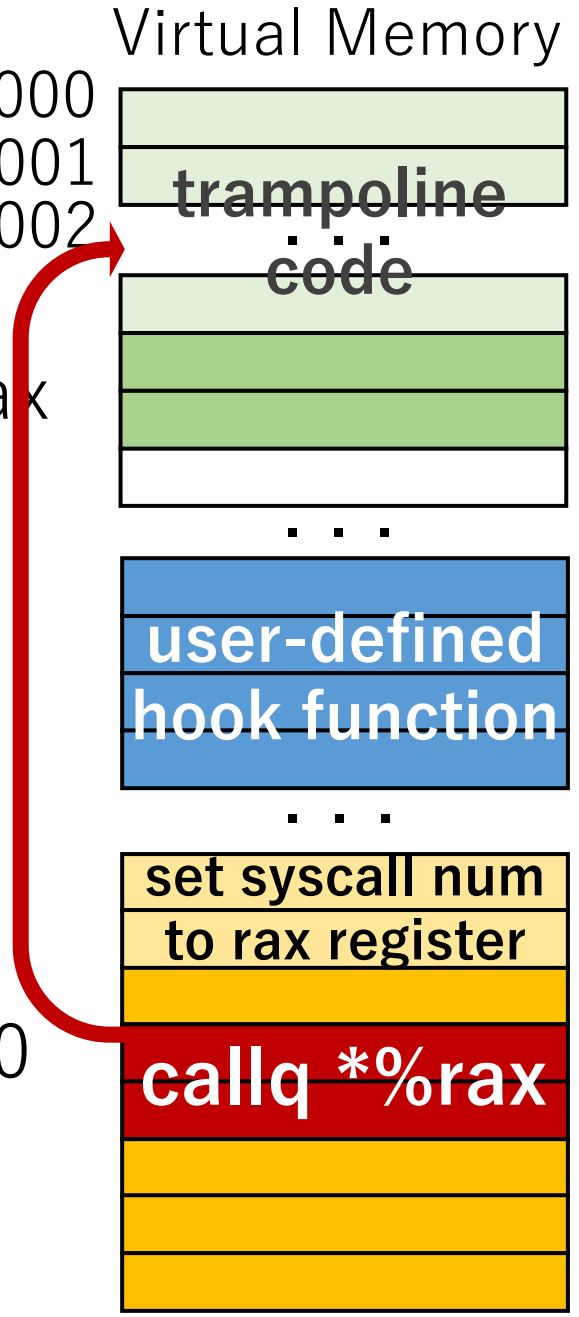

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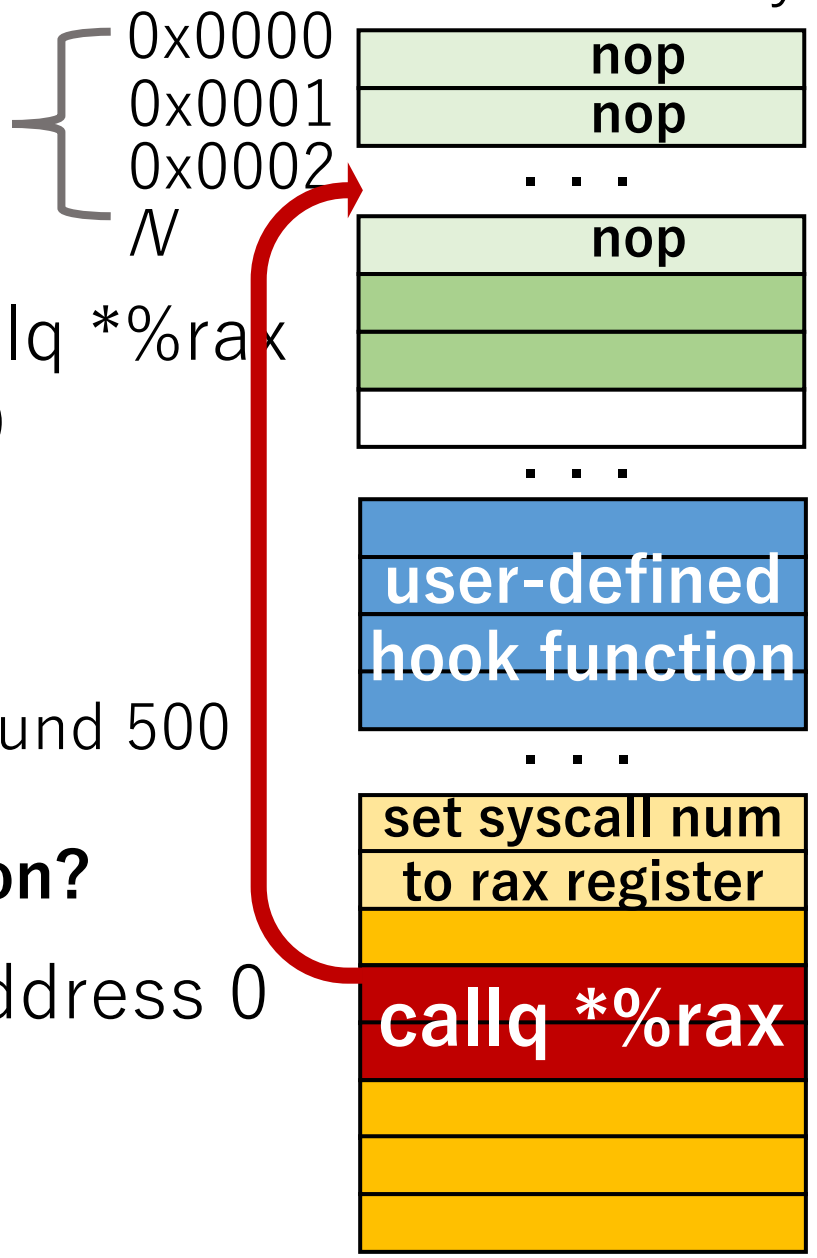

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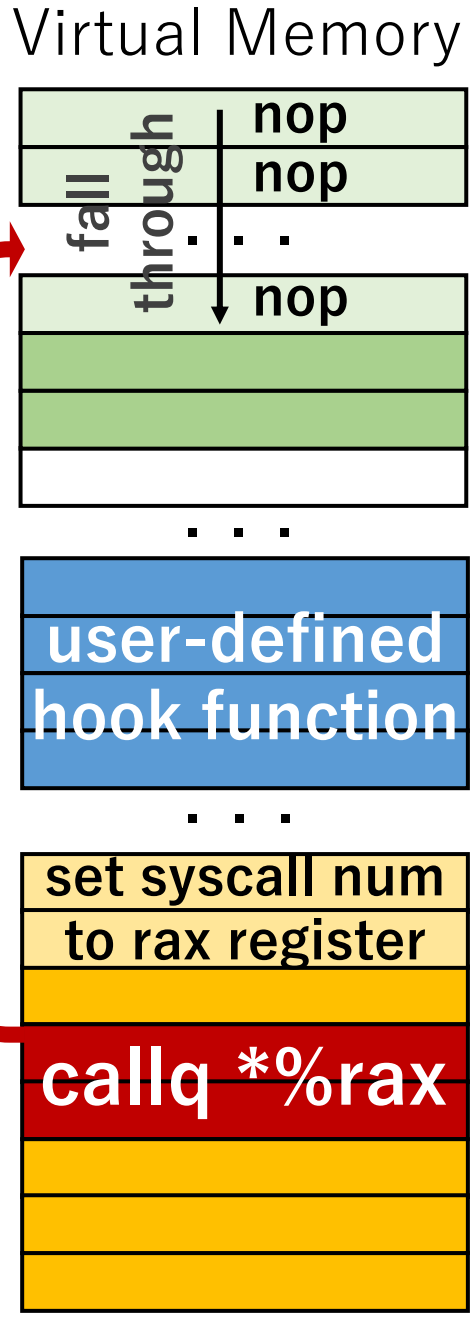

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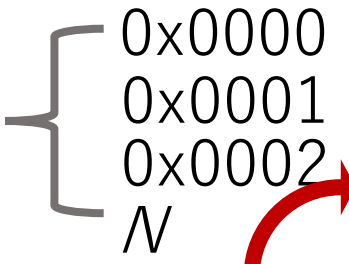

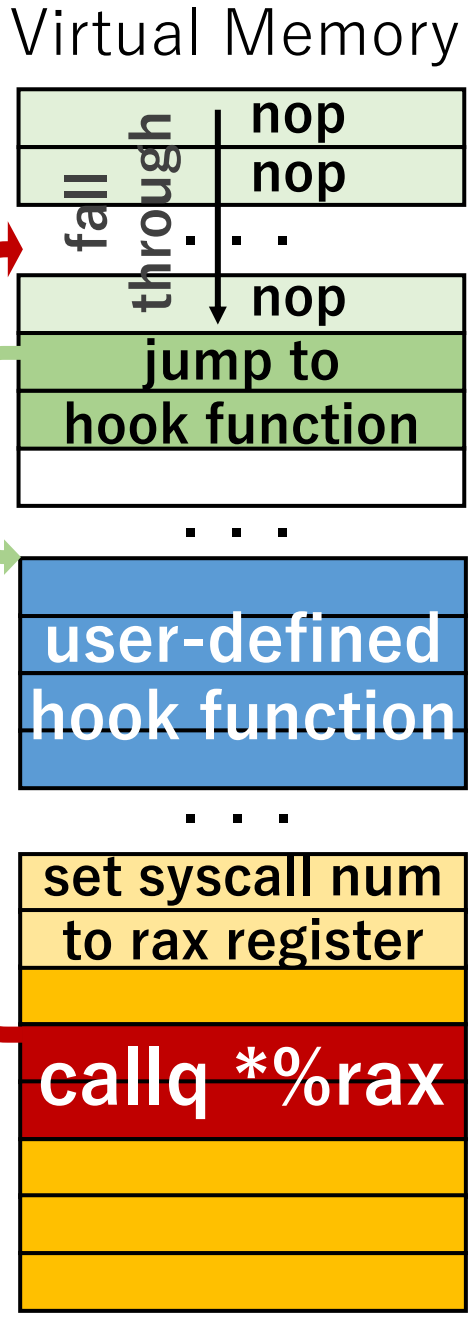

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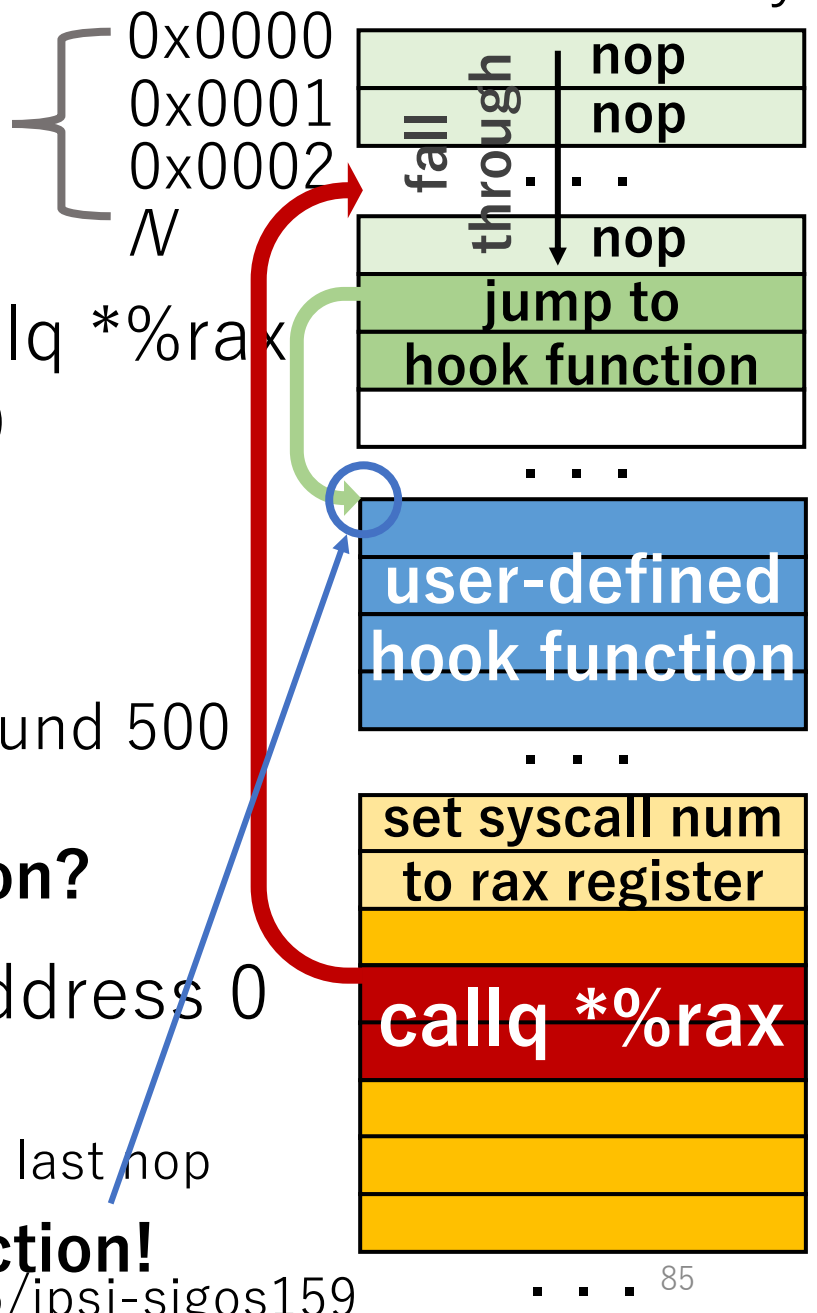

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We could reach the user-defined hook function!

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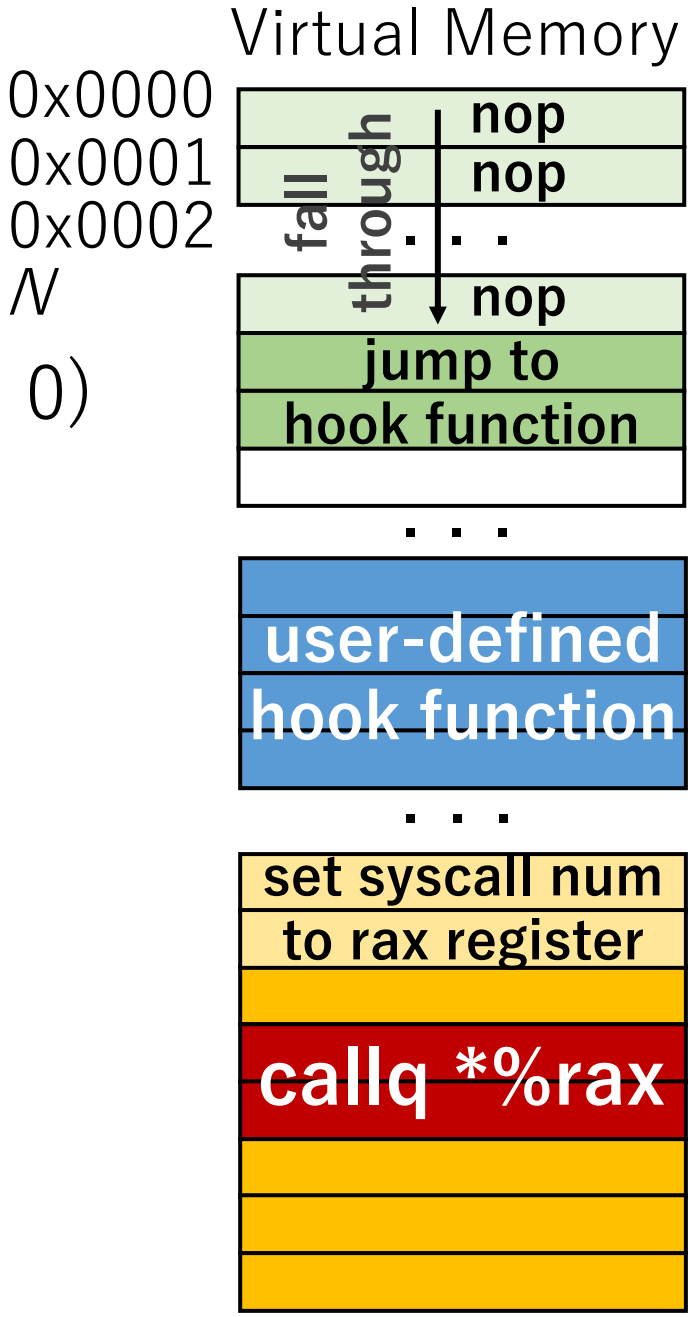
NULL Access Termination

- A buggy program may access NULL (address 0)



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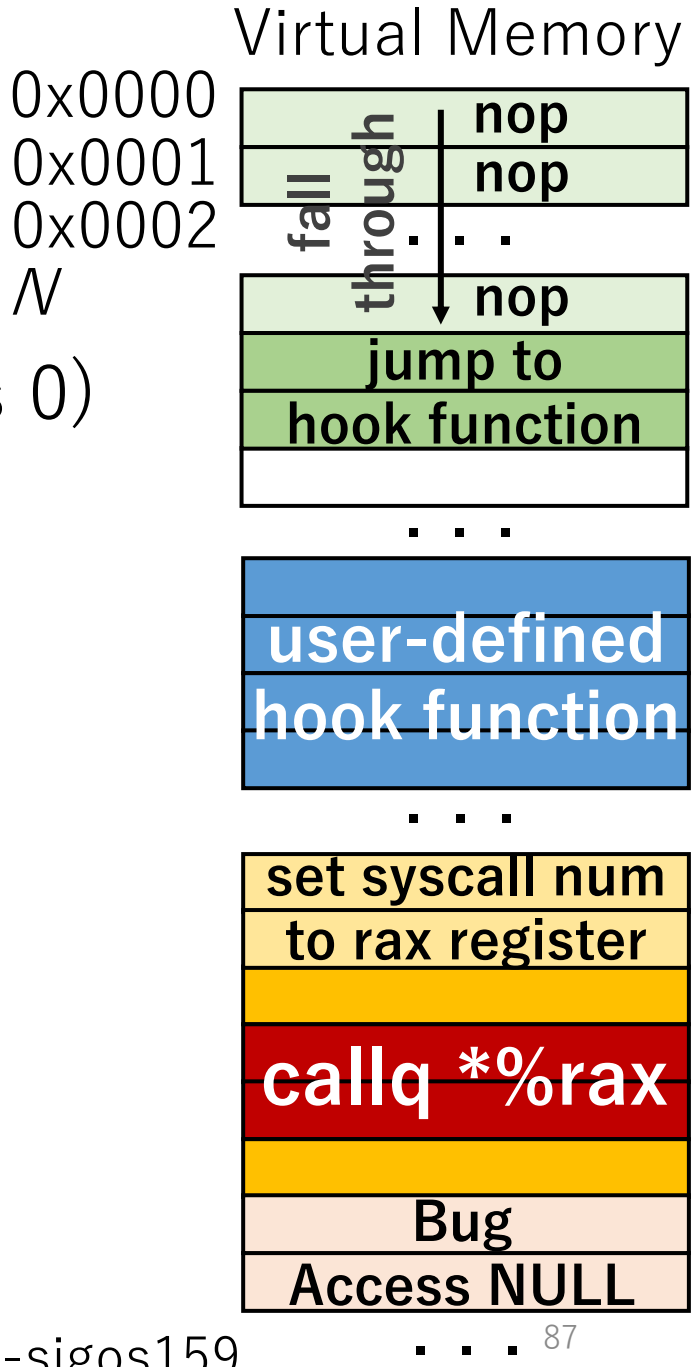

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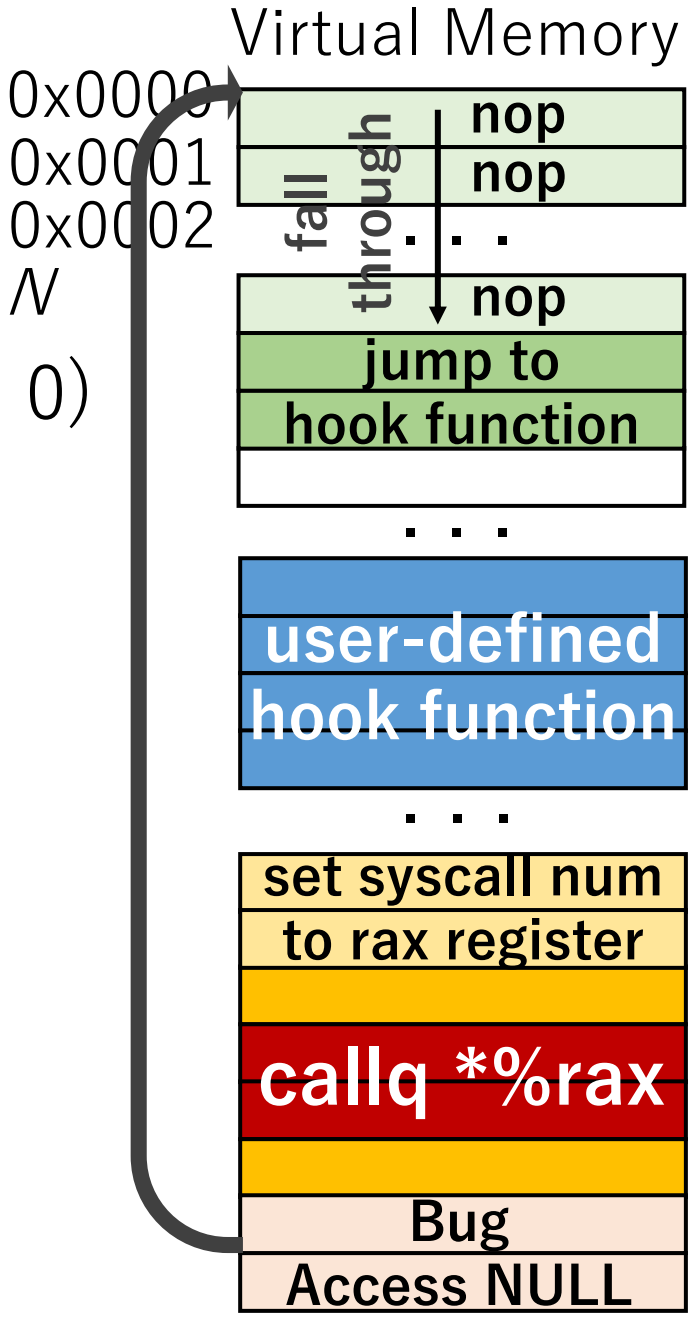

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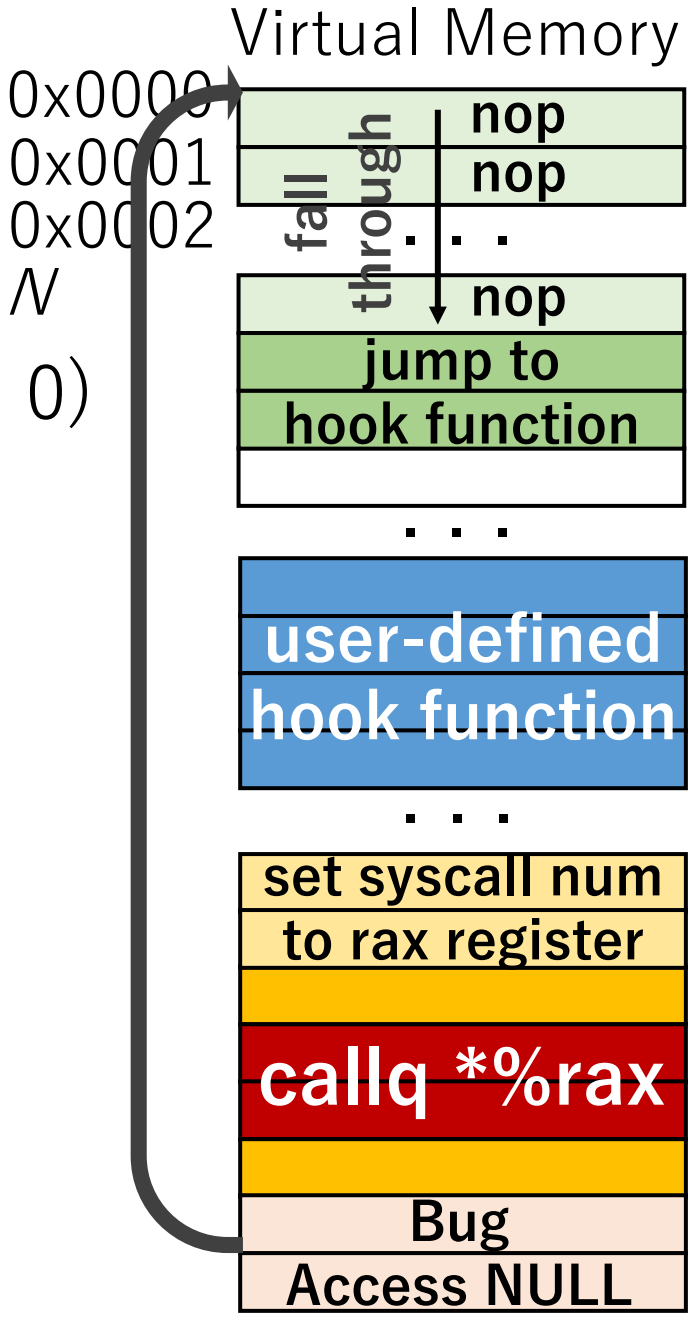

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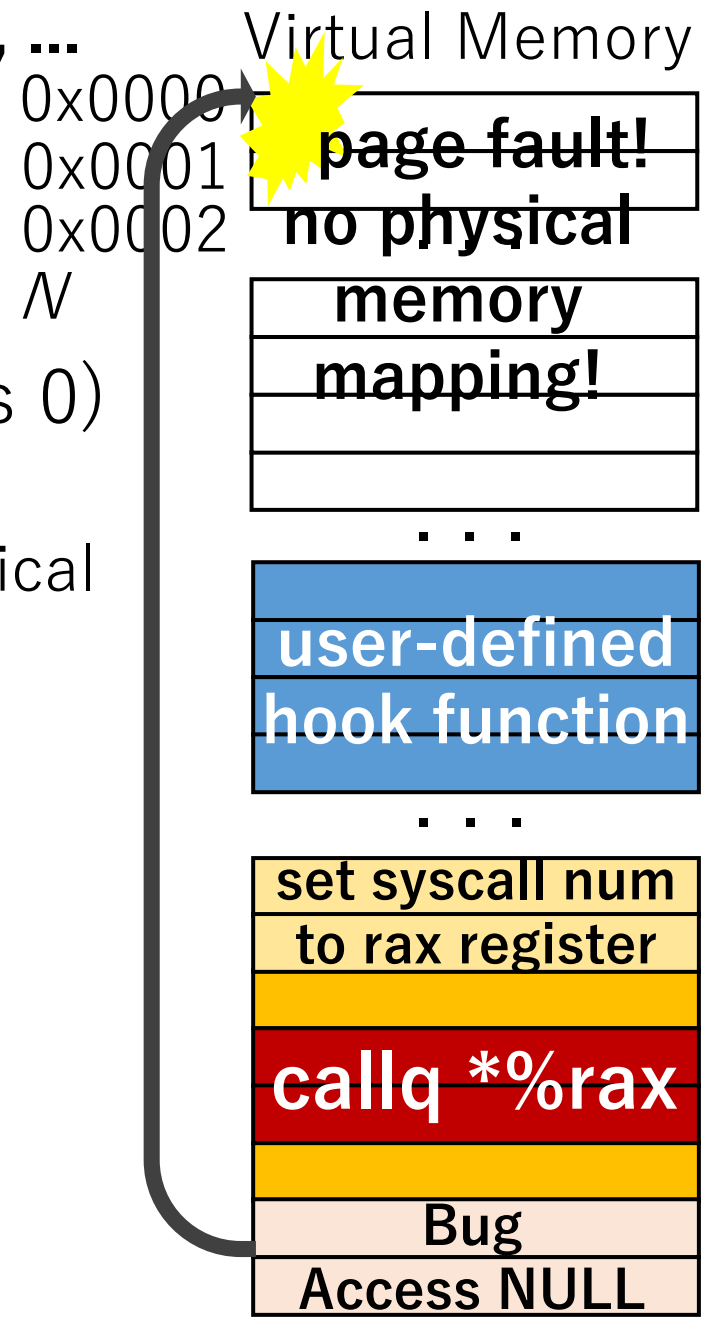

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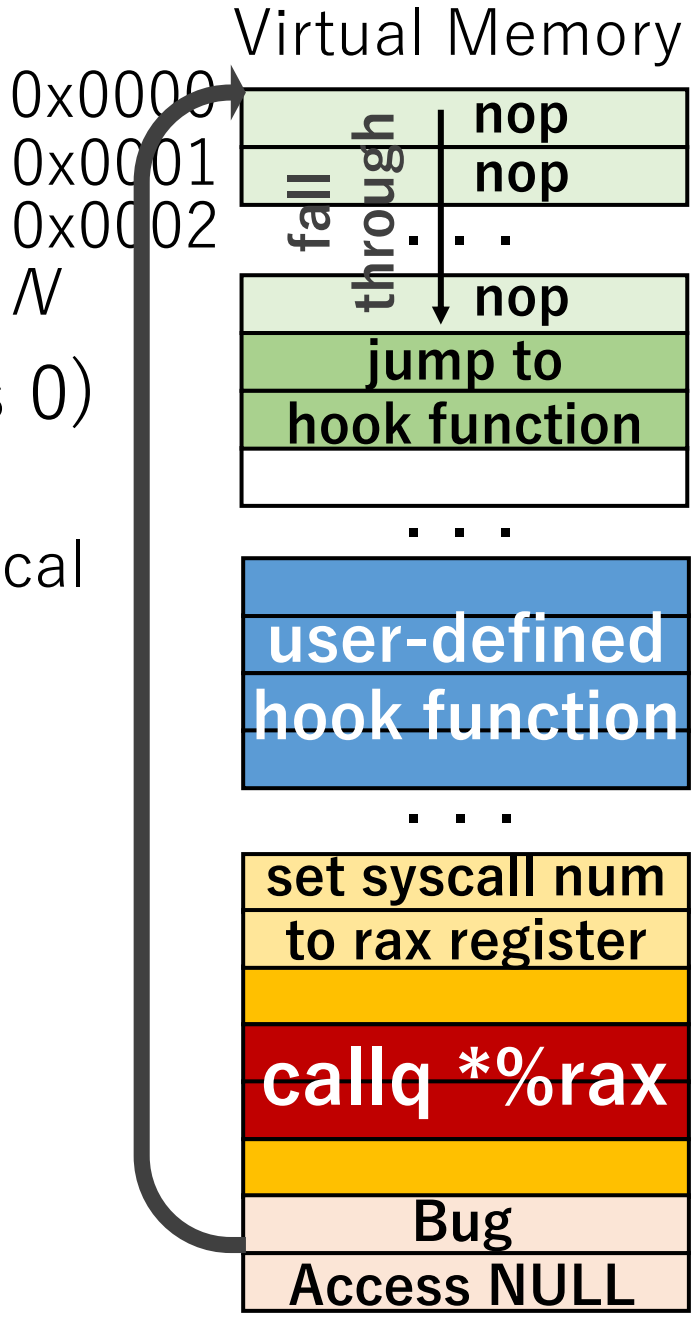

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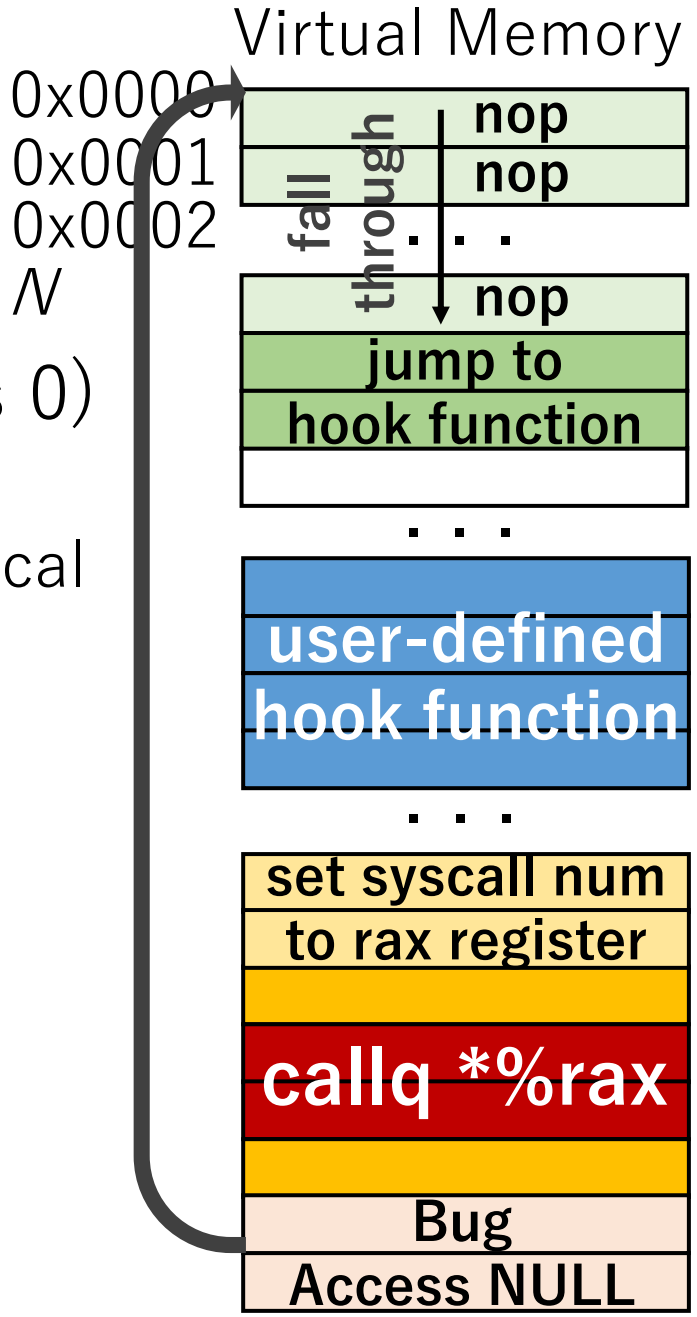

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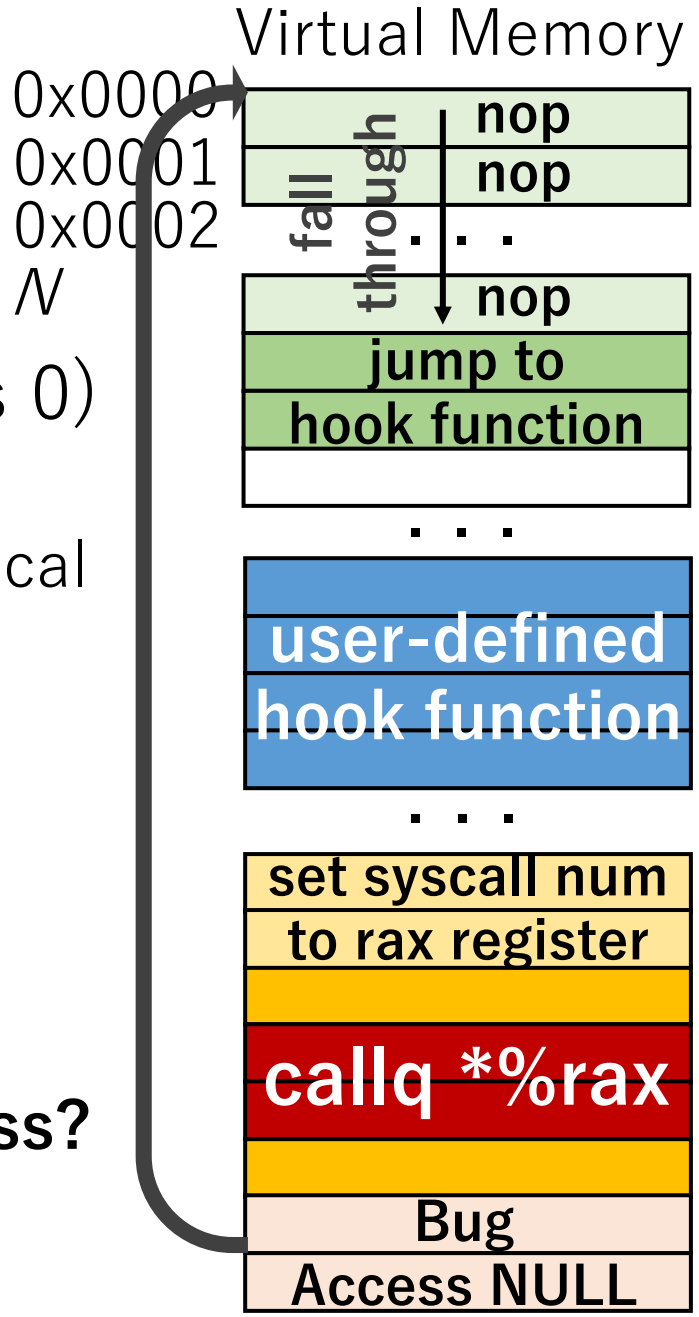
How can we detect and terminate a buggy NULL access?



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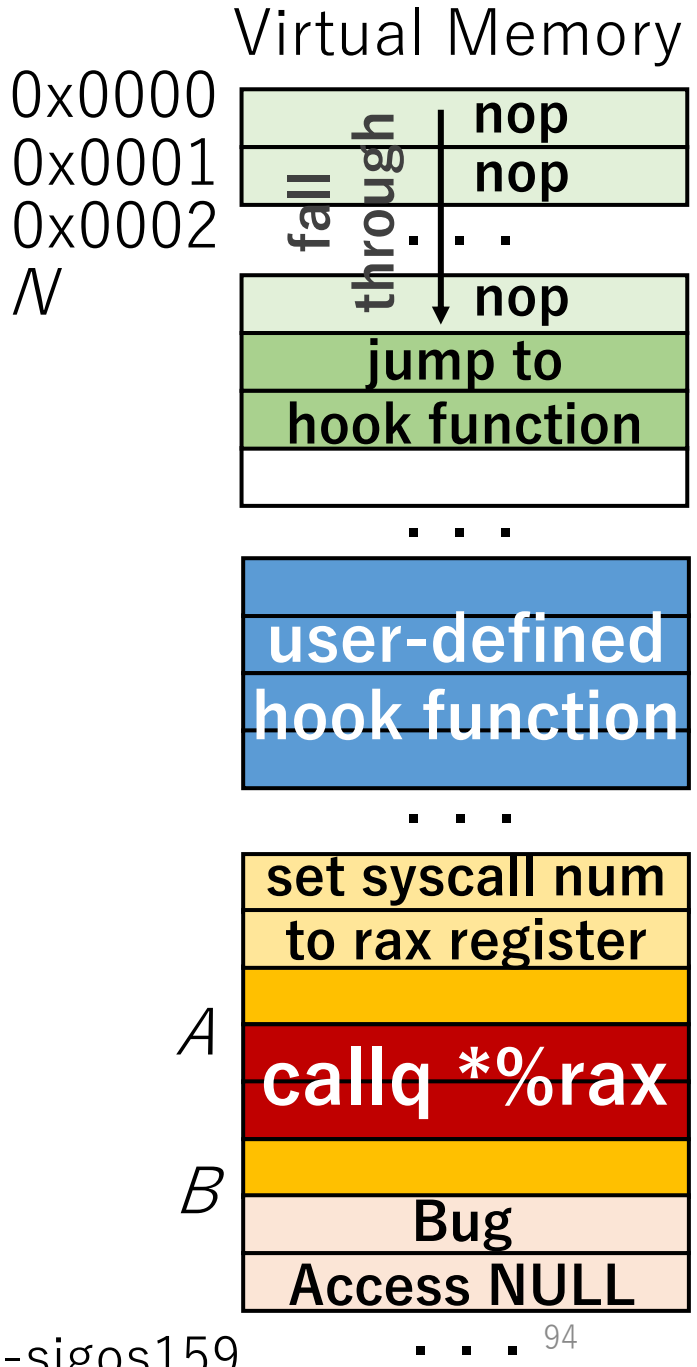

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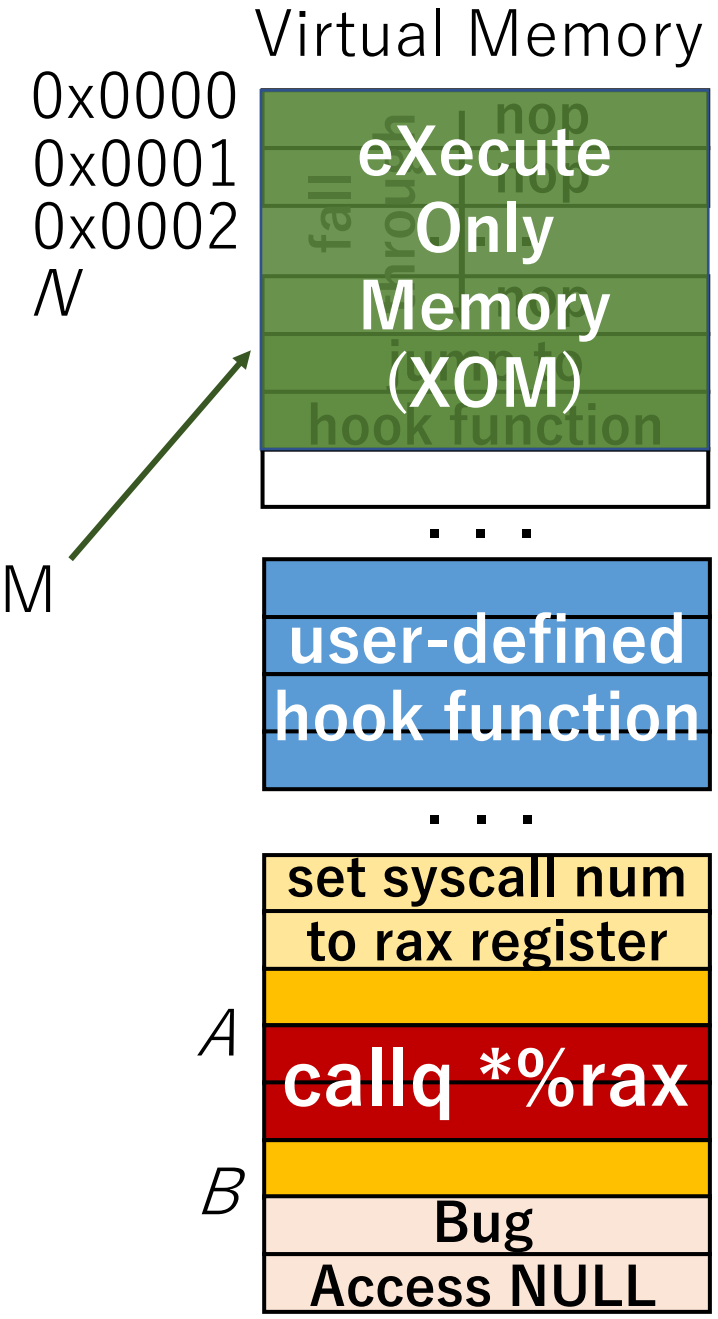

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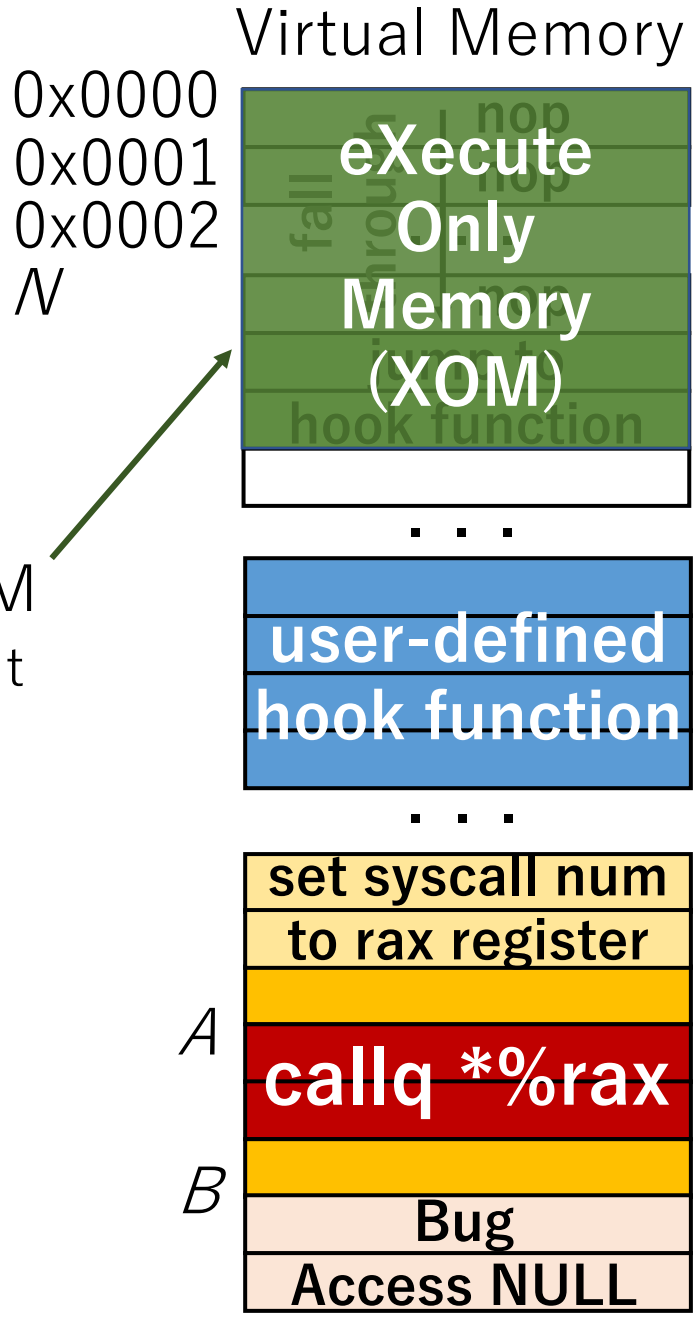

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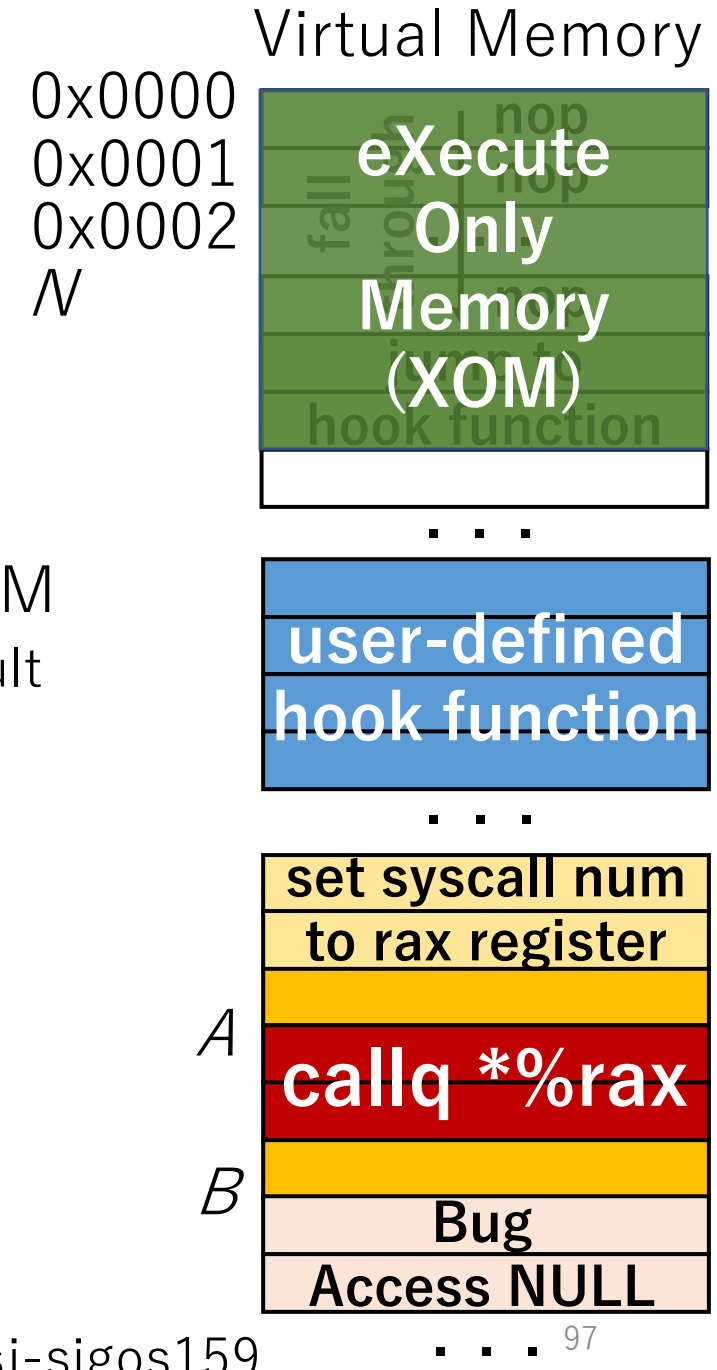

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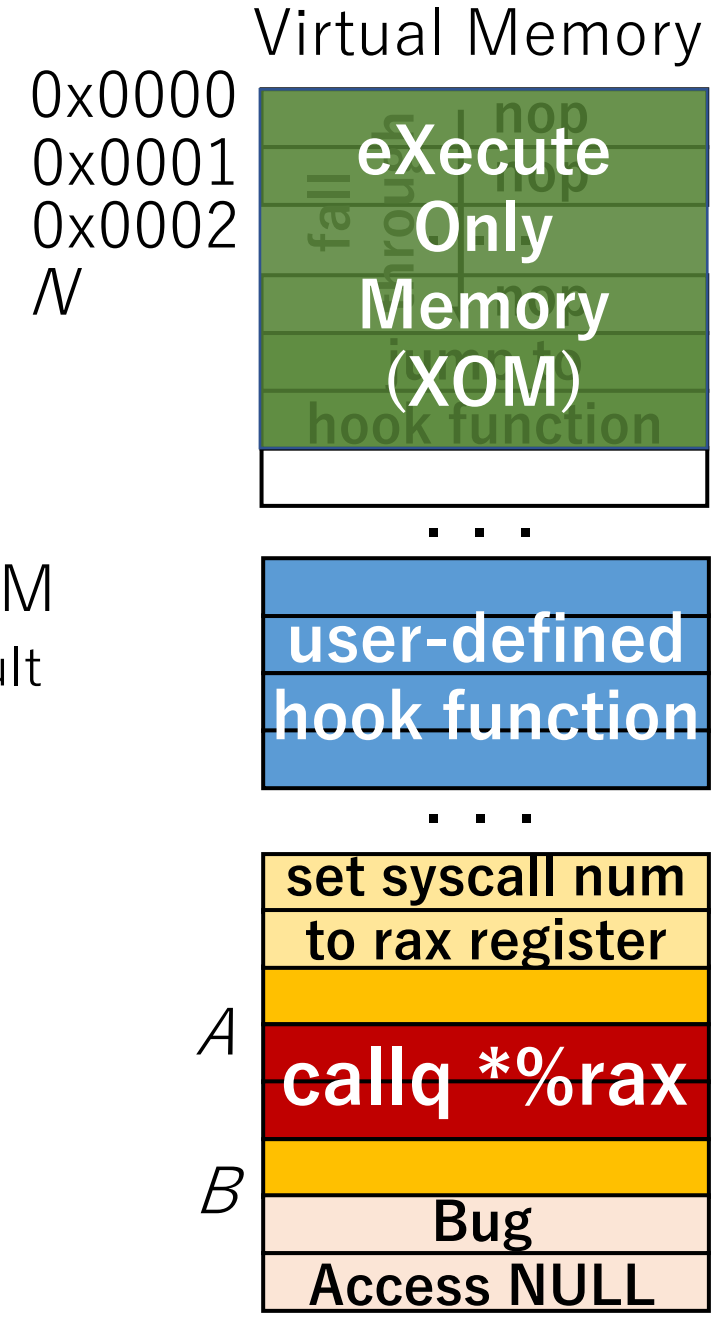

List of replaced addresses : [...]

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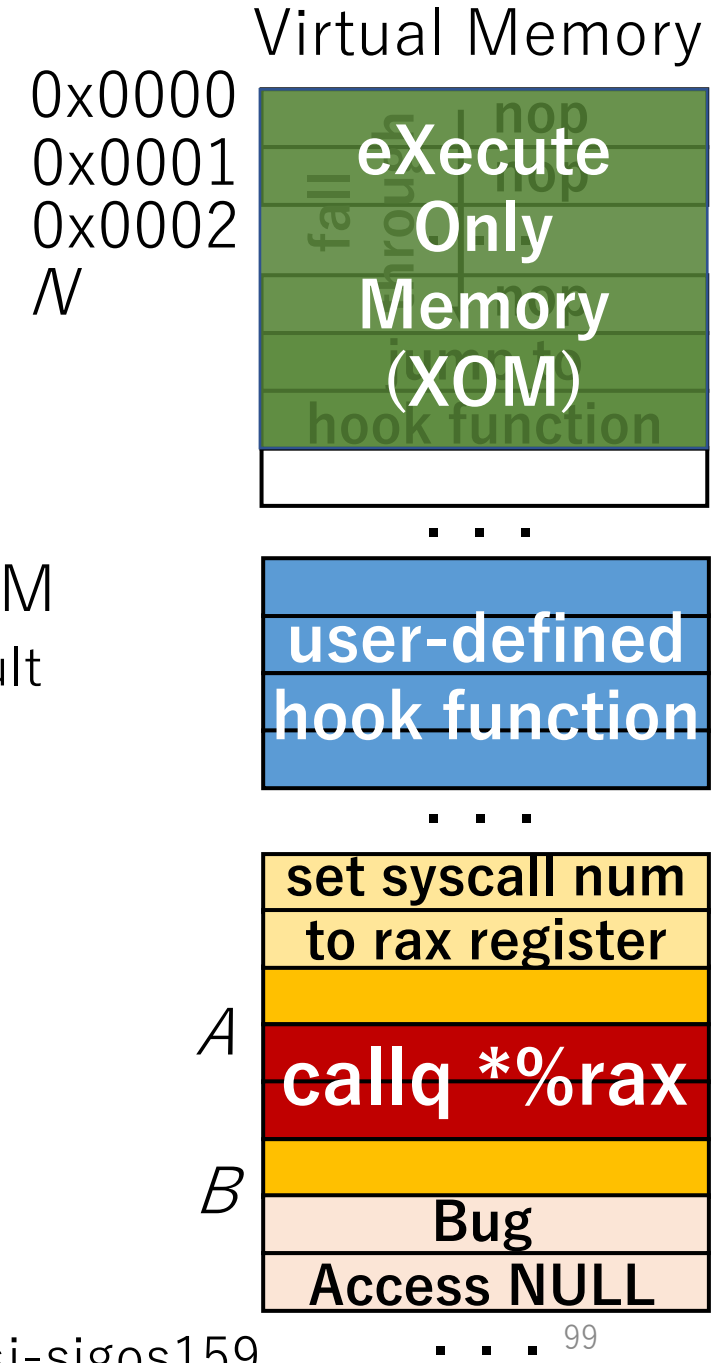

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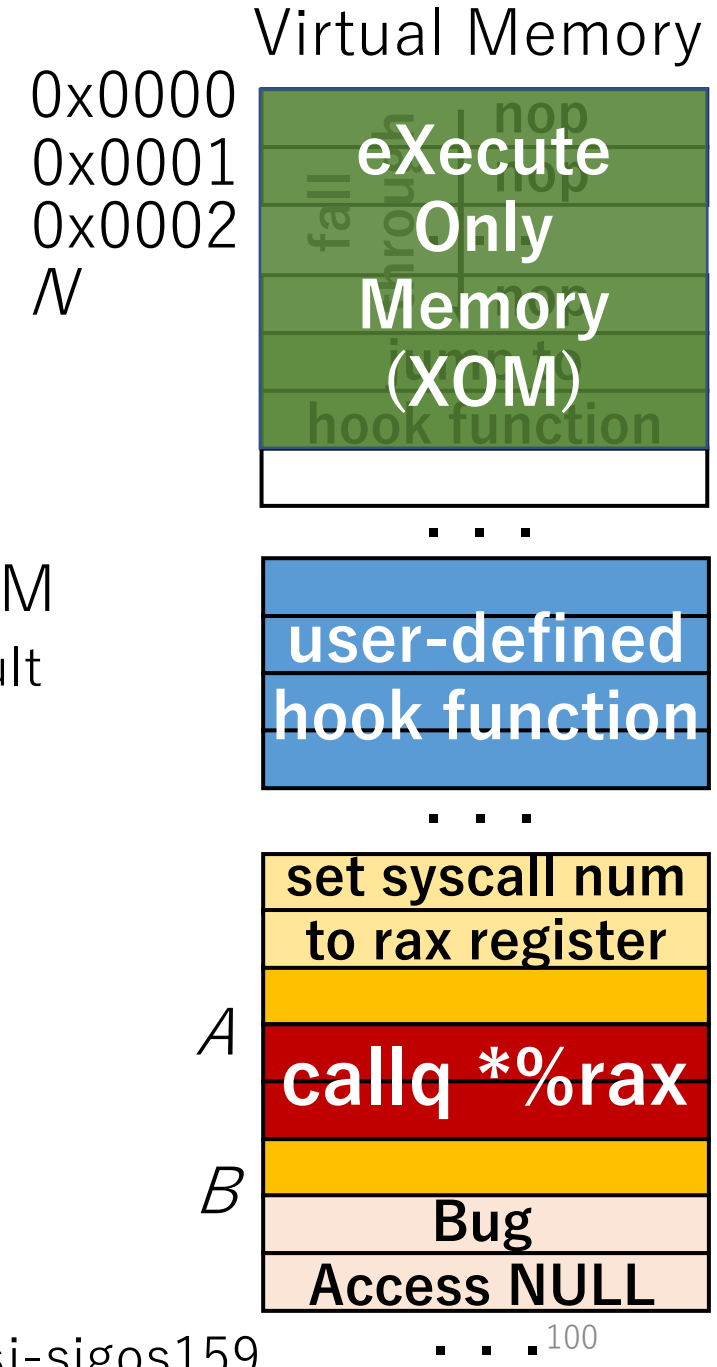

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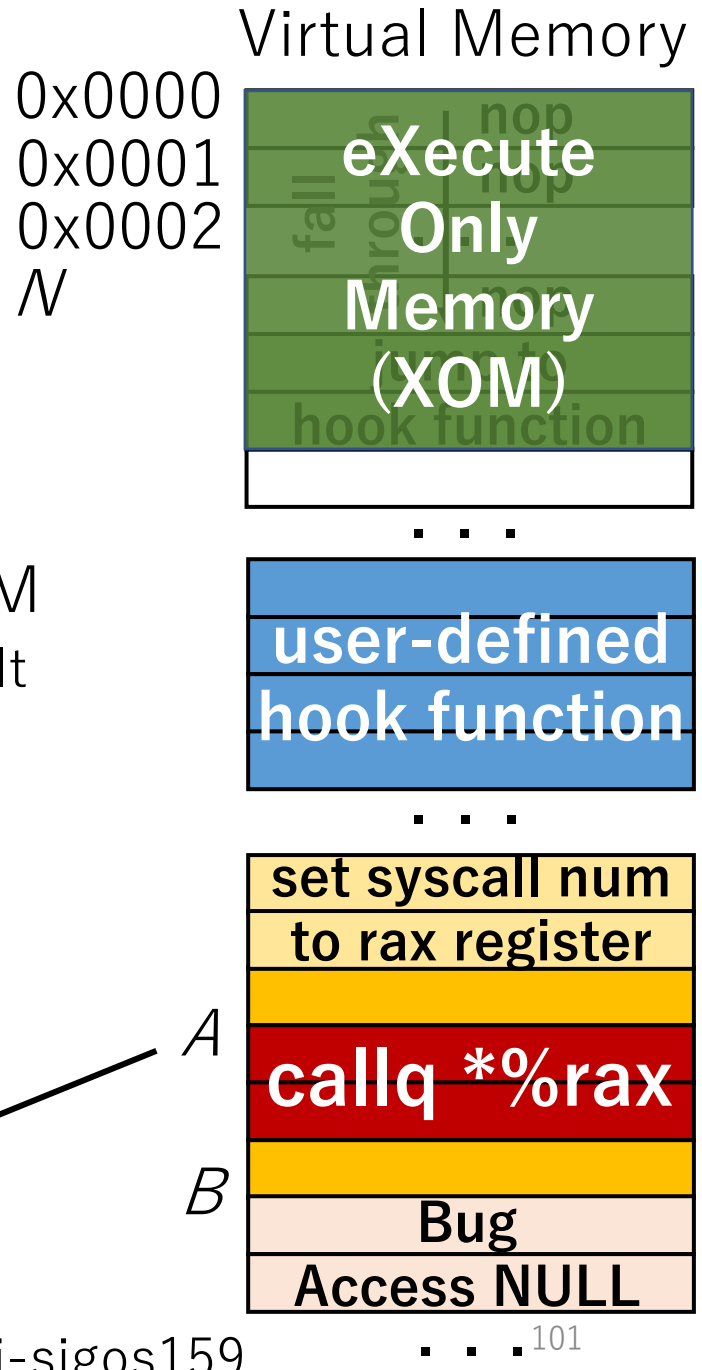

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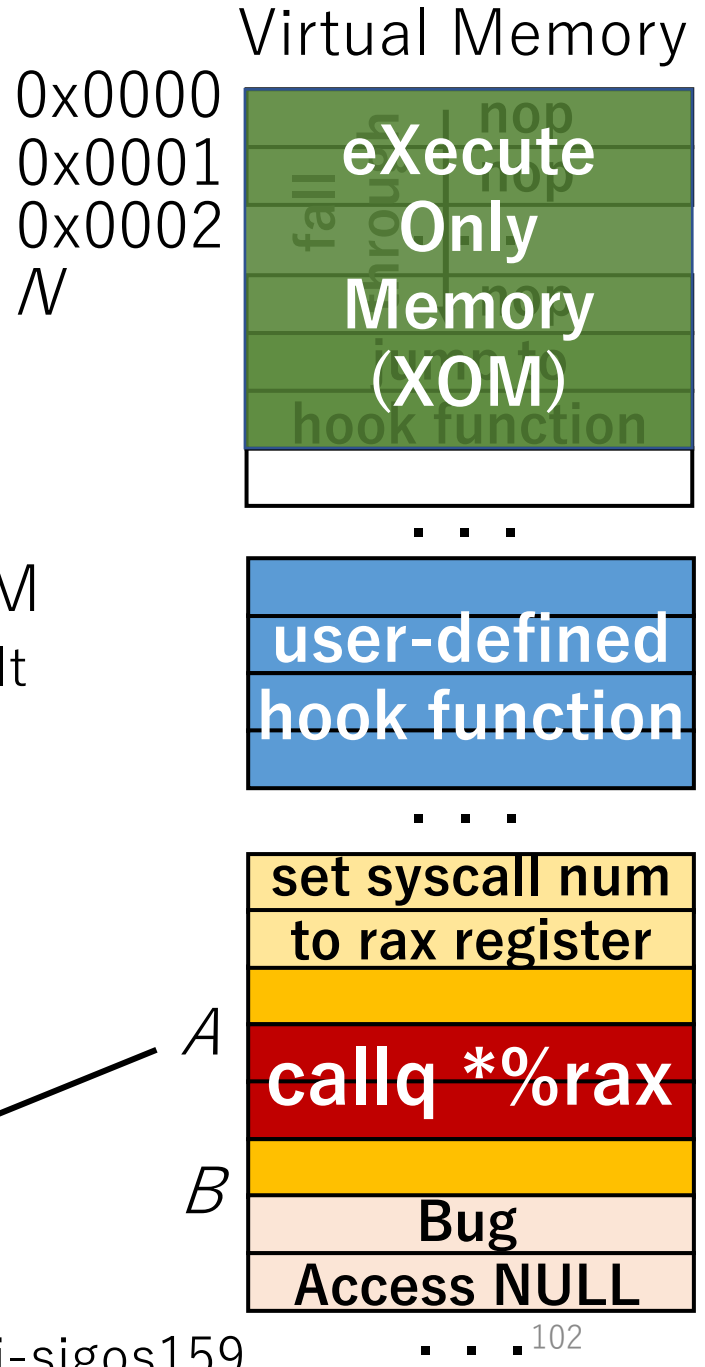
During binary rewriting phase …

List of replaced addresses : [*A* , …]



https://github.com/yasukata/presentation/tree/gh-pages/2023/05/ipsj-sigos159

NULL Access Termination

- Memory access: read / write / execute
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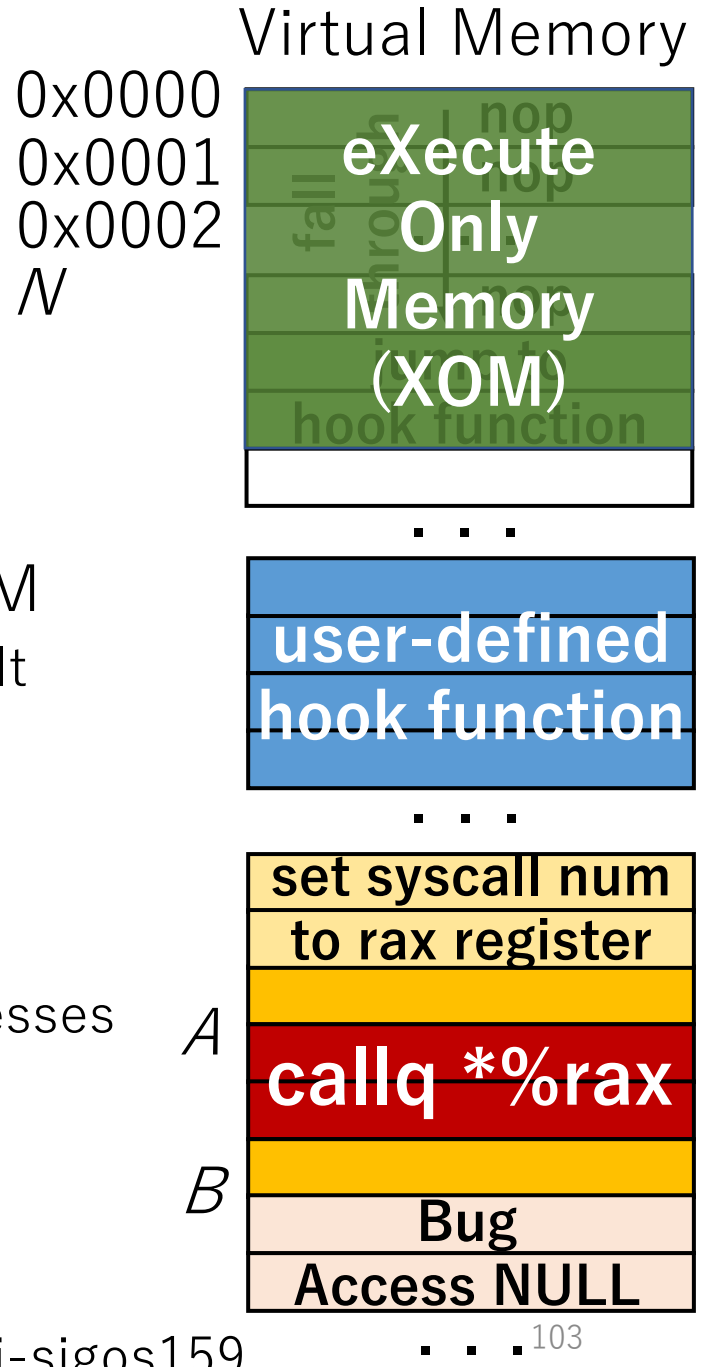

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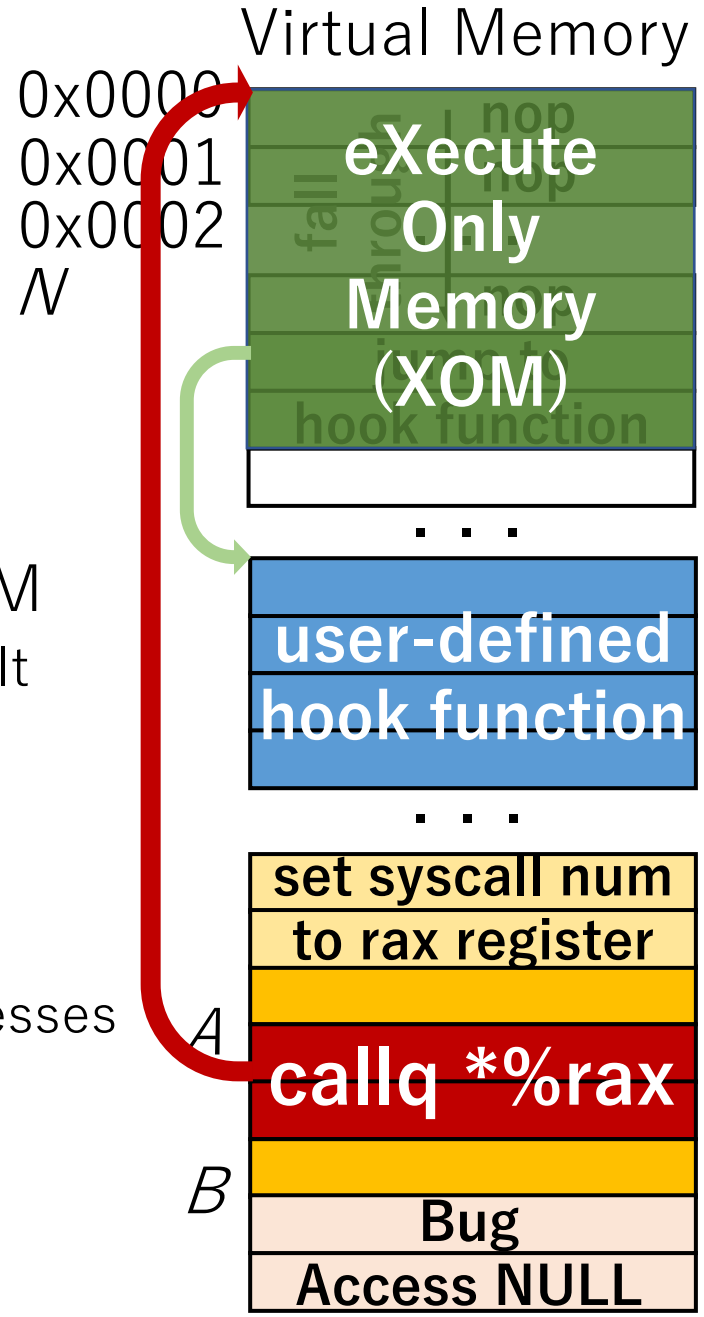

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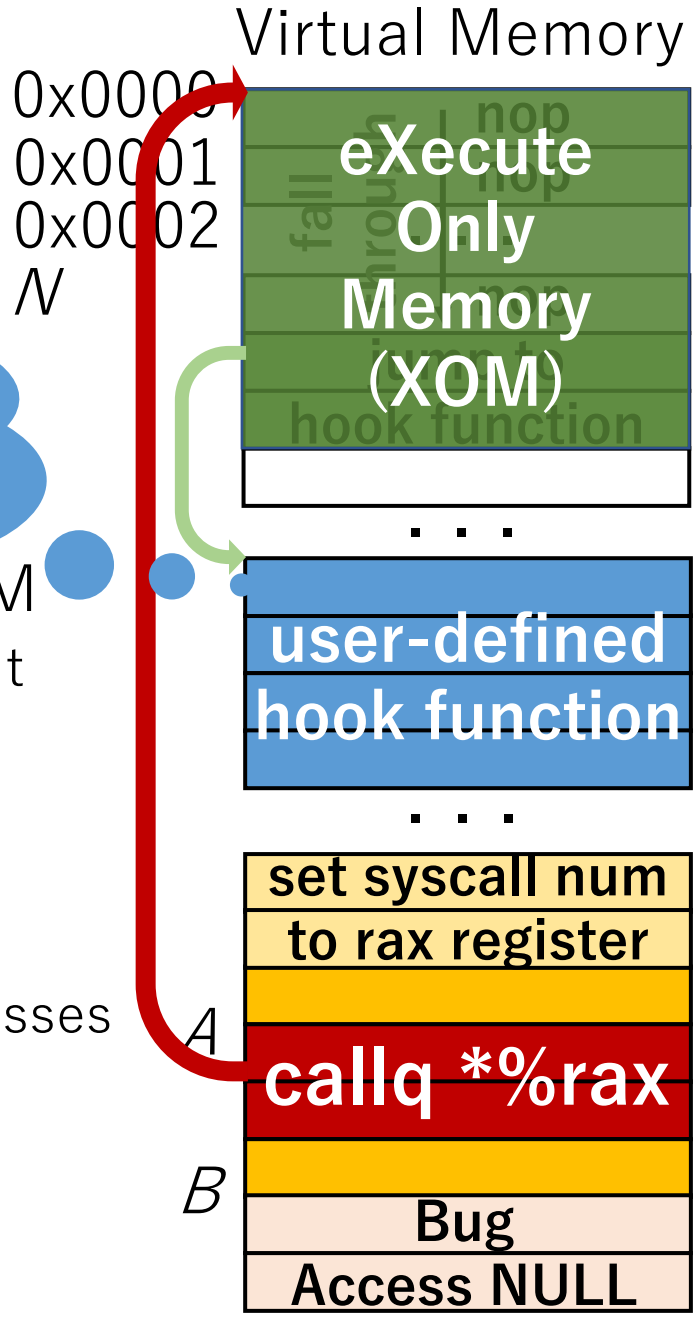
The caller address is *A*
***A* is in the list, so**
this is a valid access

List of replaced addresses : [*A* , …]



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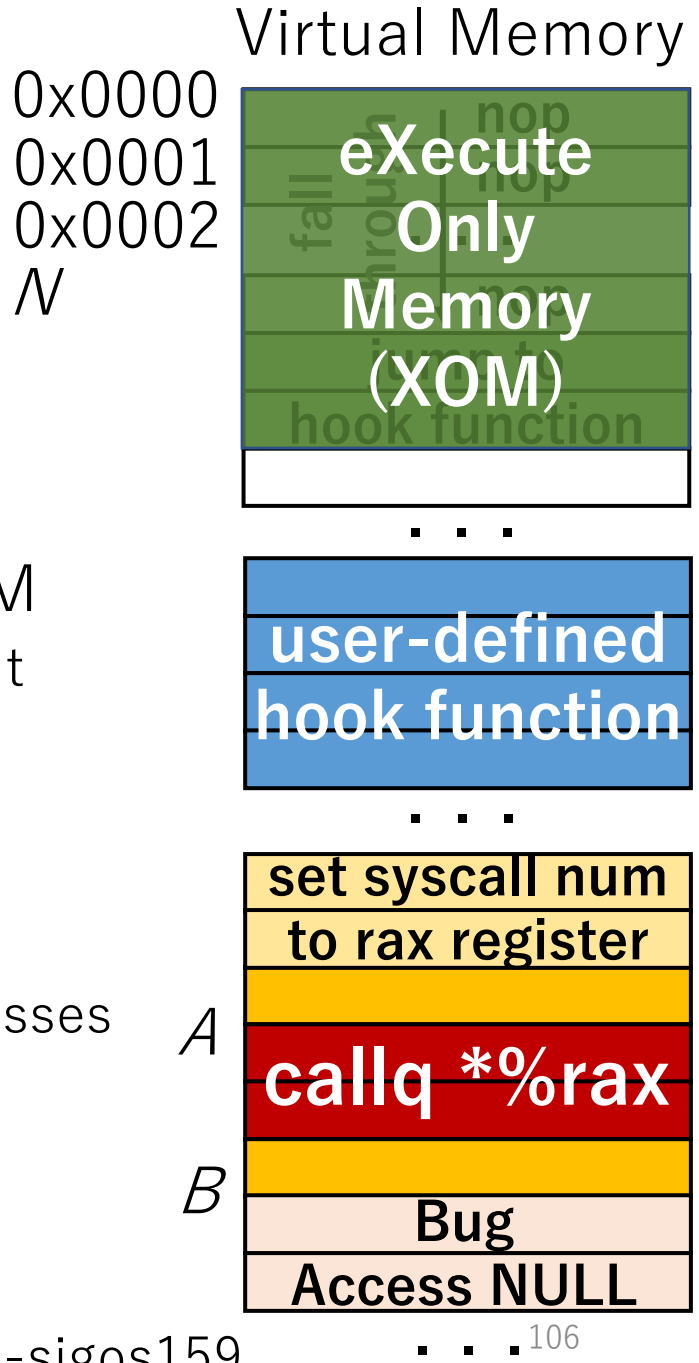

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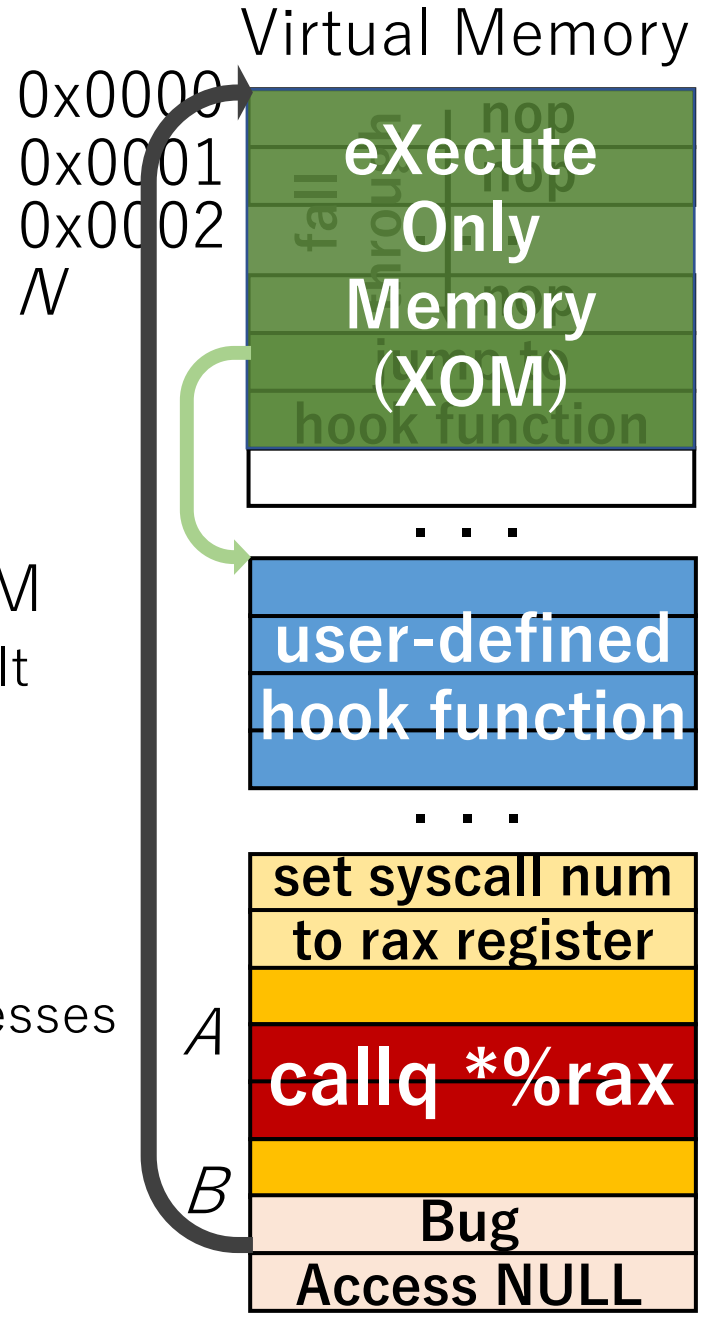

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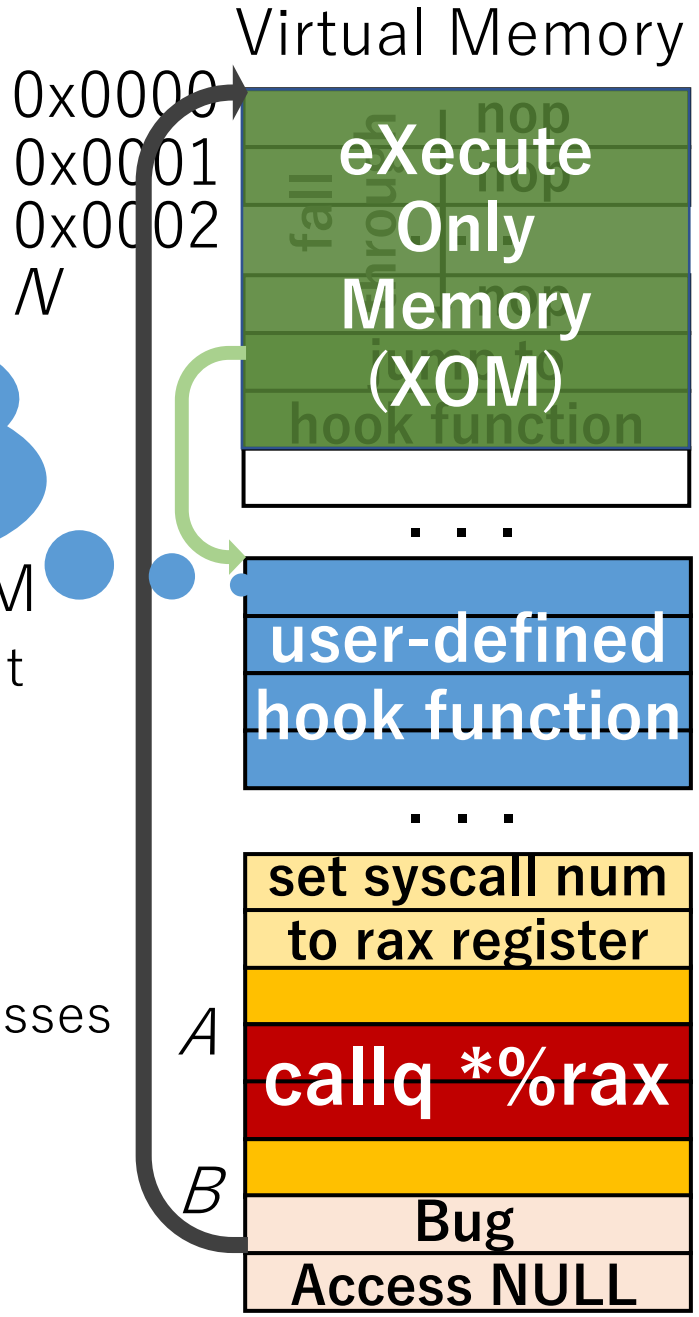
The caller address is *B*
***B* is NOT in the list, so this is an invalid access**

List of replaced addresses : [*A* , …]



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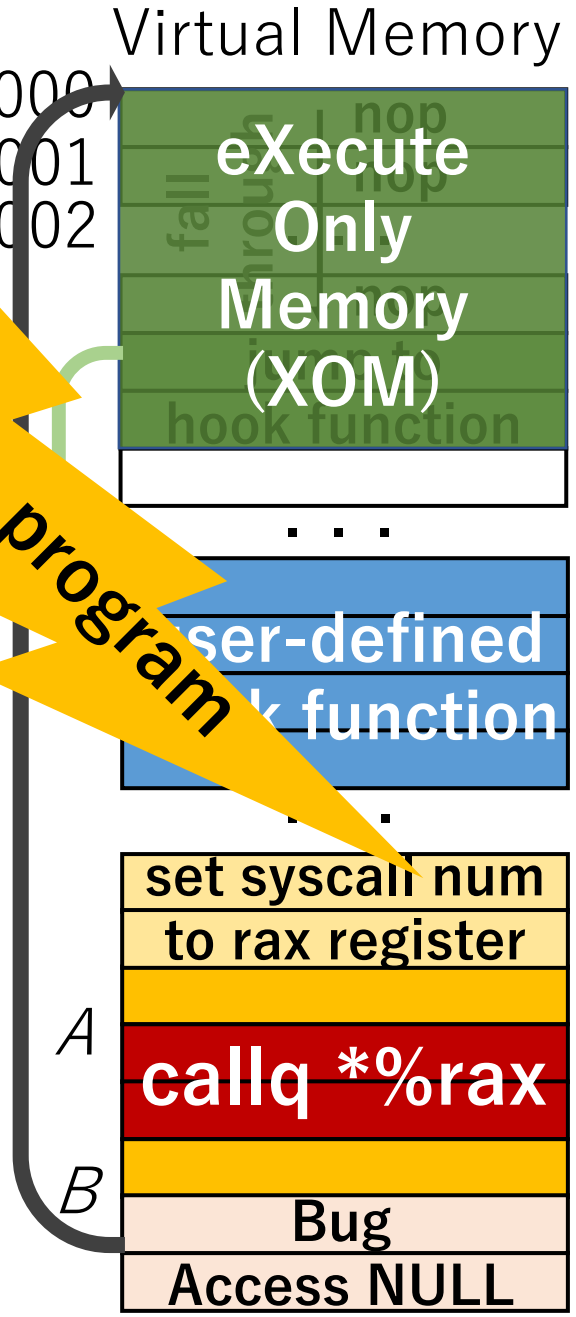
stop the program

List of replaced addresses : [*A* , …]



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       - Current prototype uses bitmap to implement this check

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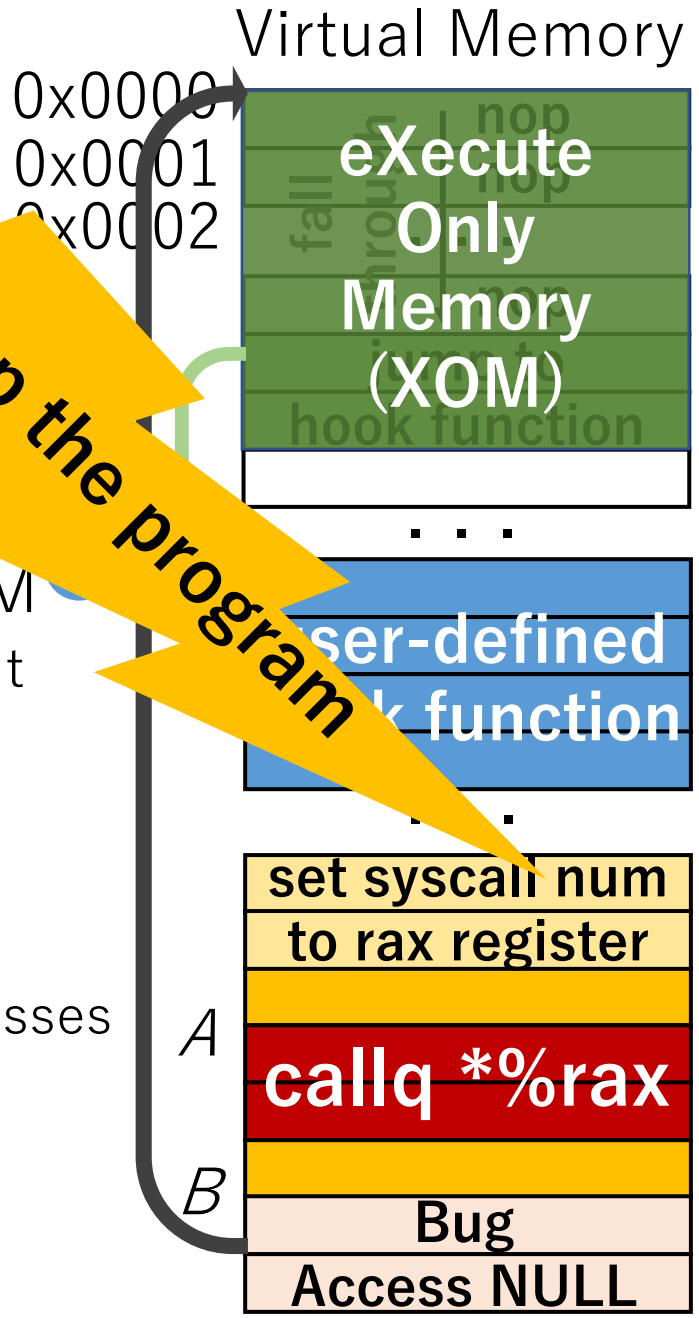

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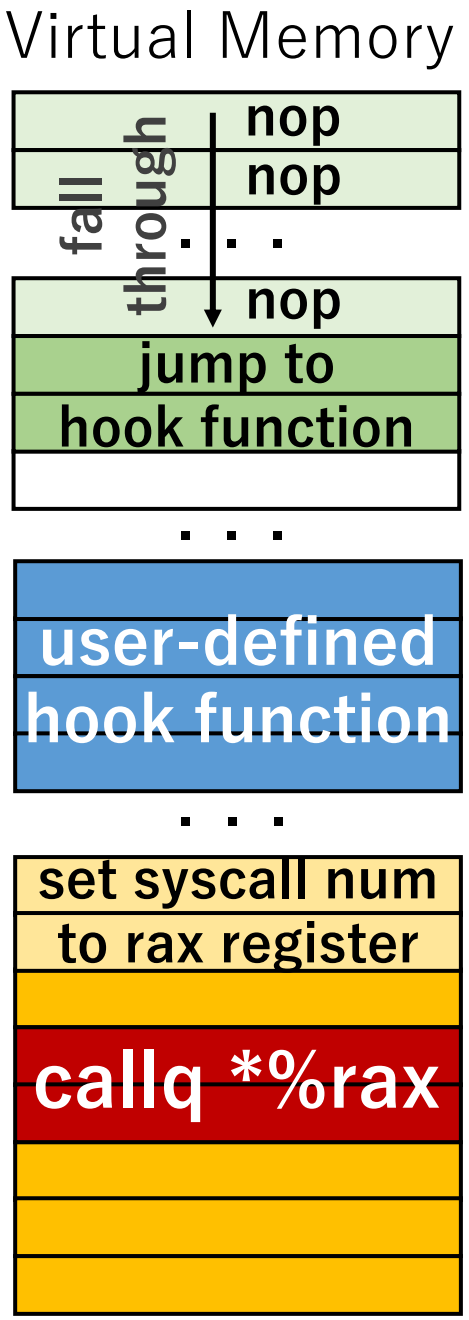
System Call Hook Overhead

- Time to hook getpid() and return a dummy value

Mechanism	Time [ns]
ptrace	31201
int3 signaling	1342
SUD	1156
zpoline	41
LD_PRELOAD	6



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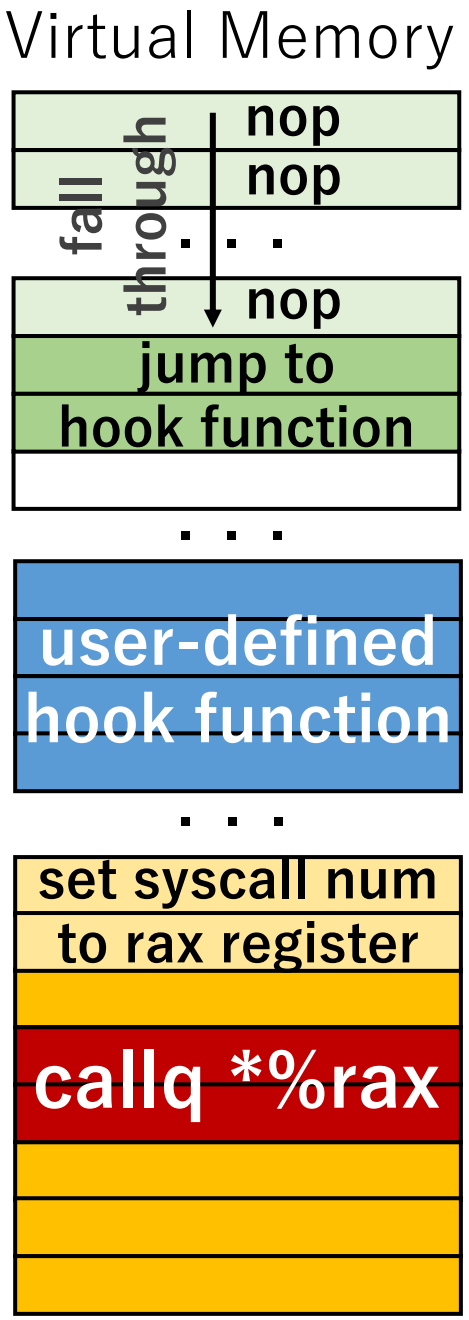
System Call Hook Overhead

- Time to hook getpid() and return a dummy value

Mechanism	Time [ns]	
ptrace	31201	716x
int3 signaling	1342	32.7x
SUD	1156	28.1x
zpoline	41	improvement
LD_PRELOAD	6	



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- Time to hook getpid() and return a dummy value

Mechanism	Time [ns]
ptrace	31201
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SUD	1156
zpoline	41
zpoline (w/o NULL exec check)	40
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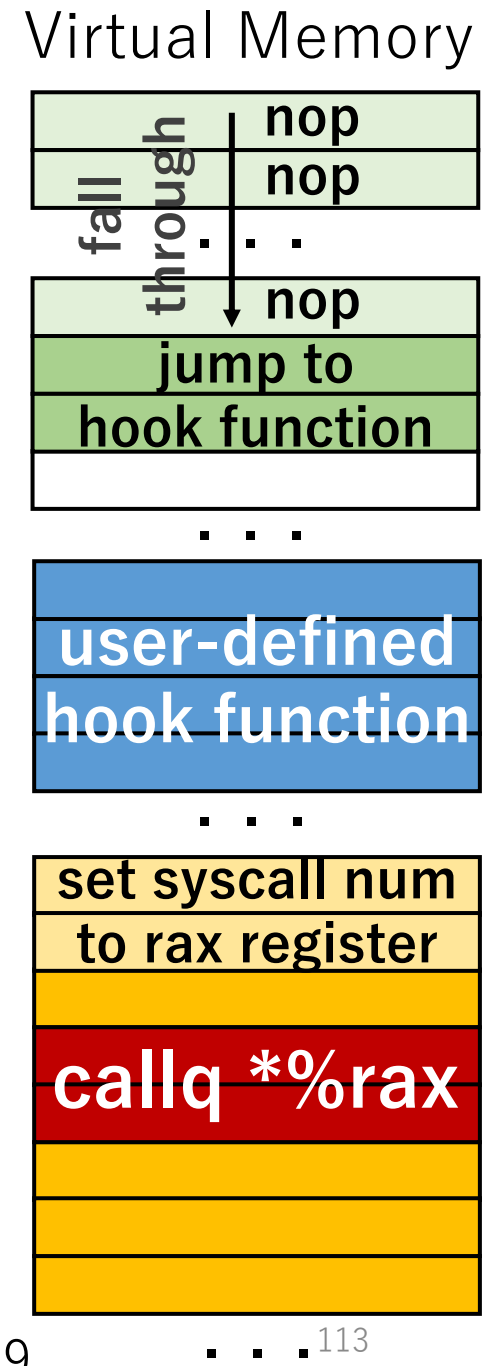

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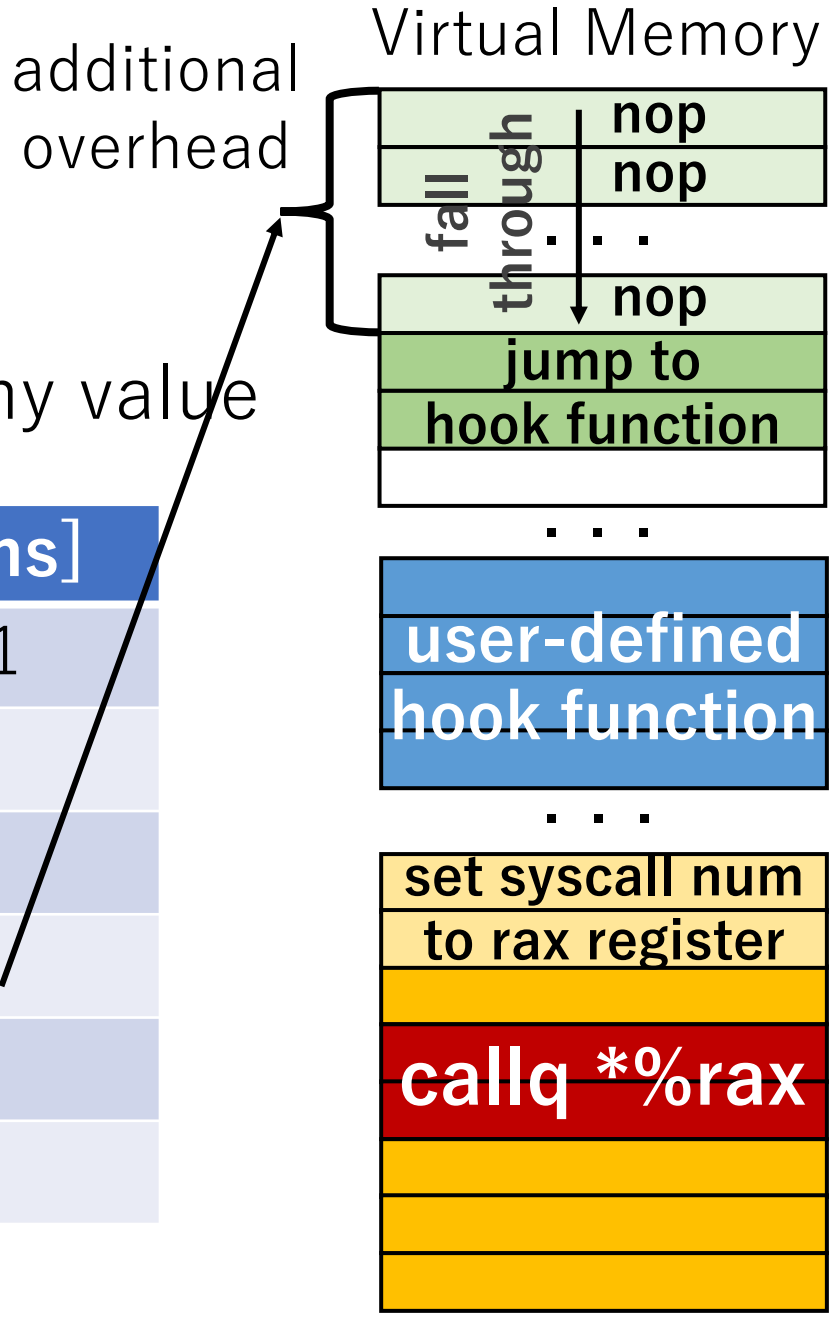

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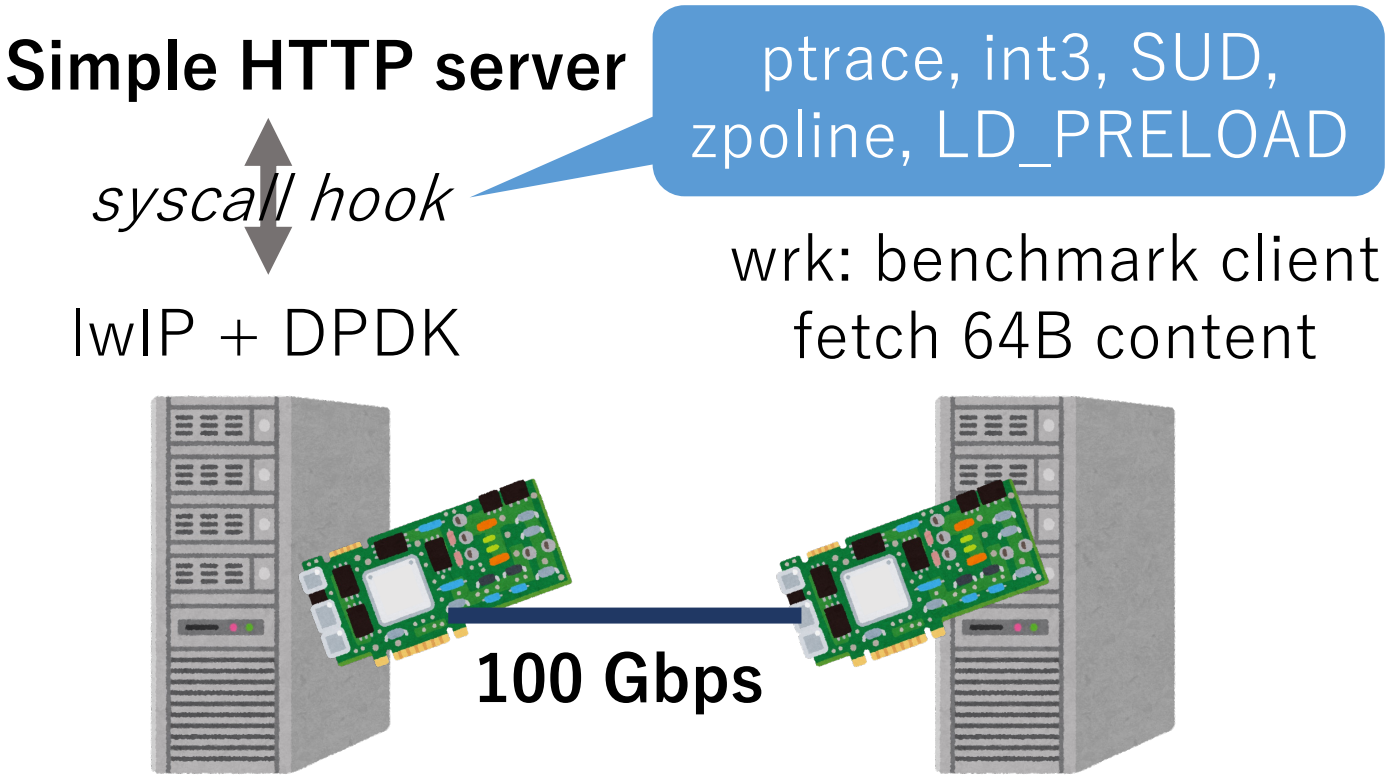
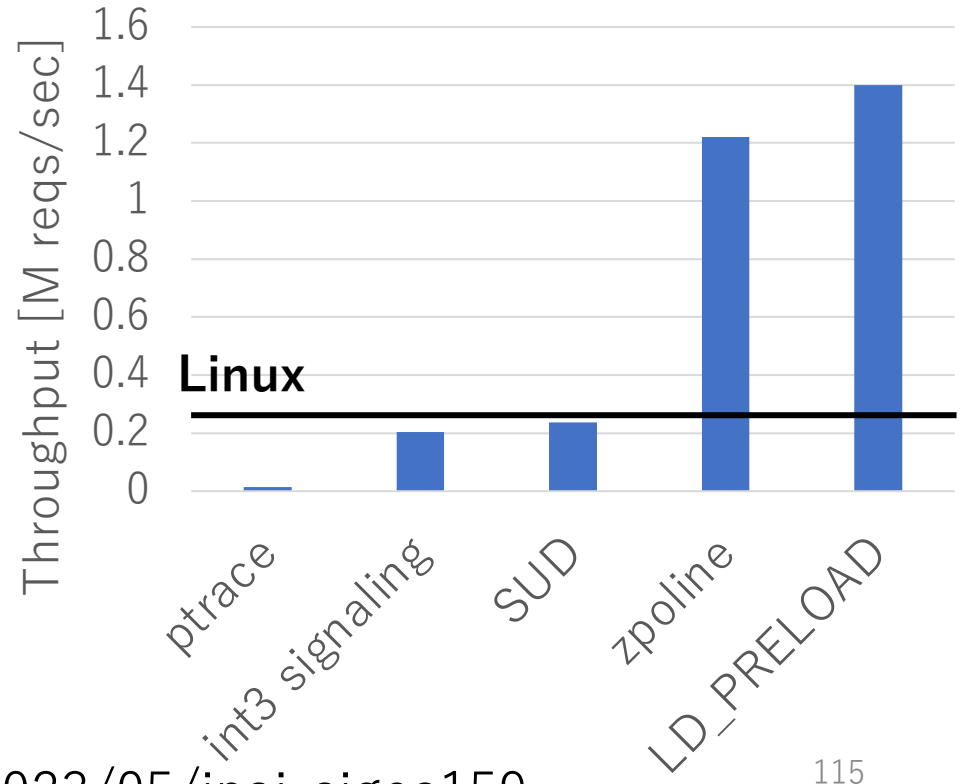
Application Performance

- We **transparently** apply lwIP + DPDK to an application using different system call hook mechanisms





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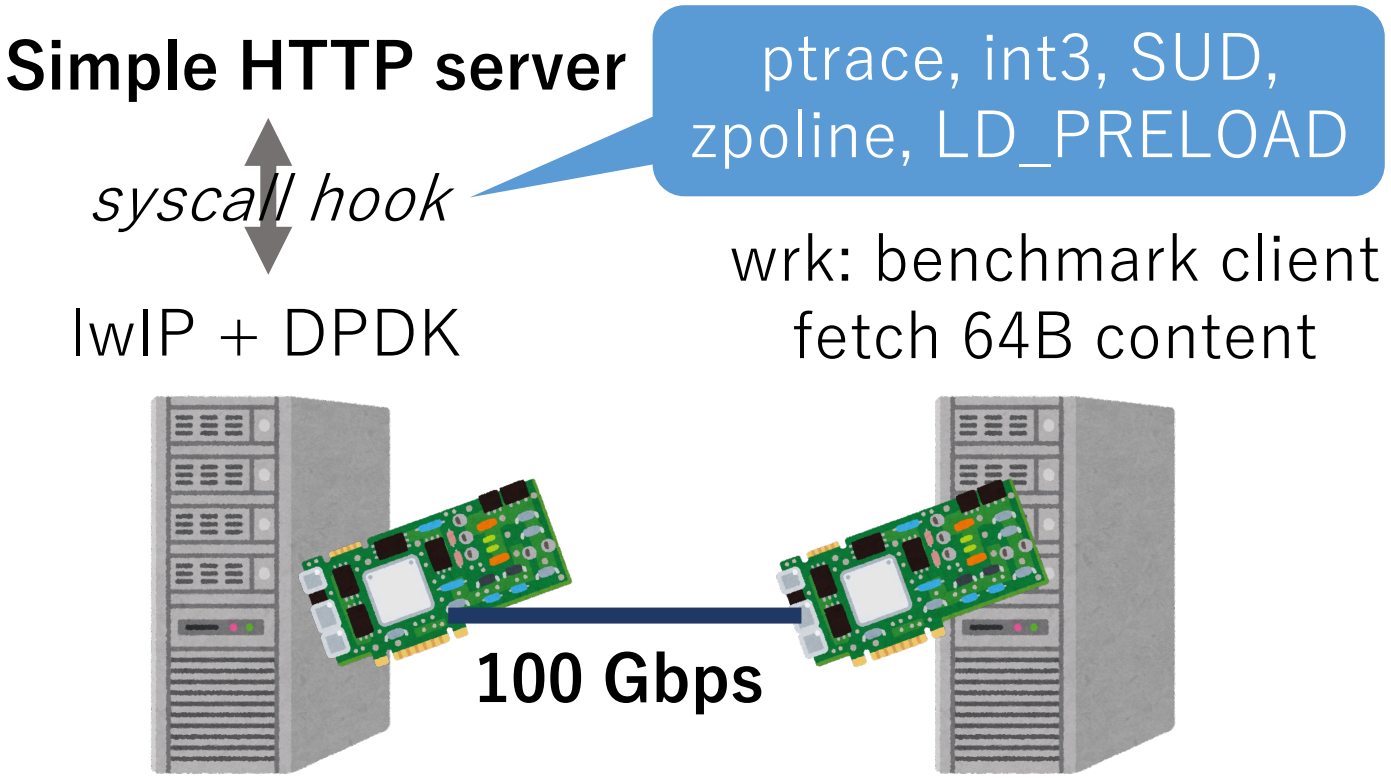

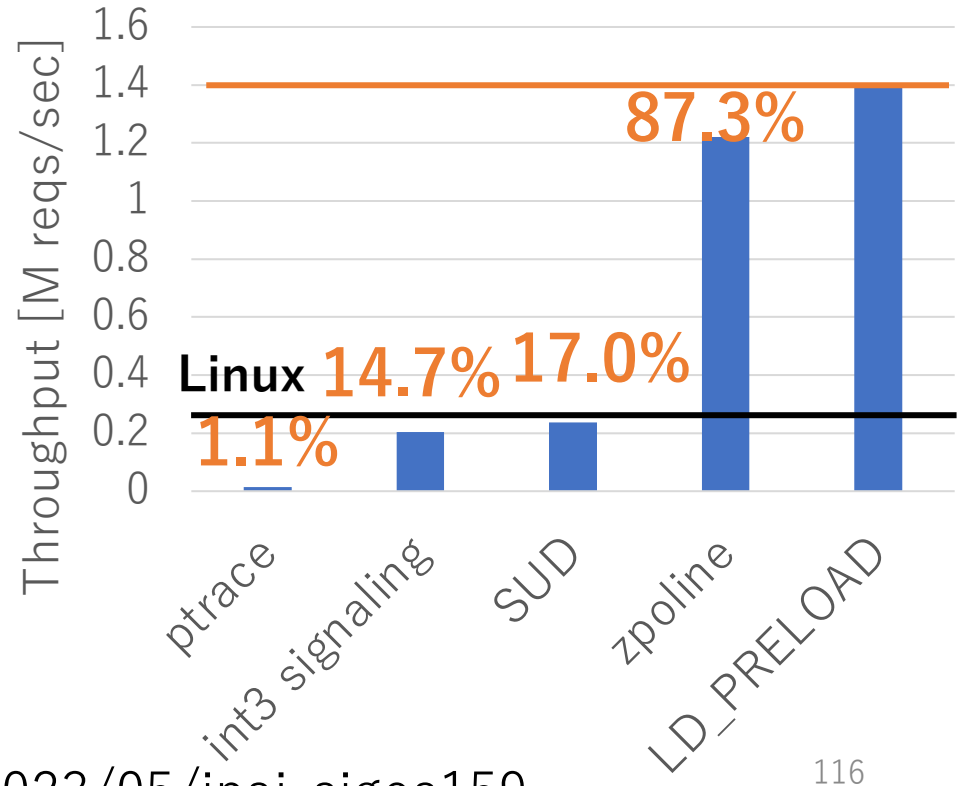

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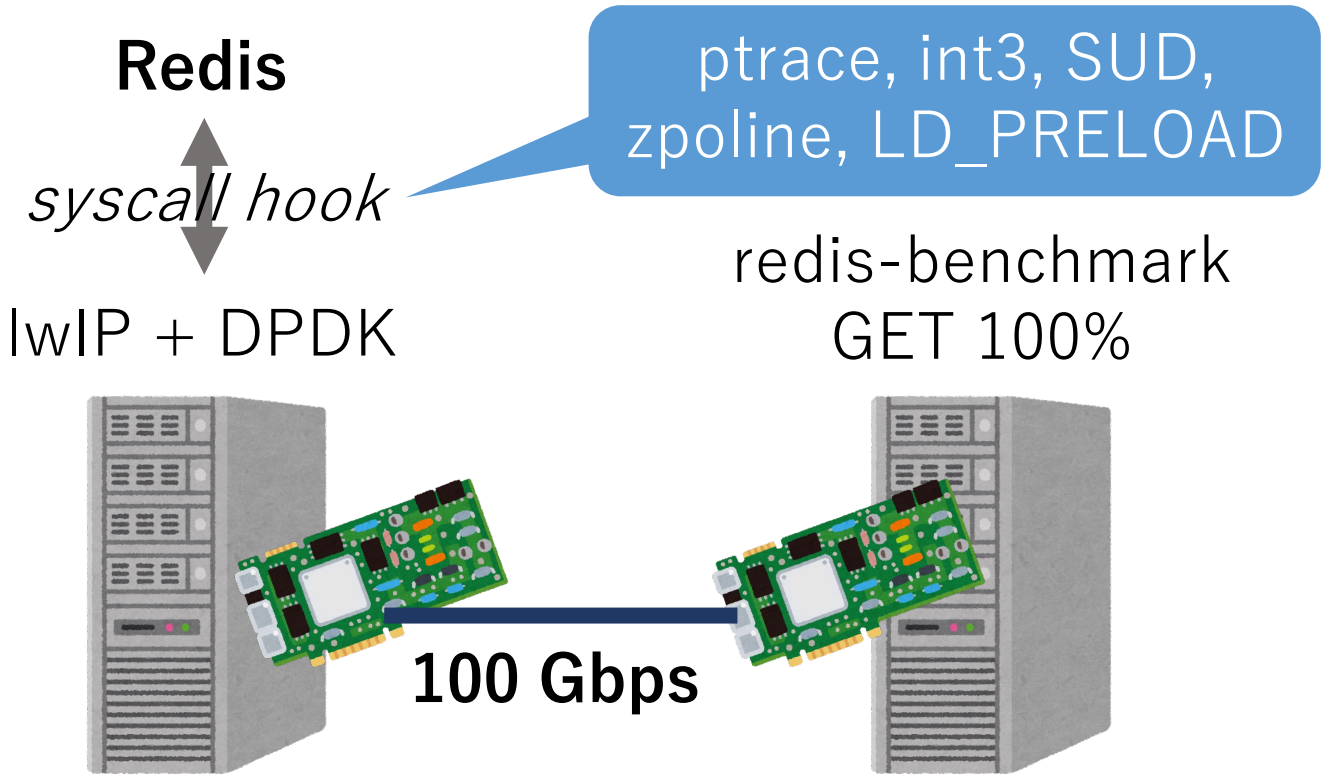

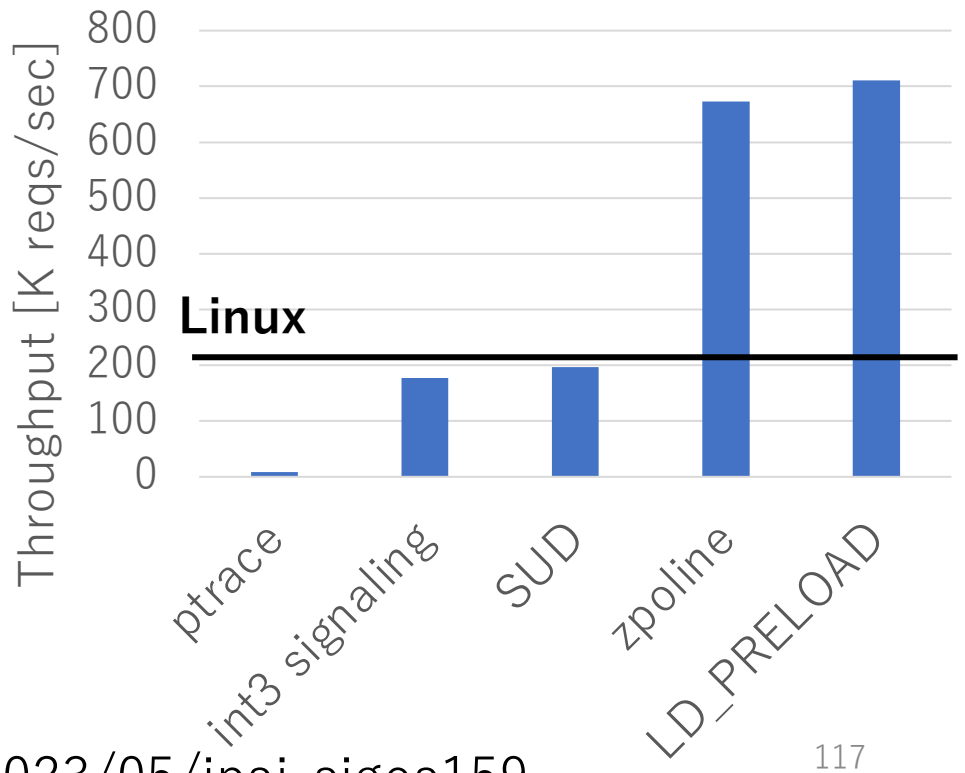

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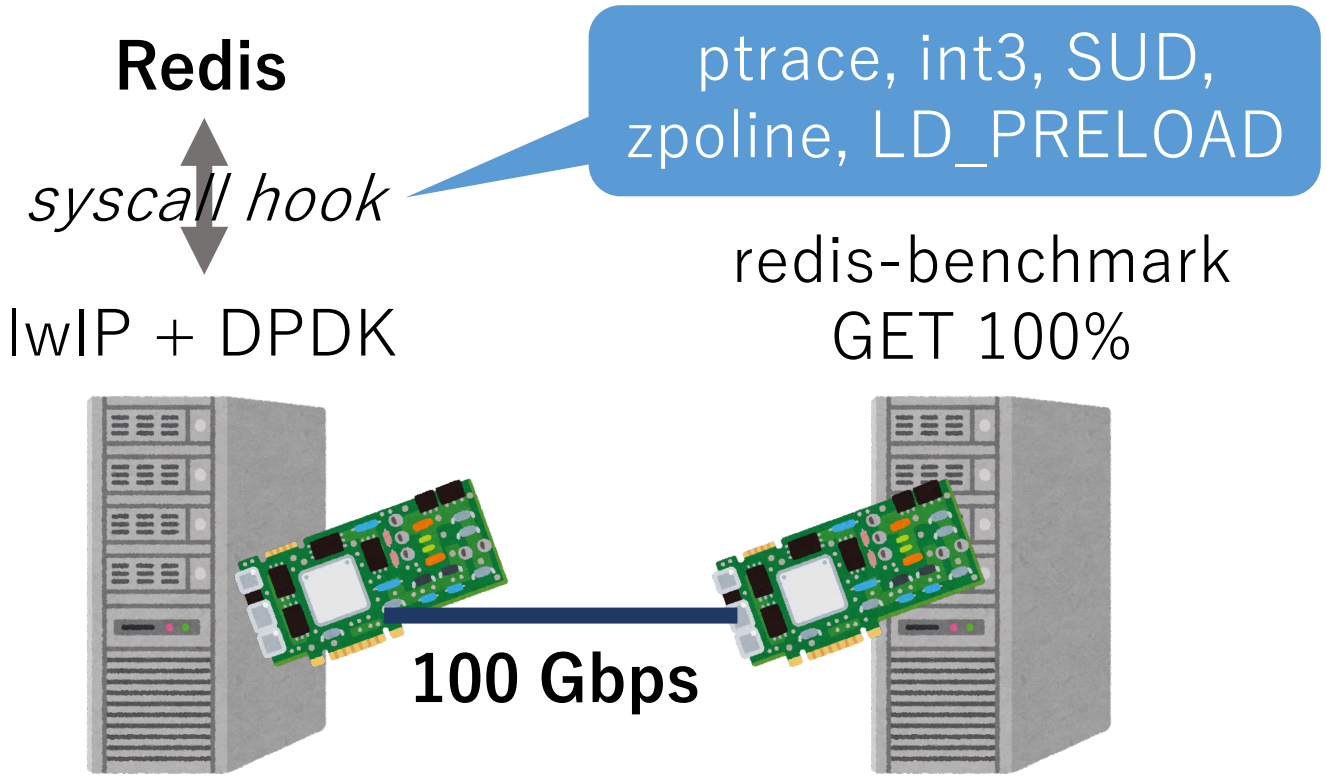

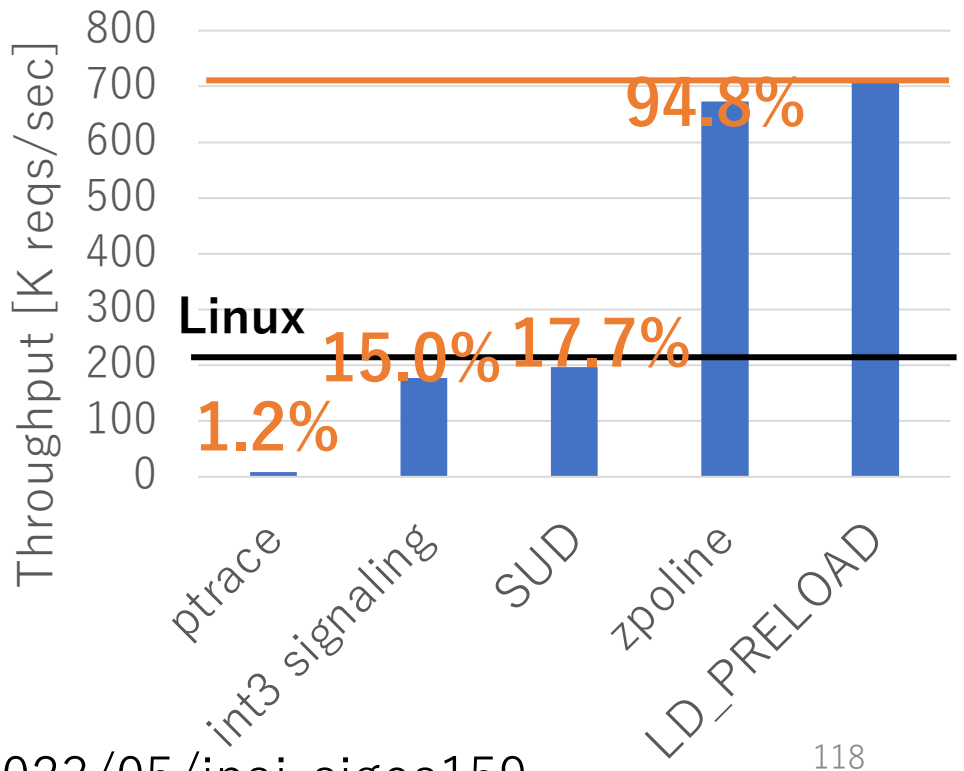

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Summary

- zpoline: a system call hook mechanism
  - replaces syscall/sysenter with callq *%rax
  - instantiates the trampoline code at virtual address 0 (zero)
- 6 advantages: good for transparently applying user-space OS subsystems to existing applications
  1. Low hook overhead
  2. Exhaustive hooking
  3. No breakage of user-space program logic
  4. No kernel change and no additional kernel module are necessary
  5. No source code of a user-space program is needed
  6. It can be used for emulating system calls

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