バイナリ書き換えを用いたシステムコールフック機構

SNIA 日本支部 次世代メモリ＆ストレージ分科会

2023 年 6 月 2 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

System Call

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

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User-space program

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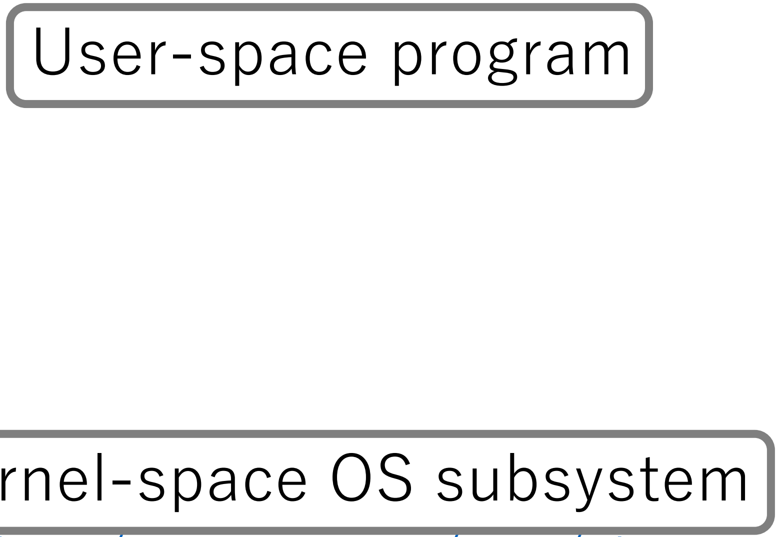

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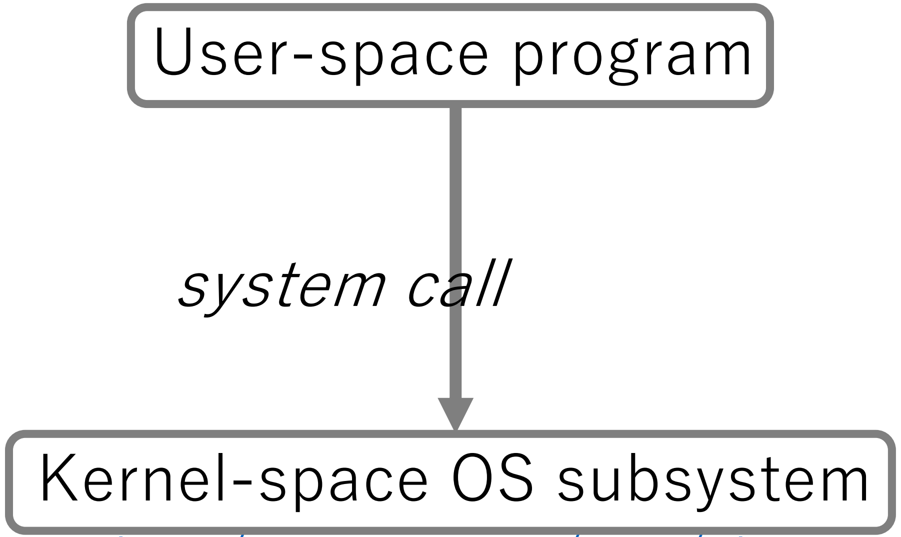

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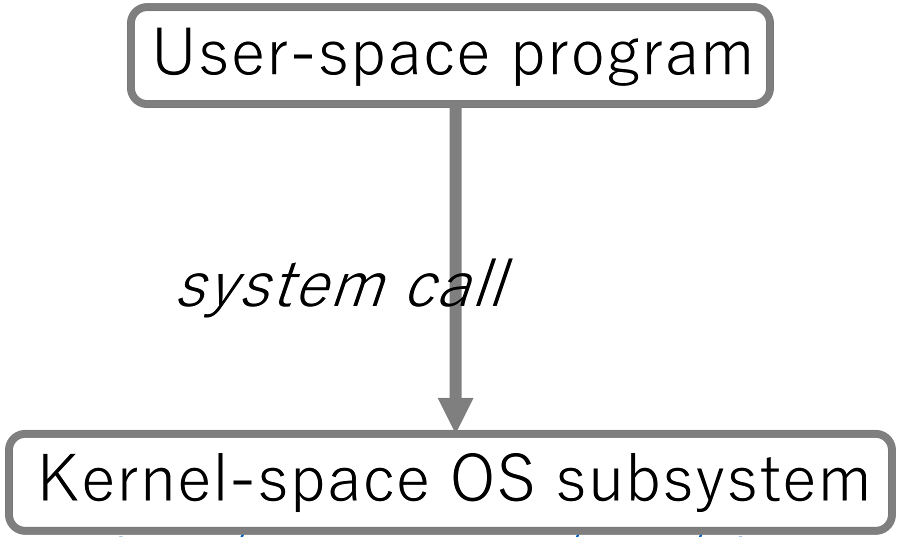
- A system call hook mechanism intercepts a system call



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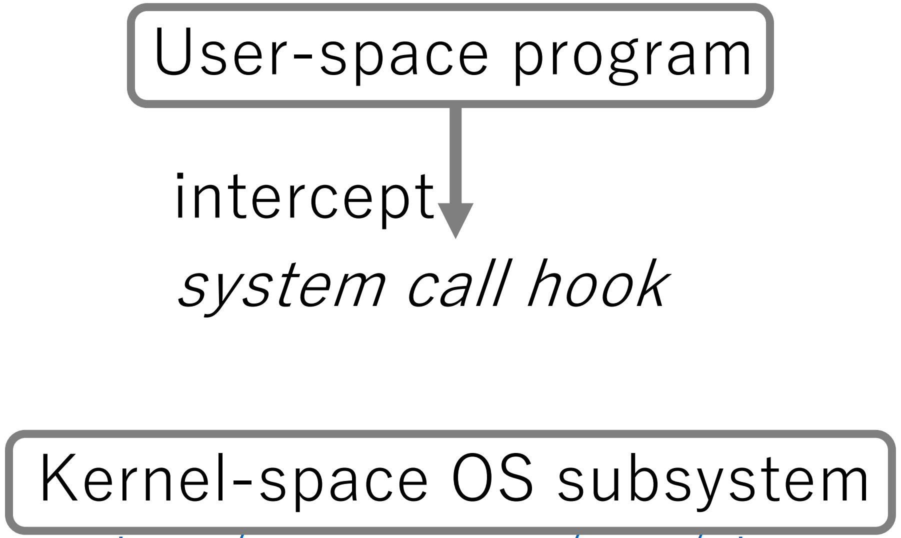

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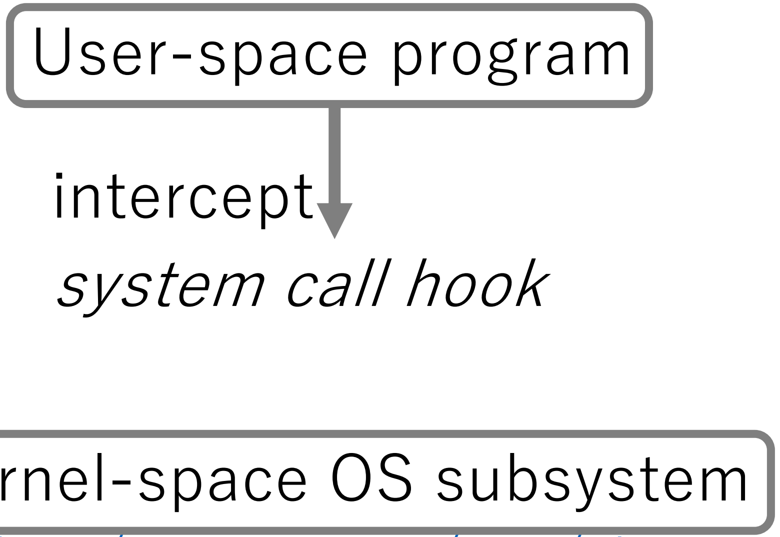

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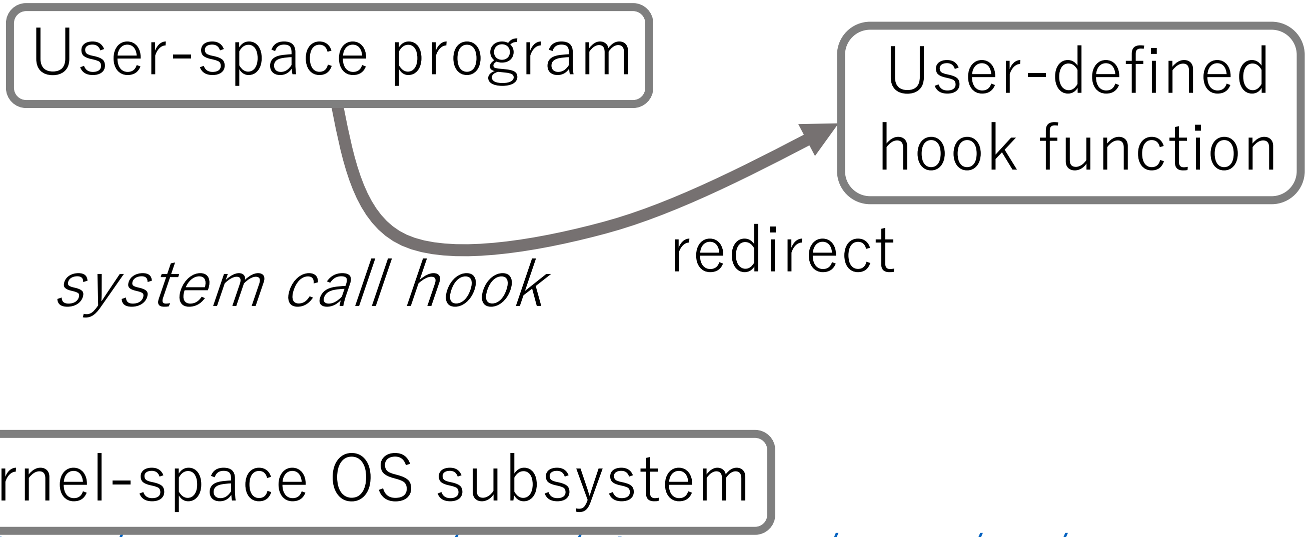

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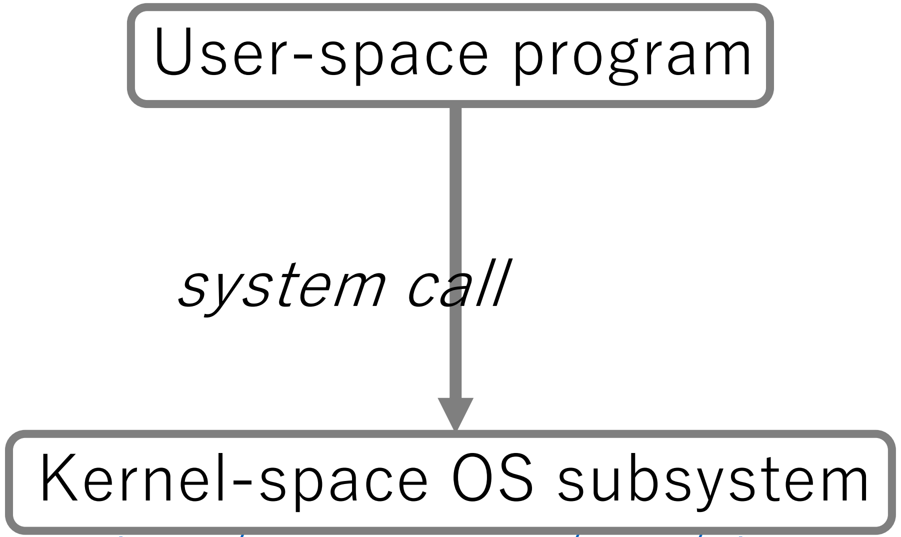
Motivating Use Case

- System call hook mechanisms allow us to transparently apply user-space OS subsystems to existing applications



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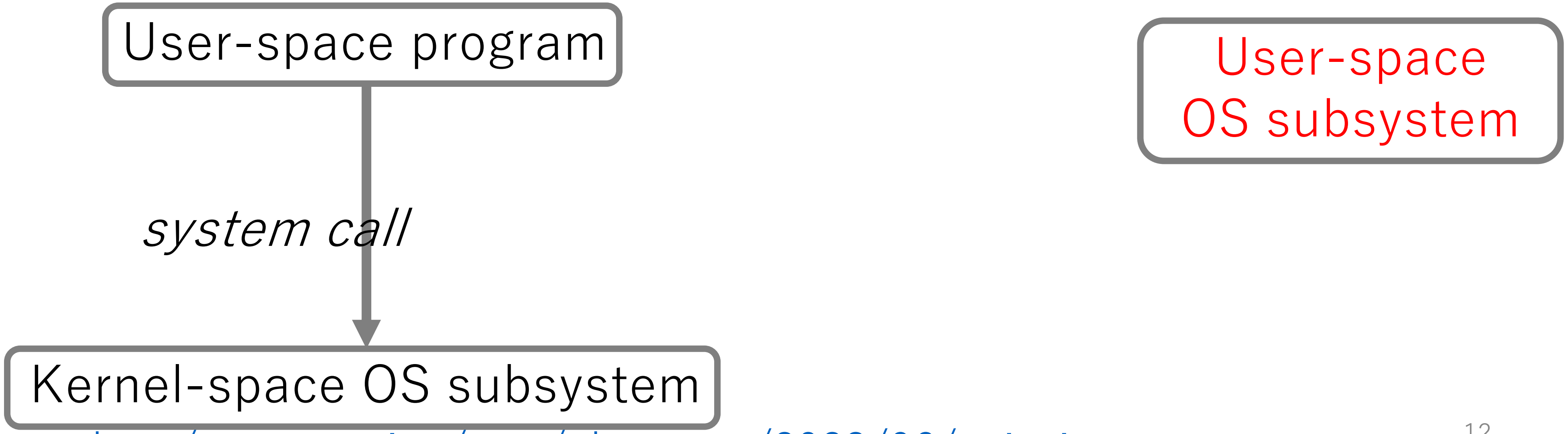

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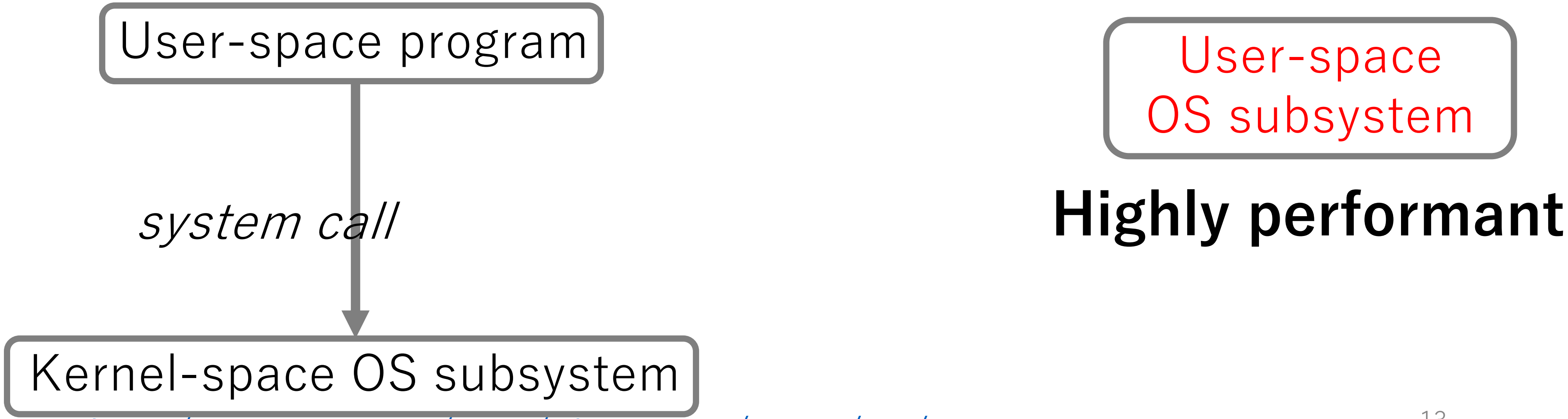

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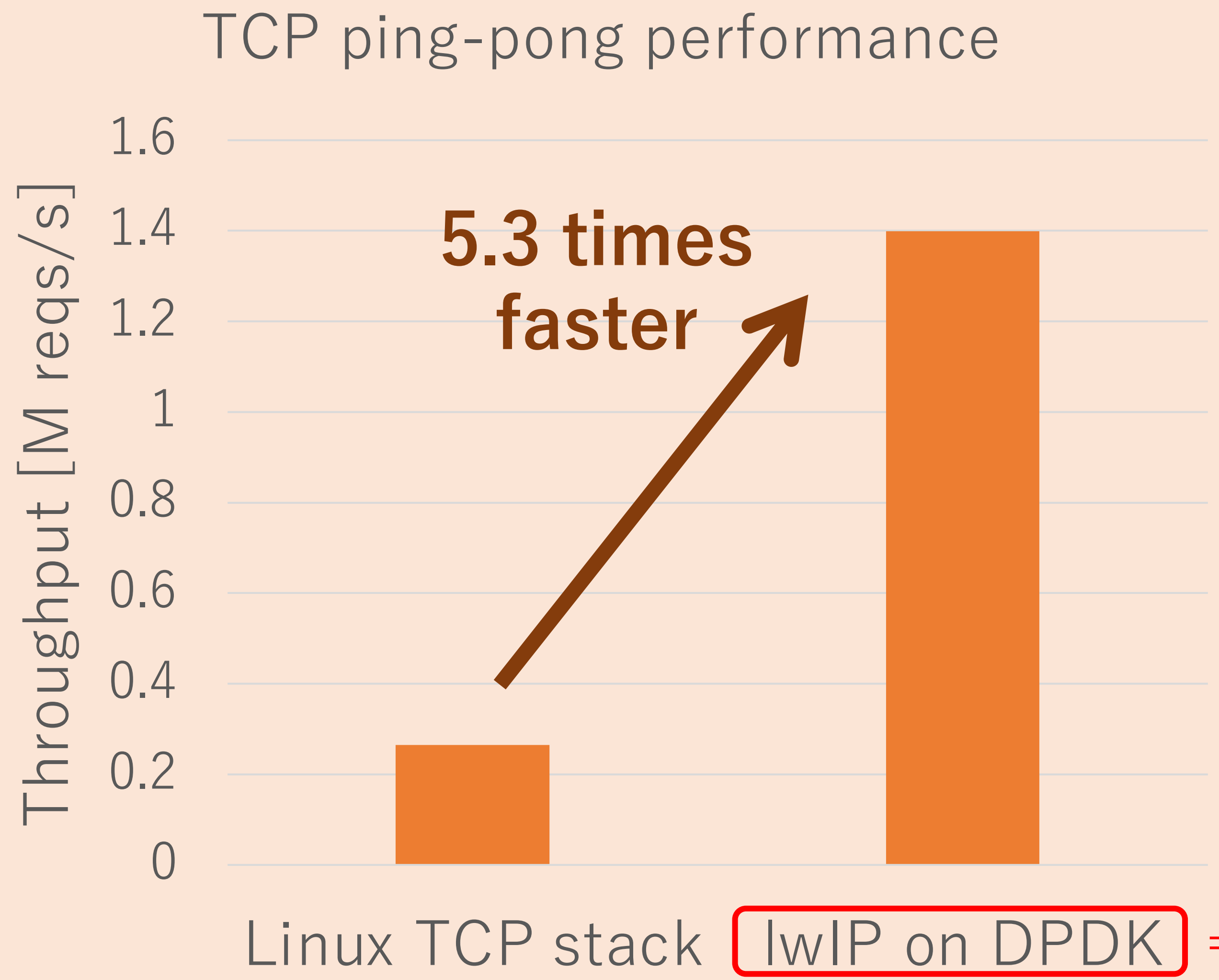

›o transparently apply
›plications

User-space
OS subsystem

Highly performant

= user-space network stack

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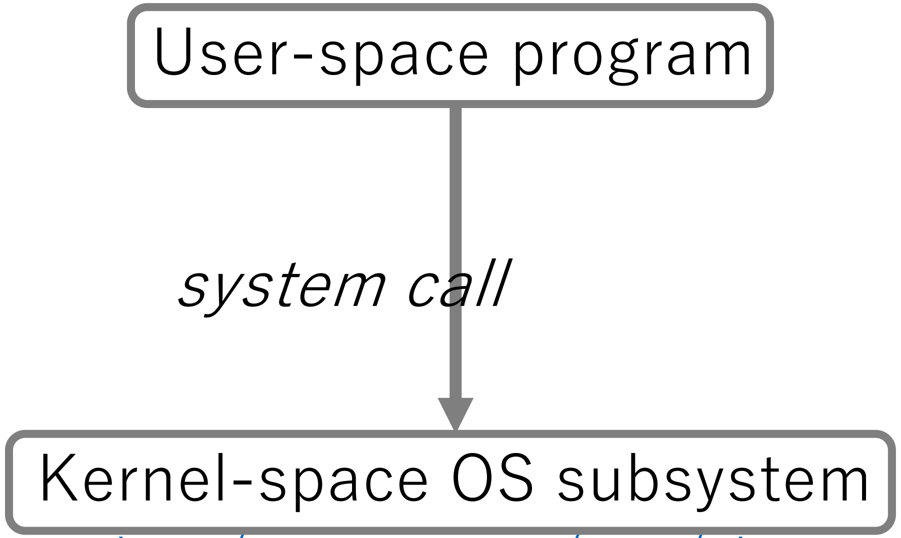

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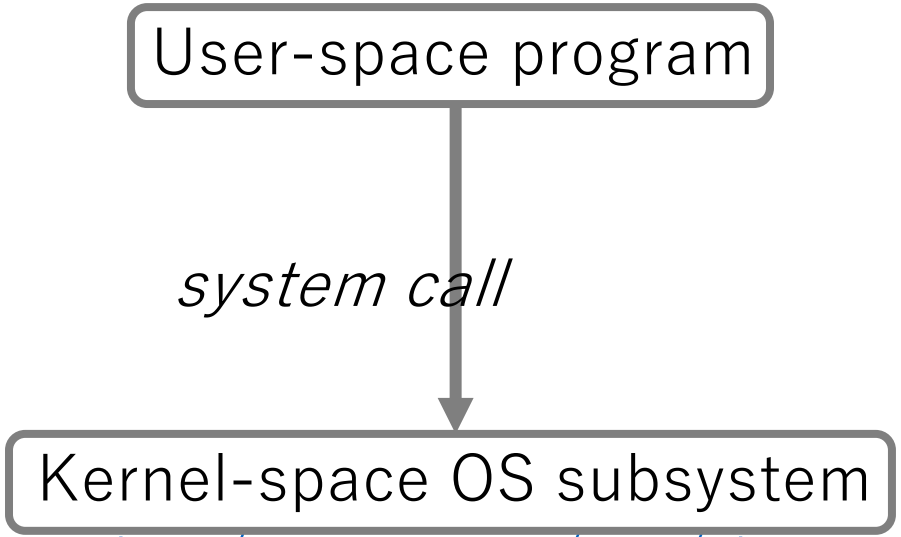
Normally, adaptation requires changes of a user-space program to apply a specific API of a user-space OS subsystem



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Modified

User-space program

Specific API

User-space OS subsystem

Highly performant

Kernel-space OS subsystem

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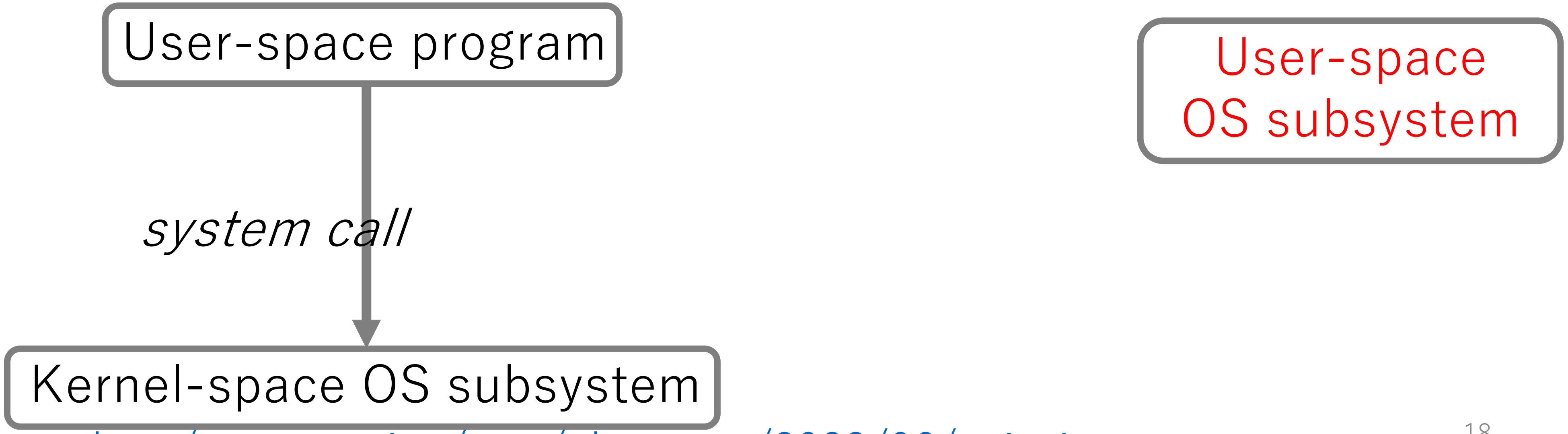
If we use a system call hook mechanism, ...



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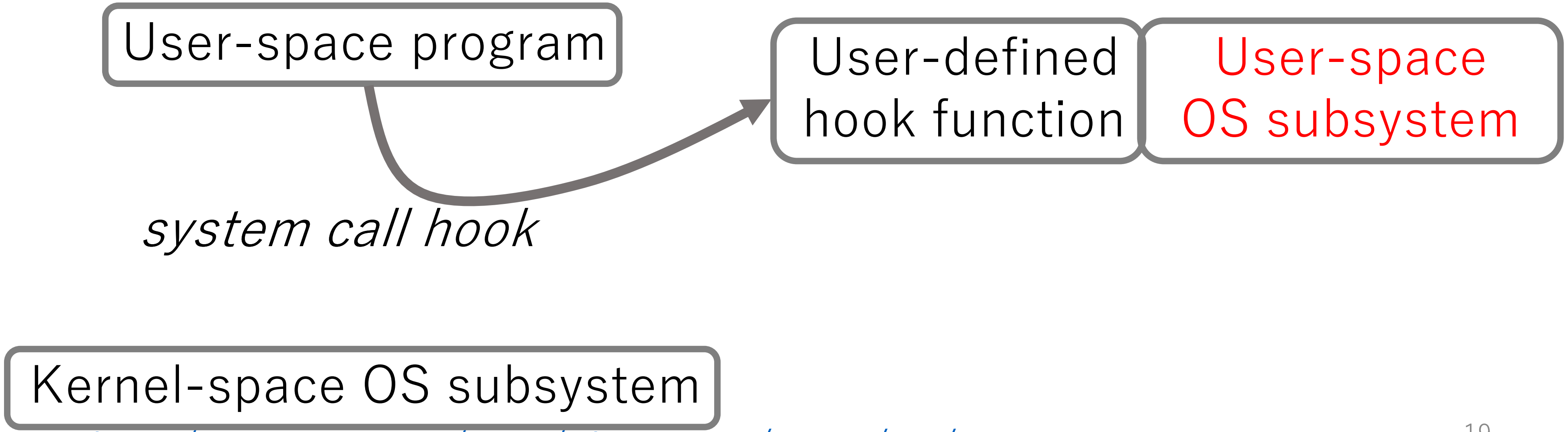

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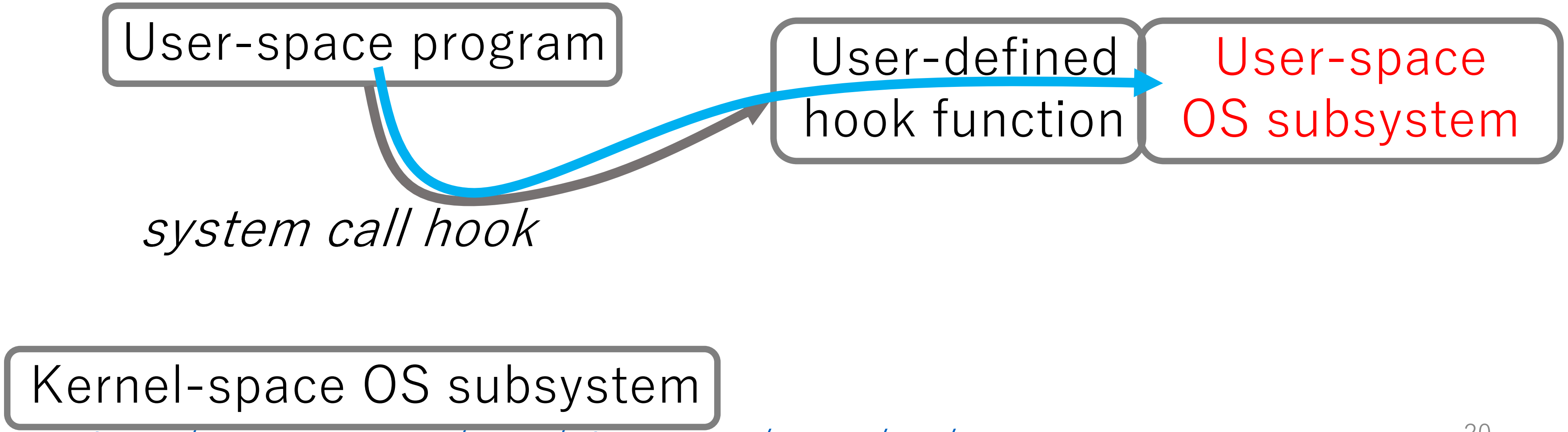

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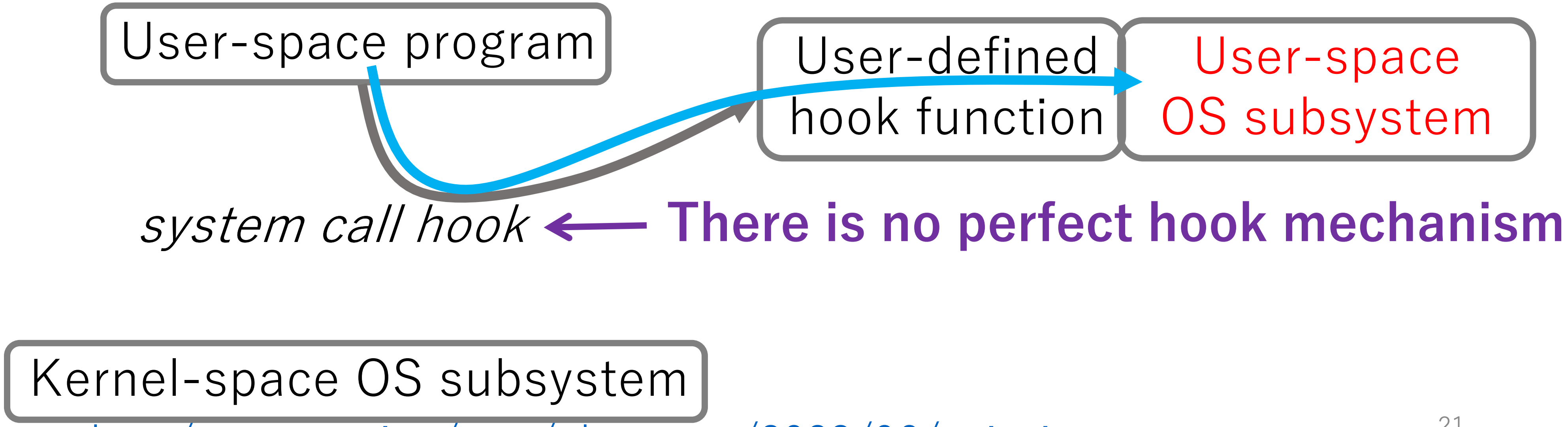

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Problem

Existing Mechanisms

- ptrace
- Syscall User Dispatch (SUD)
- int3 signaling technique
- LD_PRELOAD trick
- Binary rewriting techniques
- …

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ok mechanism, …

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User-defined hook function

User-space OS subsystem

system call hook ← **There is no perfect hook mechanism**

Kernel-space OS subsystem

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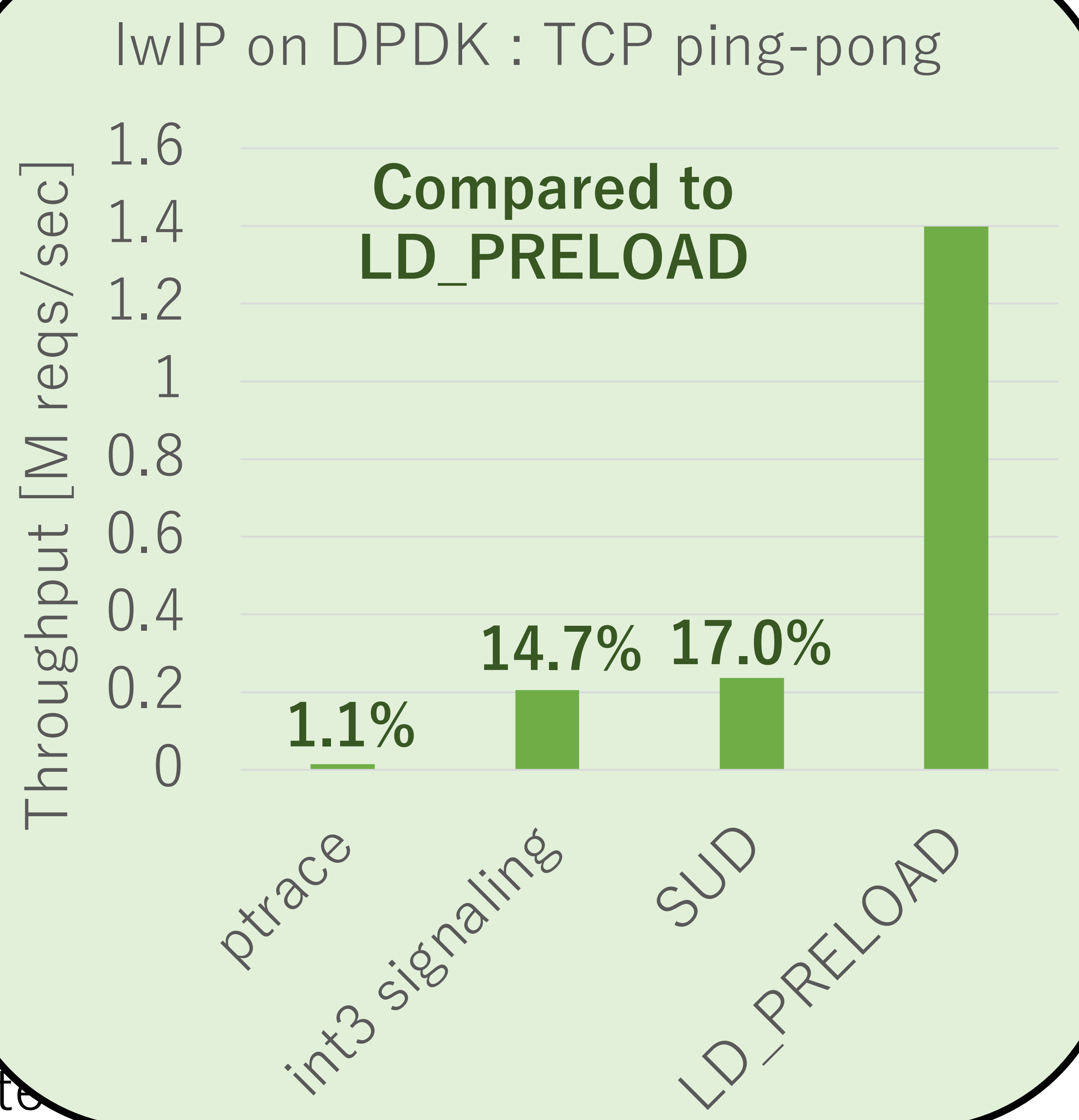
Kernel-space OS subsyste



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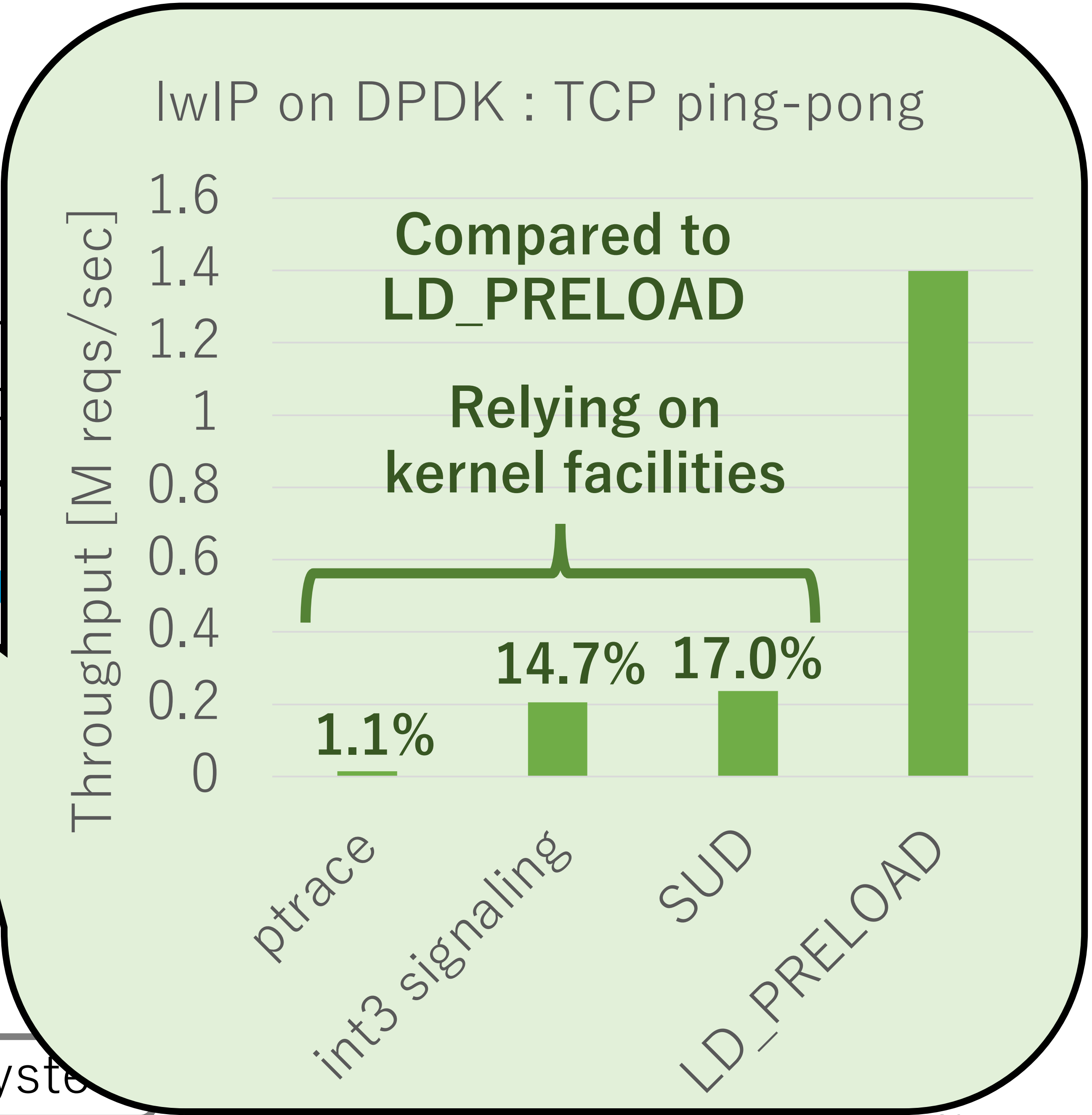

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Prob

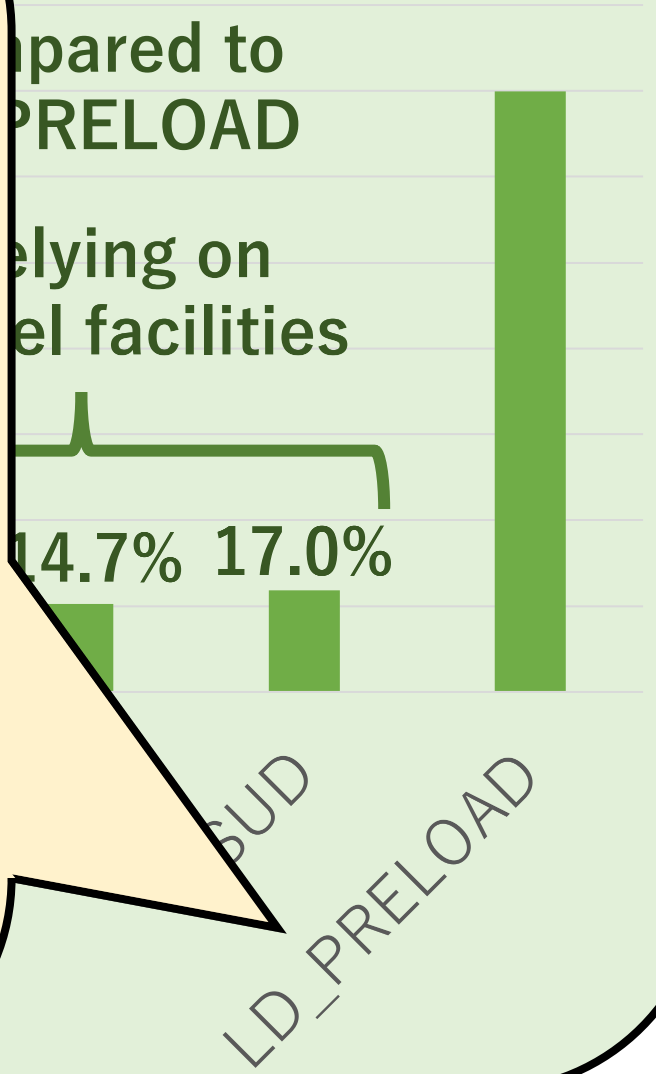
Ex

- ptra
- Sysc
- int3
- LD_
- Bina
- …

```
app_function(...)
{
  …
  write(...)
  …
}
```

libc
write()
library call

K : TCP ping-pong



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libc write() library call

User-defined write() library call

LD_PRELOAD

K : TCP ping-pong

pared to PRELOAD

elying on el facilities

14.7% 17.0%

SUD

LD_PRELOAD

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```
app_function(...)
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libc
write()
library call

function call
replacement

User-defined
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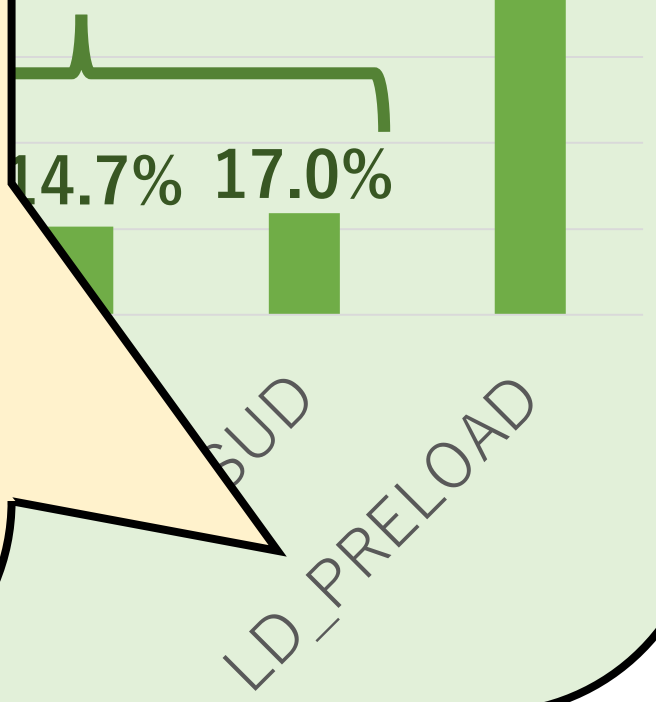

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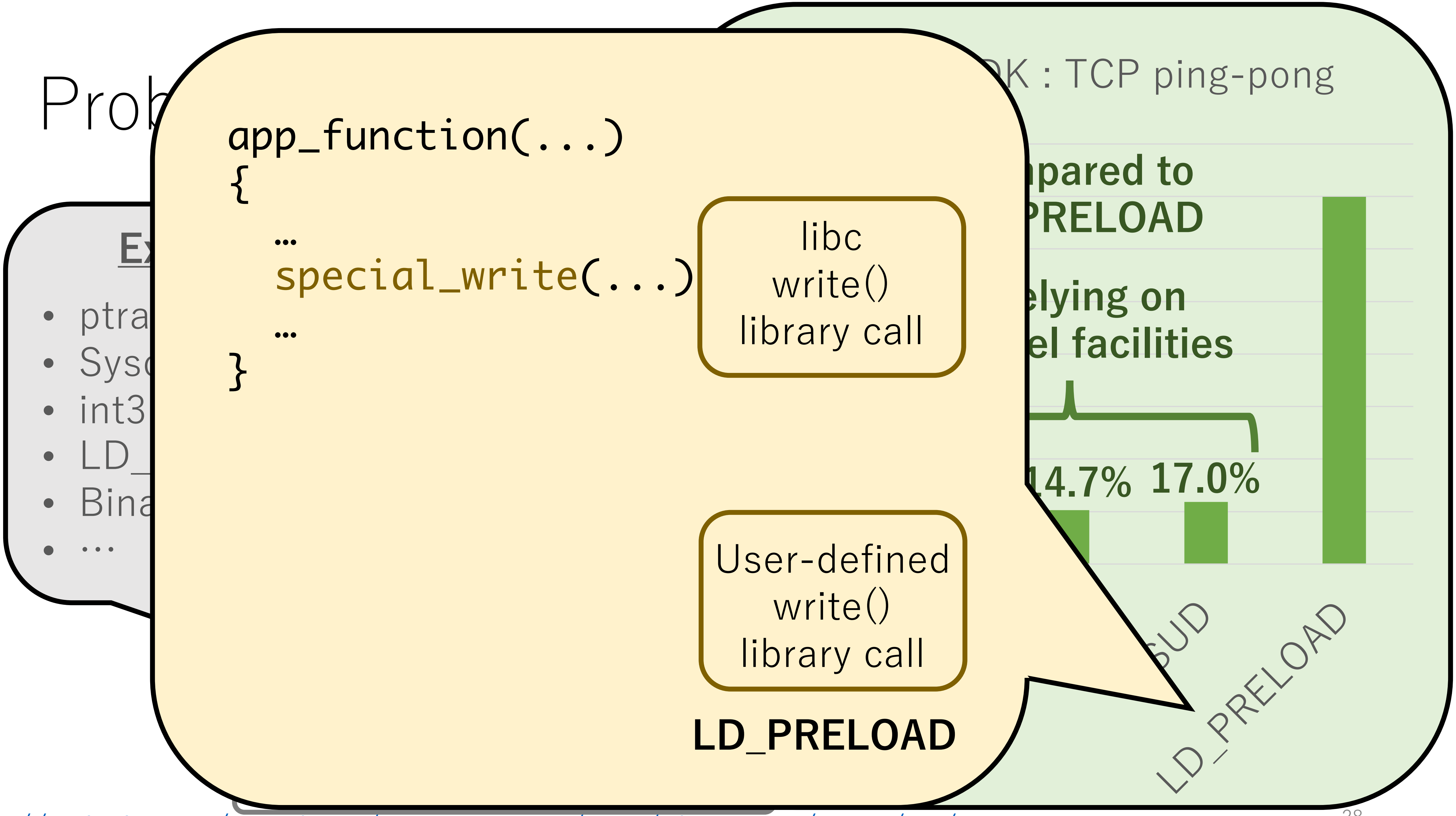

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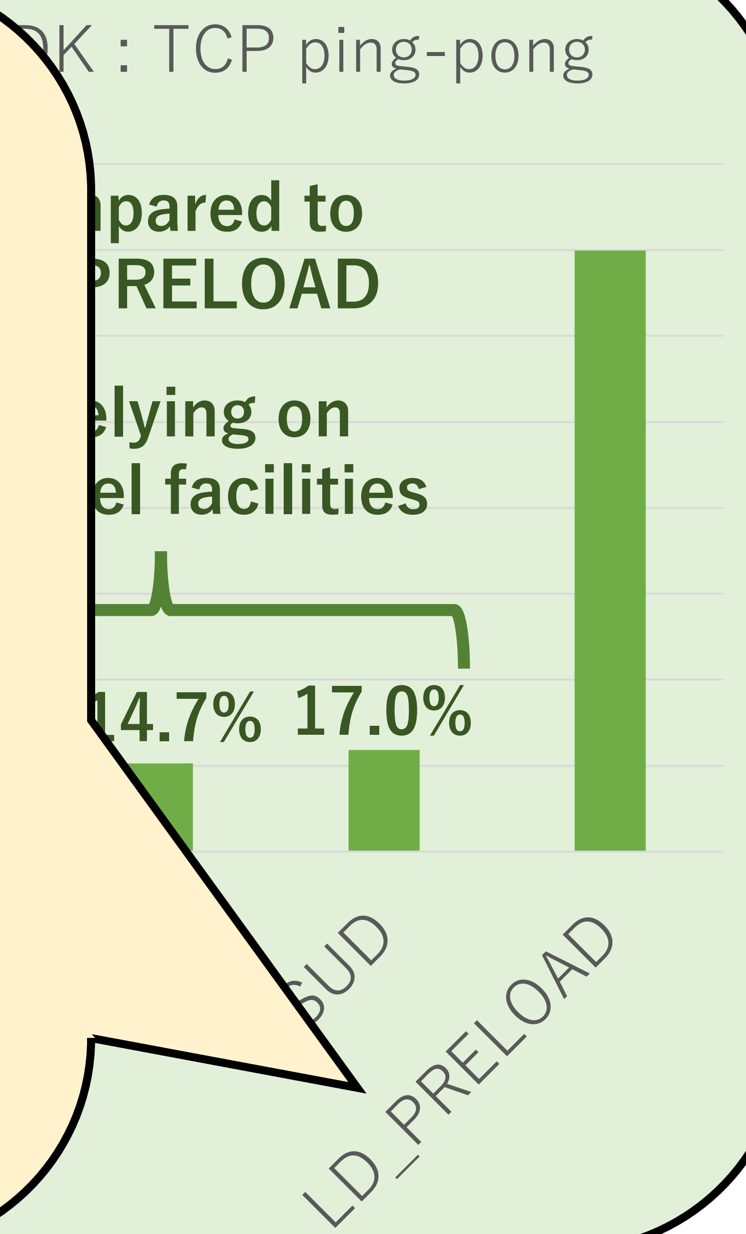

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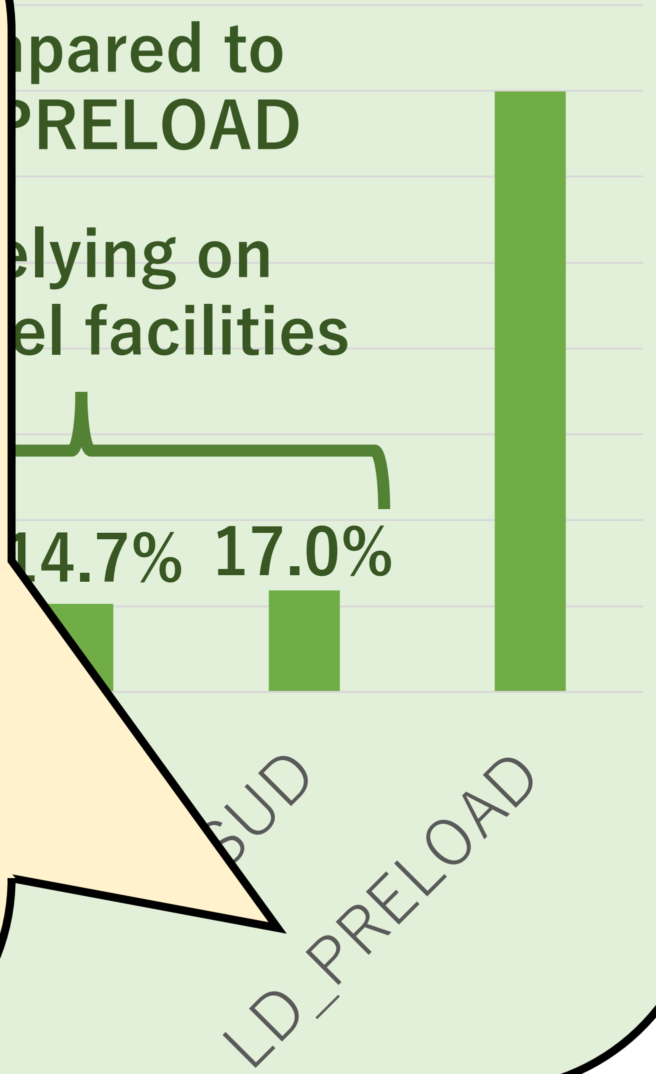

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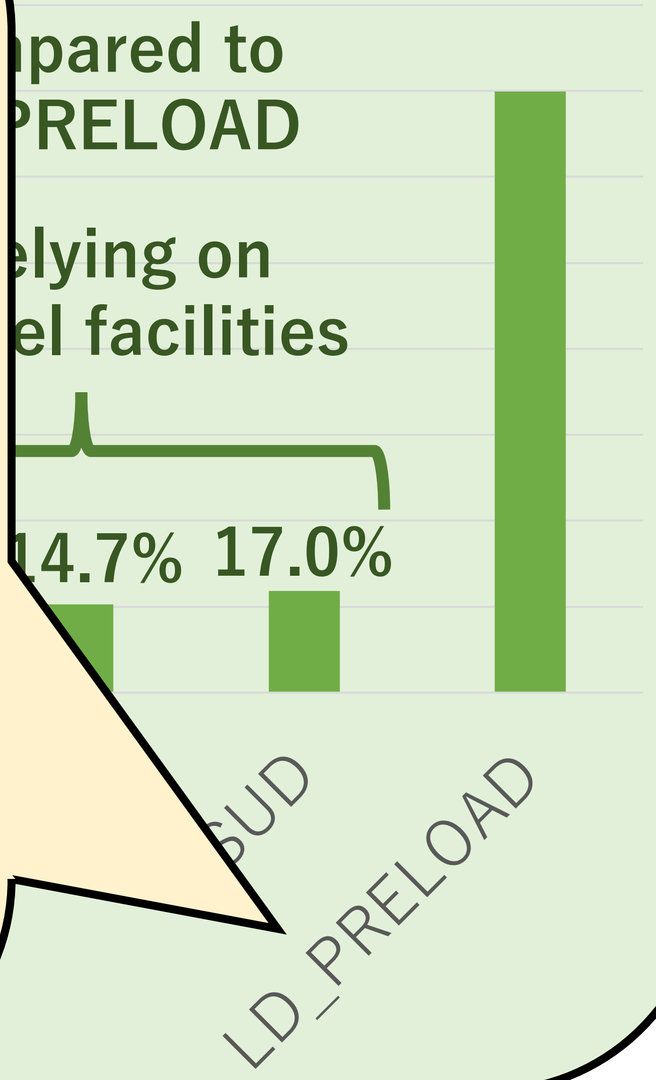

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libc
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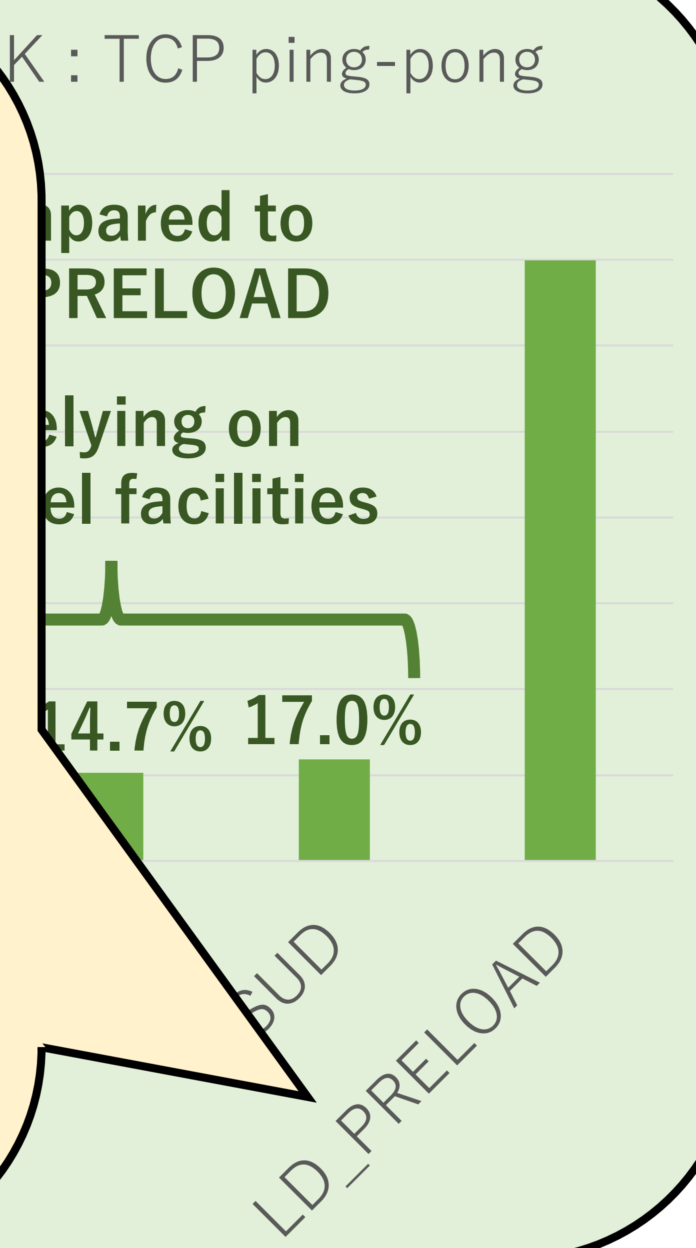

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libc
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User-defined
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14.7% 17.0%

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We see this case in glibc often

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User-space OS subsystem

system call hook ← **There is no perfect hook mechanism**

Kernel-space OS subsystem

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Problem

Existing Mechanisms

High performance penalty

- Sysca… atch (SUD)
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Problem

Existing Mechanisms

- Sysca… …atch (SUD)
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High performance penalty

Sometimes fail to hook

…ms allow us to transparently apply … to existing applications

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

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Existing Mechanisms

High performance penalty

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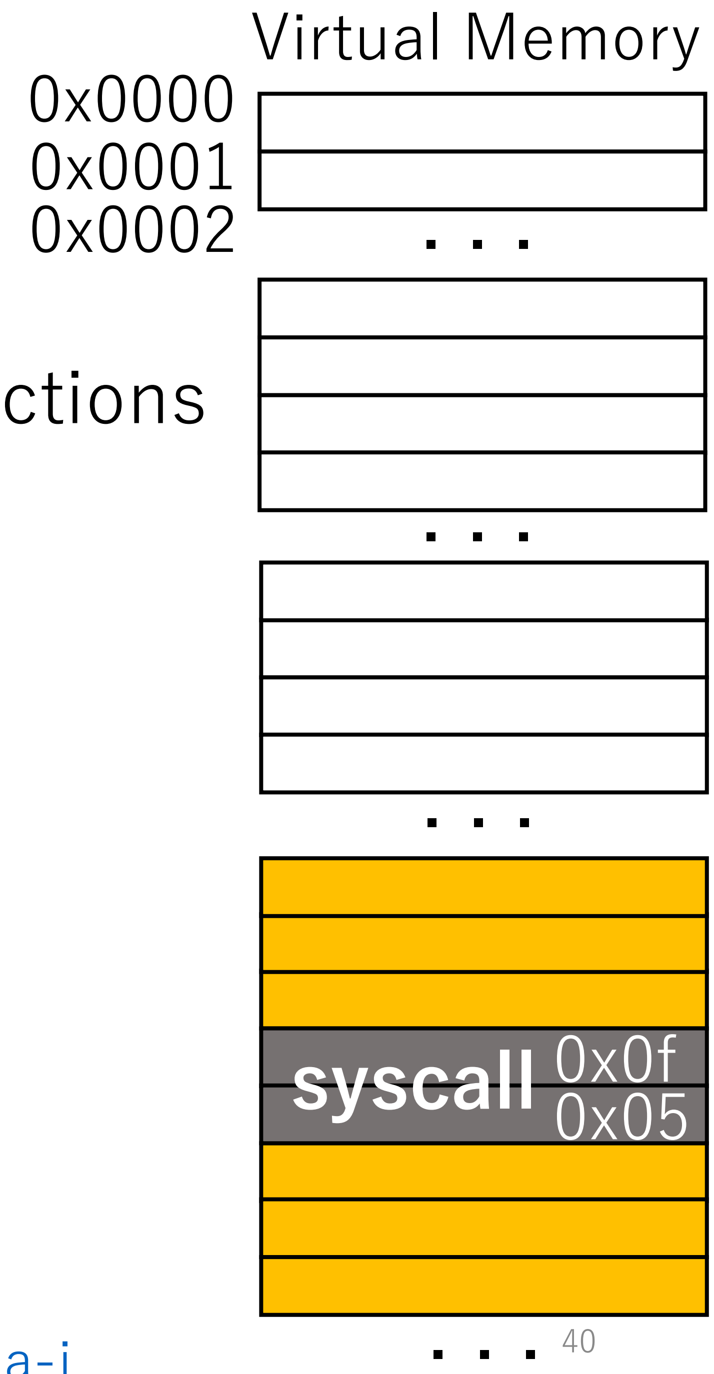
Contribution

- 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

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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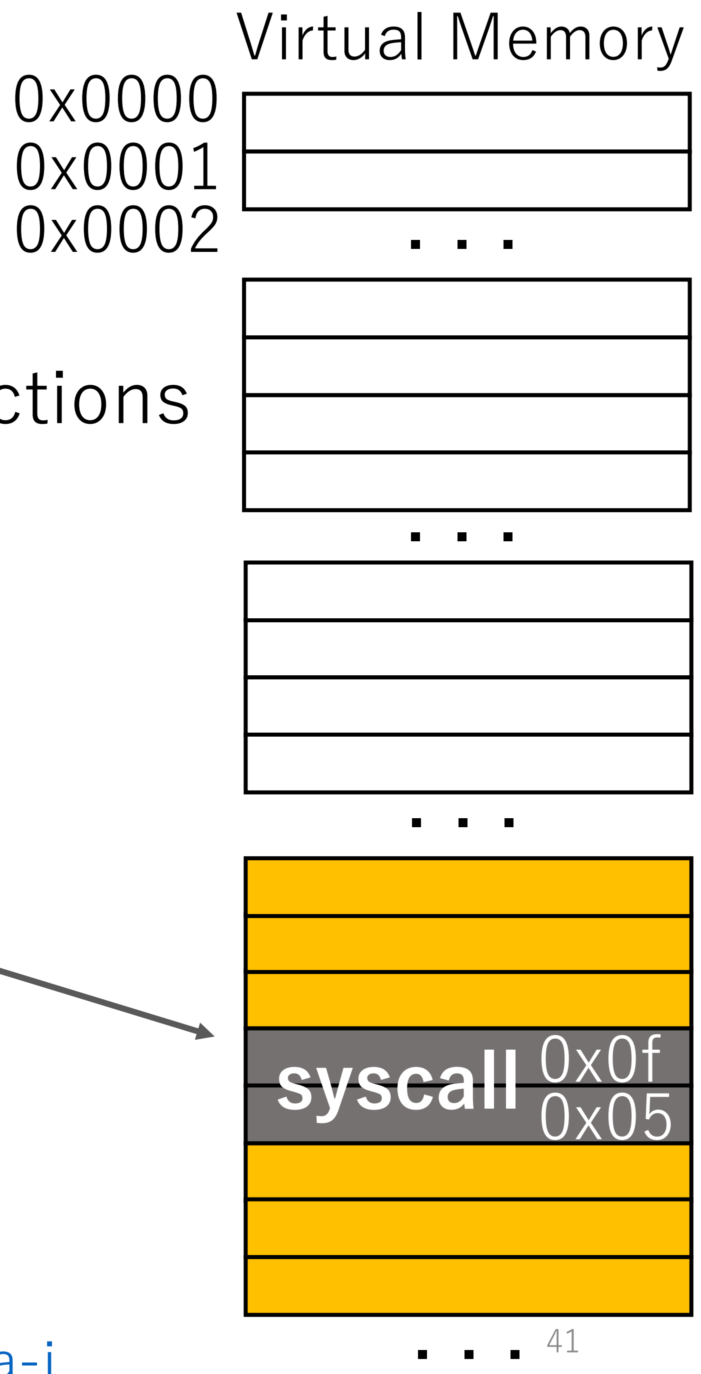

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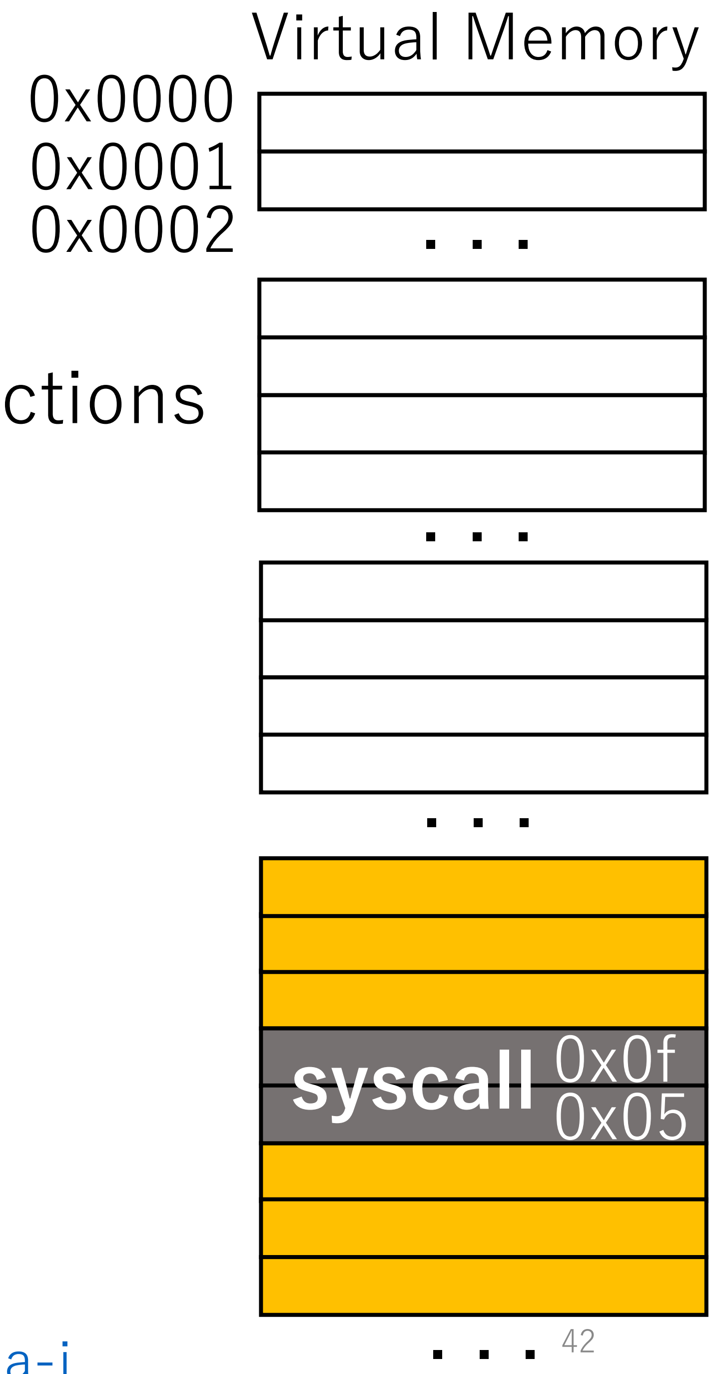

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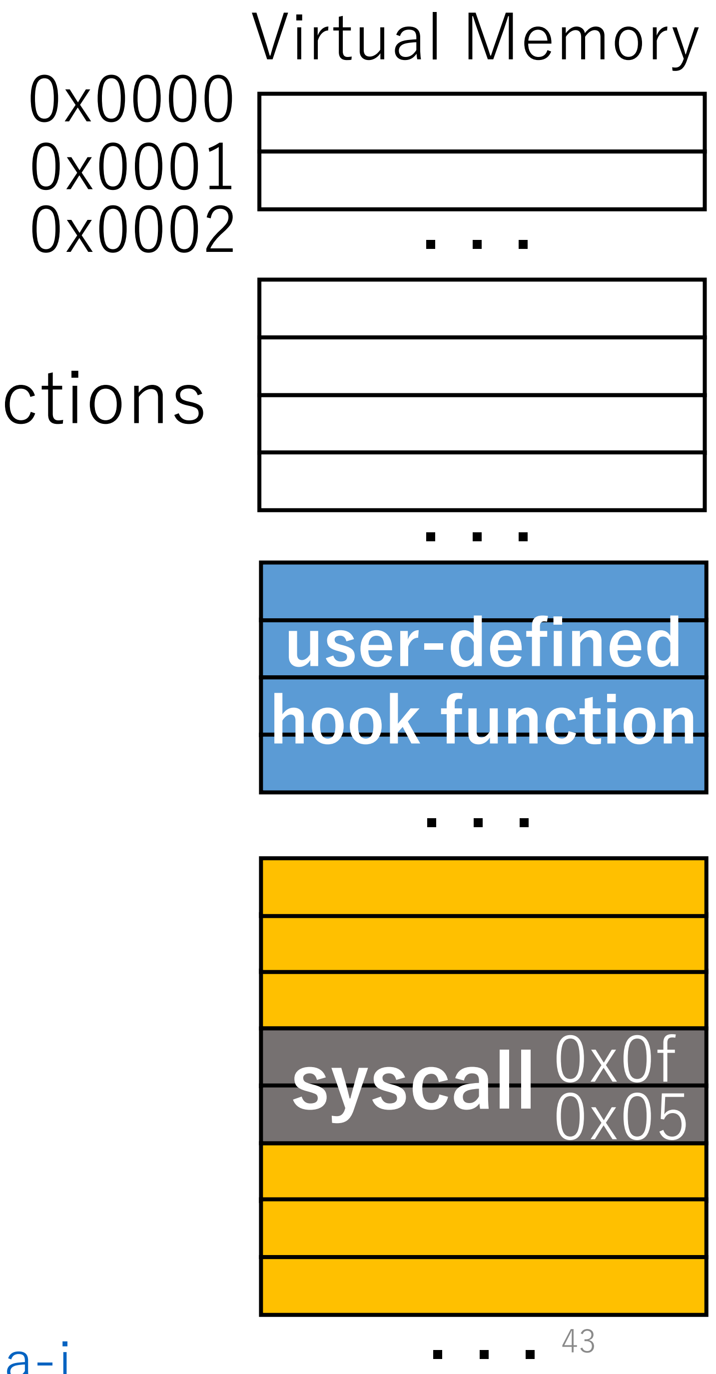

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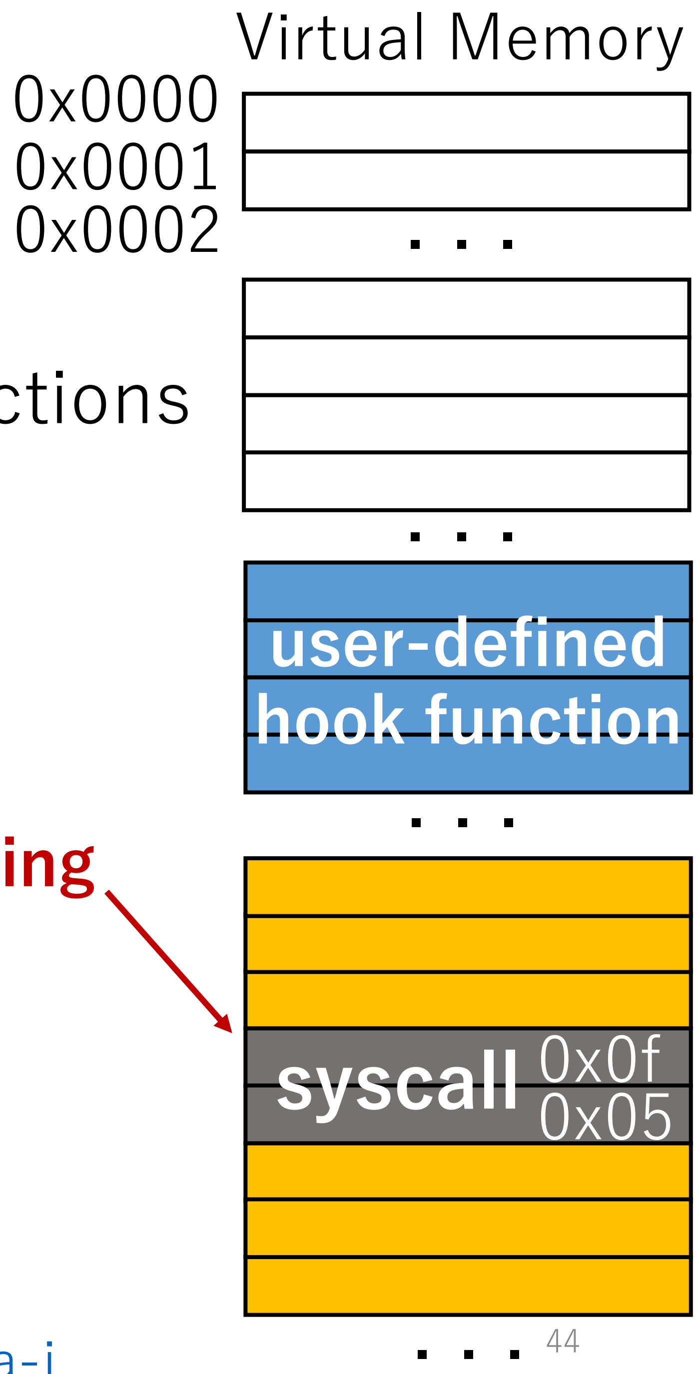

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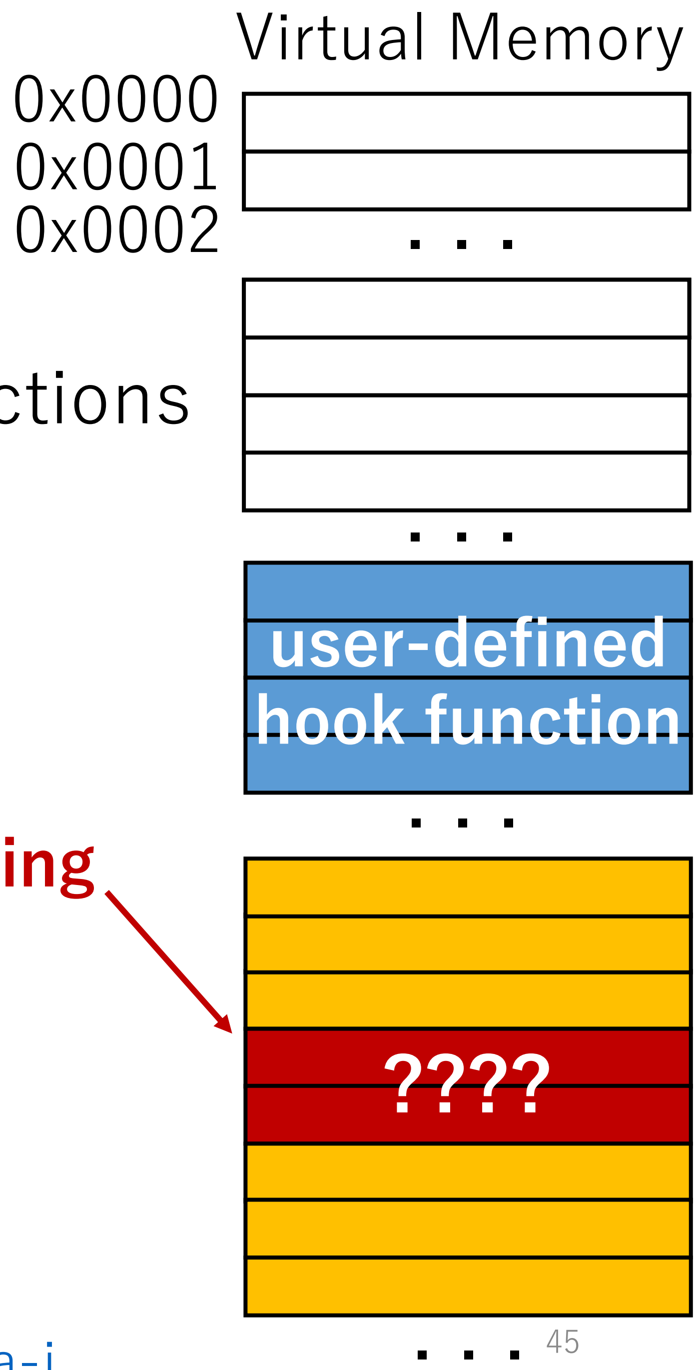

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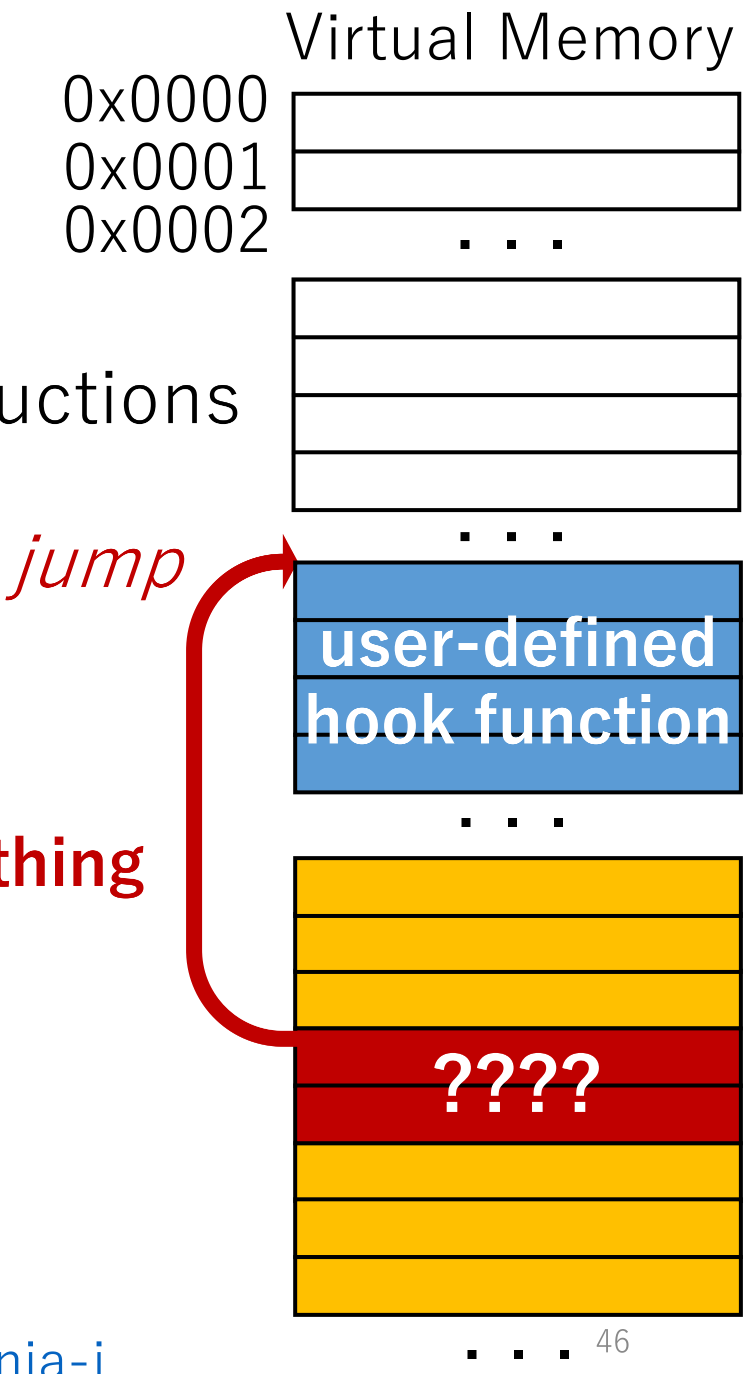
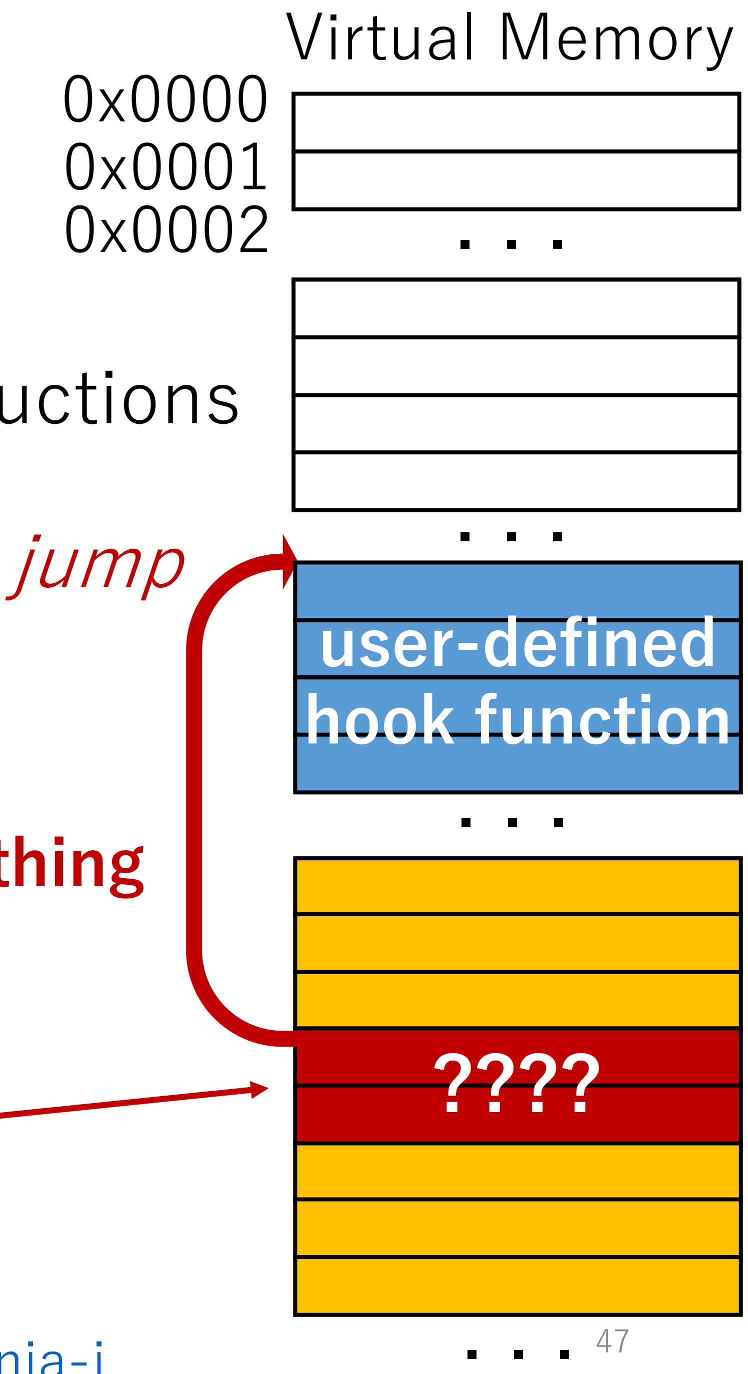
  - to jump to a user-defined hook function



https://github.com/yasukata/presentation/tree/gh-pages/2023/06/snia-j

Binary Rewriting Approach

- On x86-64 CPUs, syscall and sysenter instructions trigger a system call
  - syscall: 0x0f 0x05, sysenter: 0x0f 0x34
- What we wish to achieve
  - replace syscall/sysenter instruction with **something**
  - to jump to a user-defined hook function
- **<u>Question: what should we put here?</u>**



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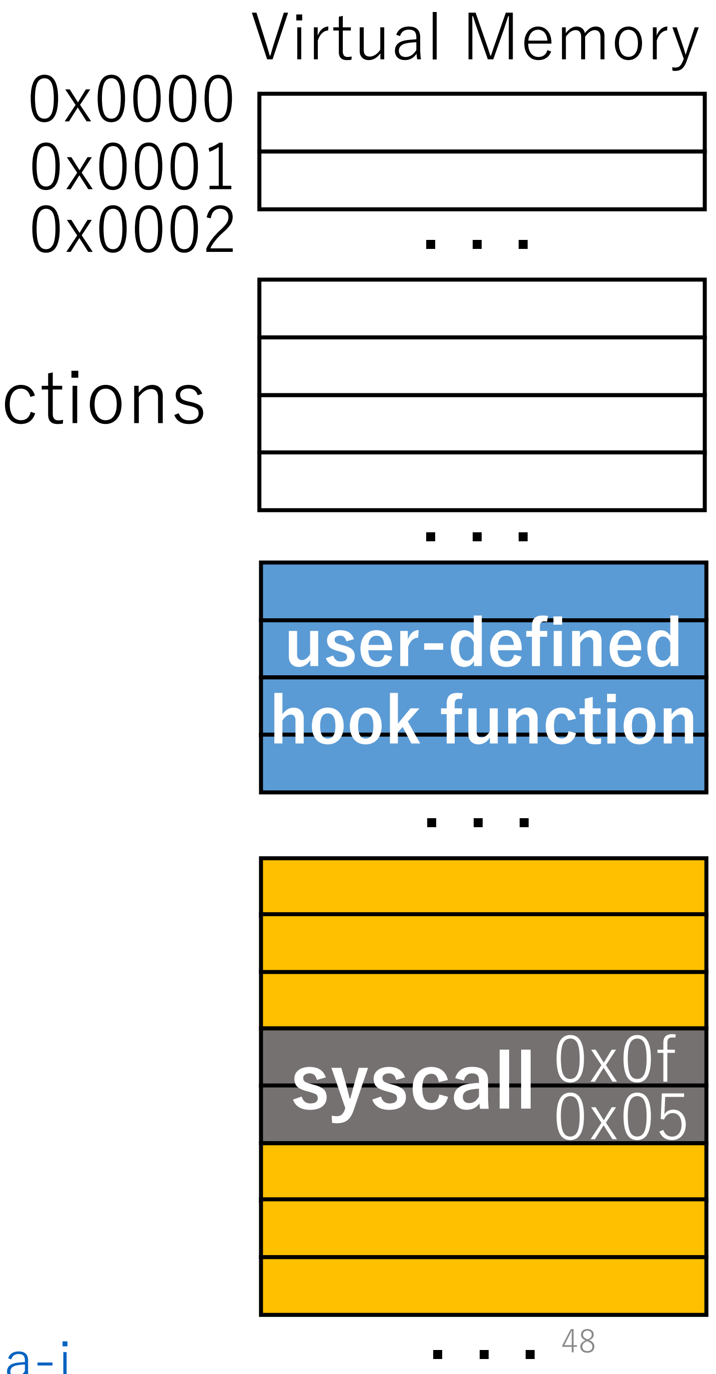

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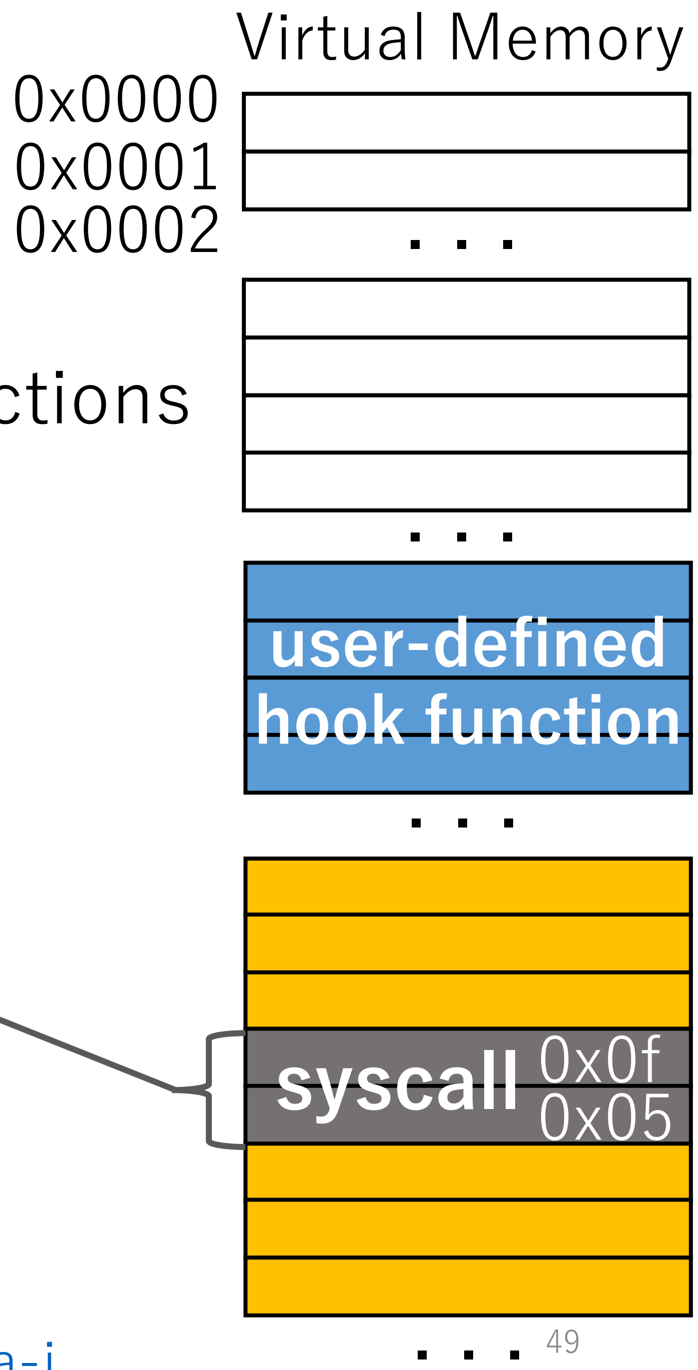

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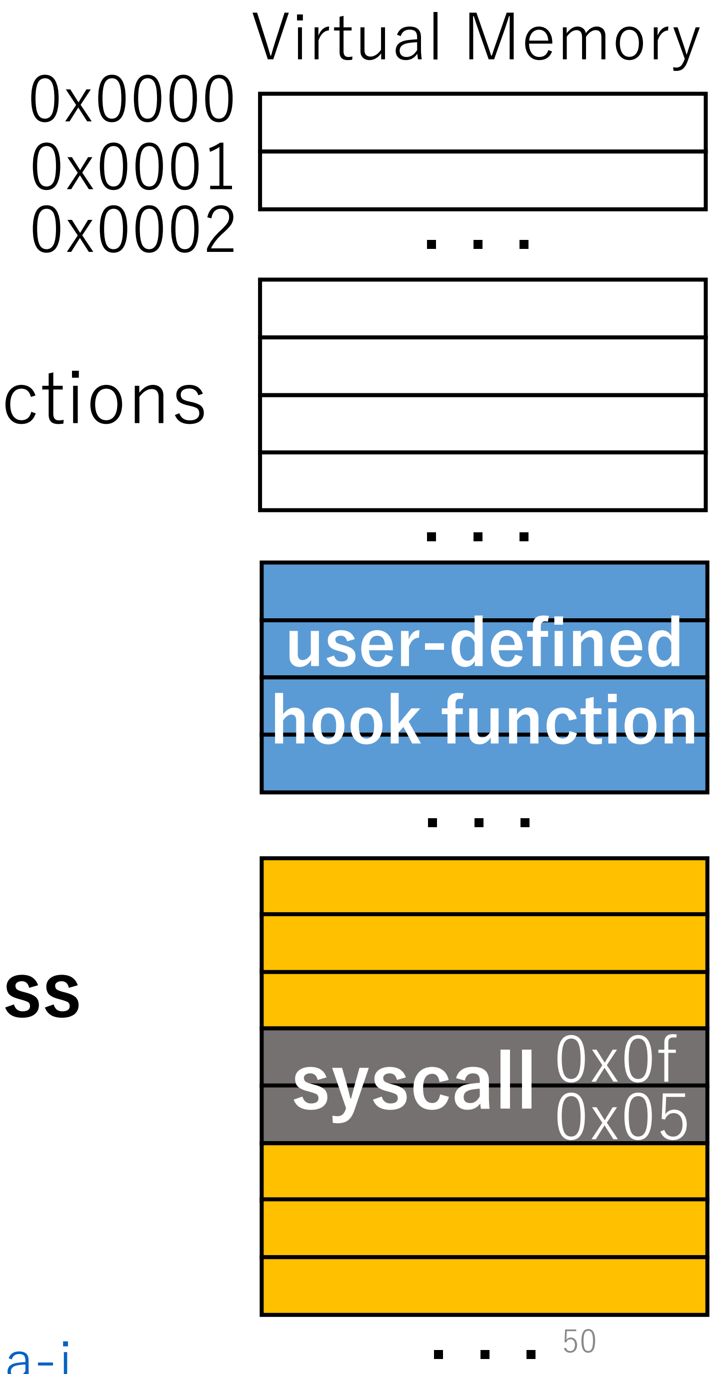

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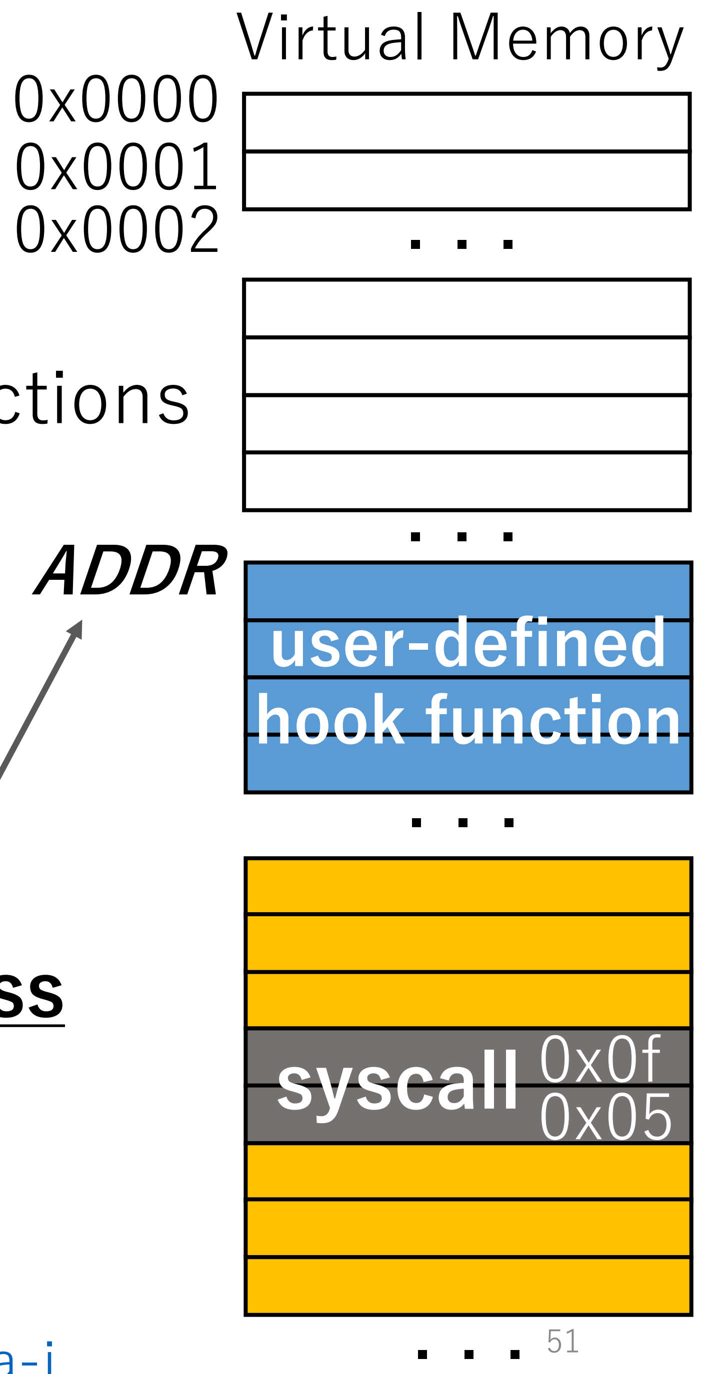

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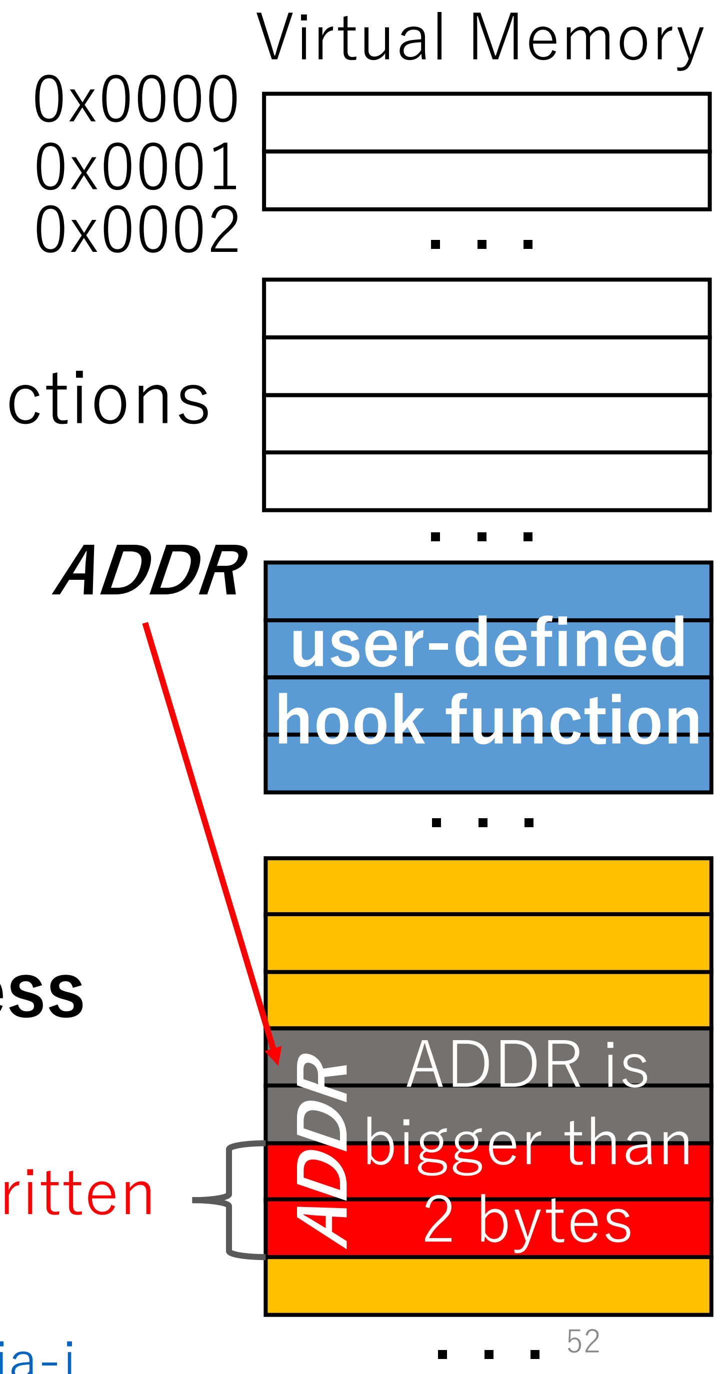

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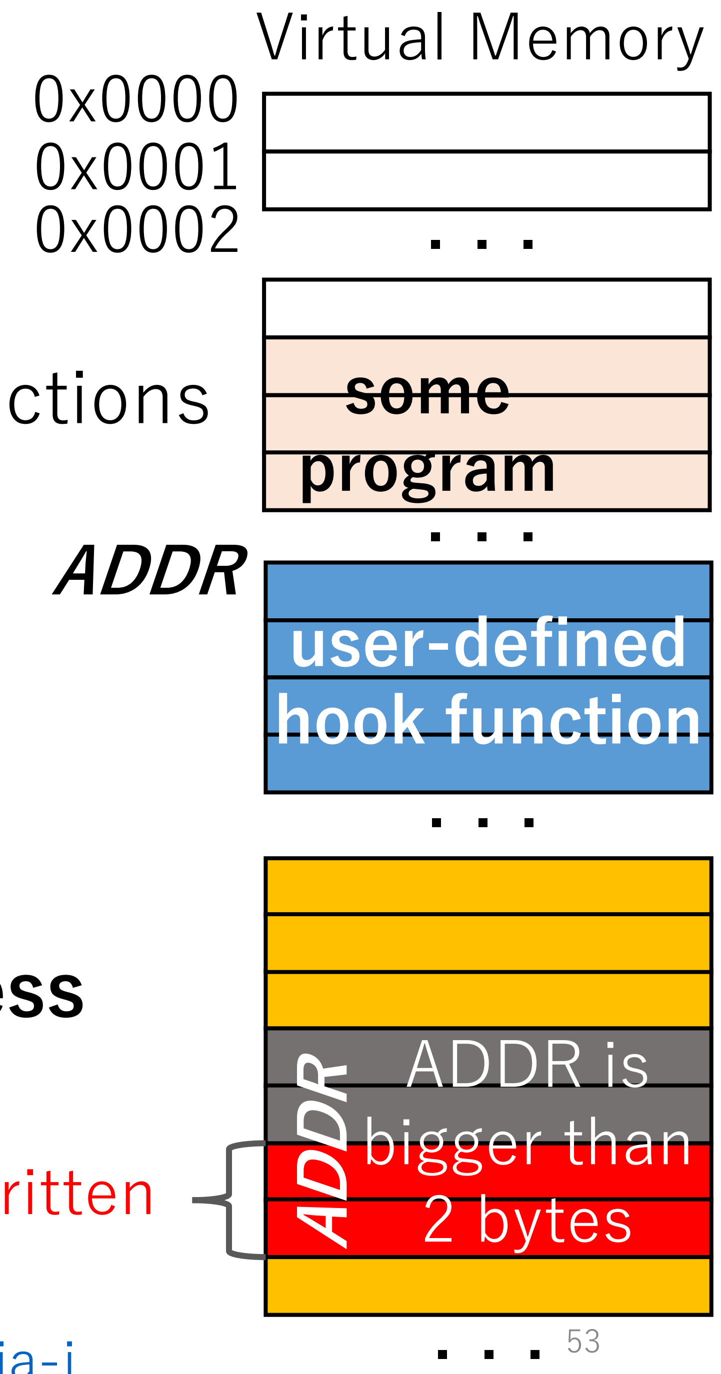

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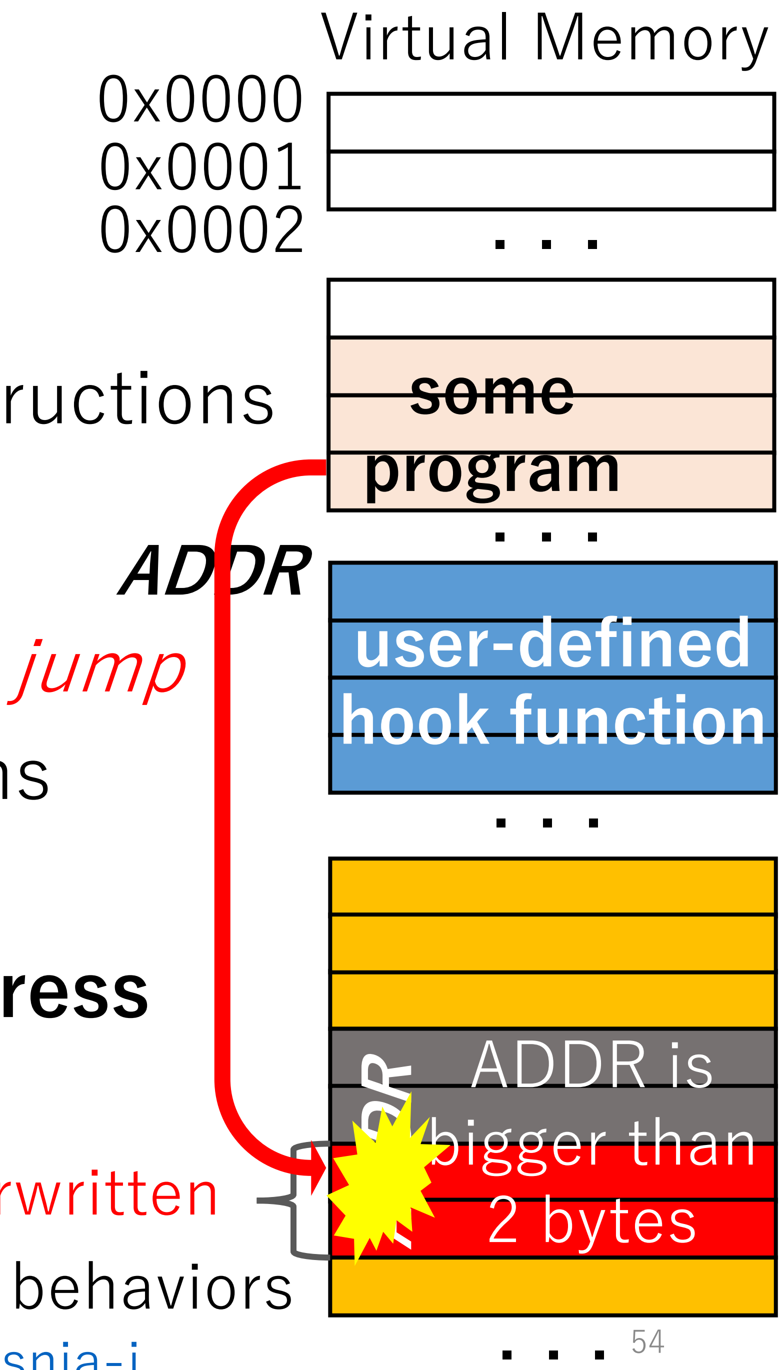
jump to the overwritten part leads to unexpected behaviors



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

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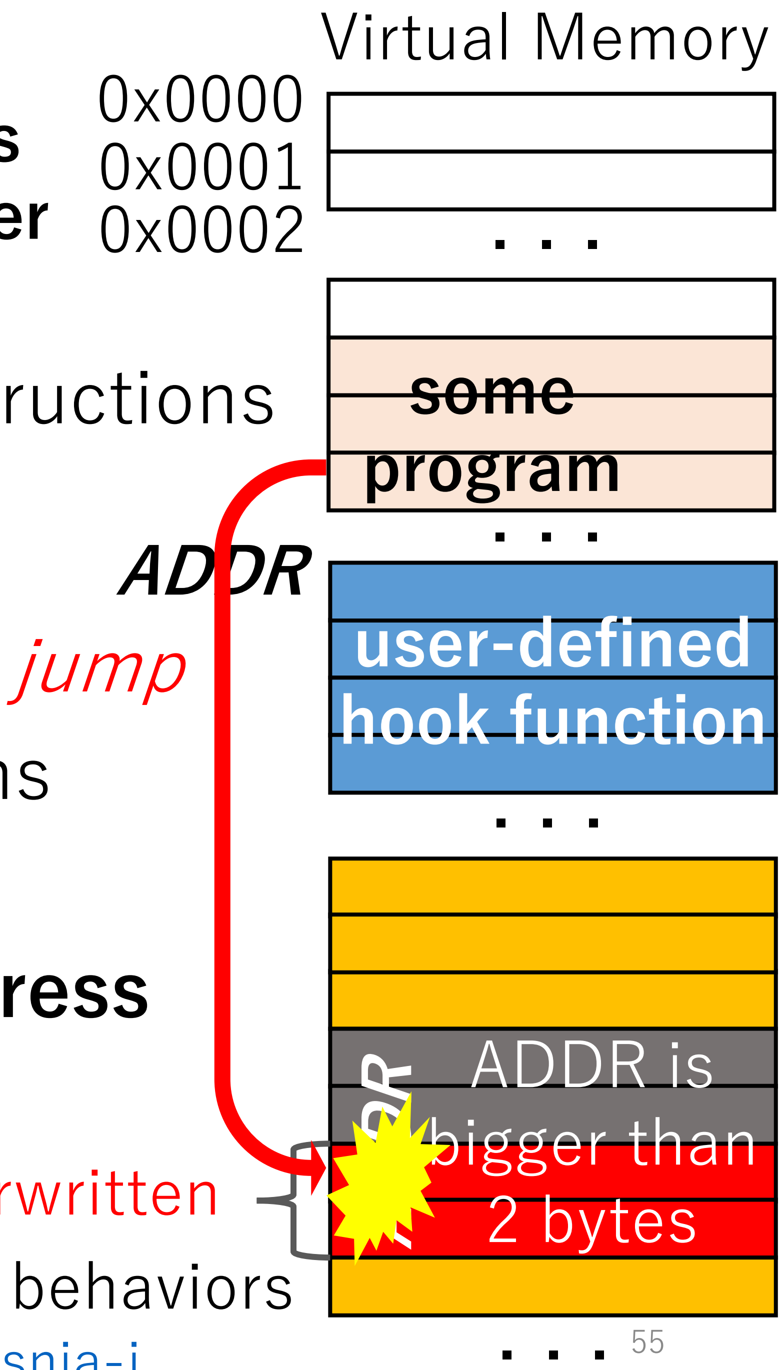

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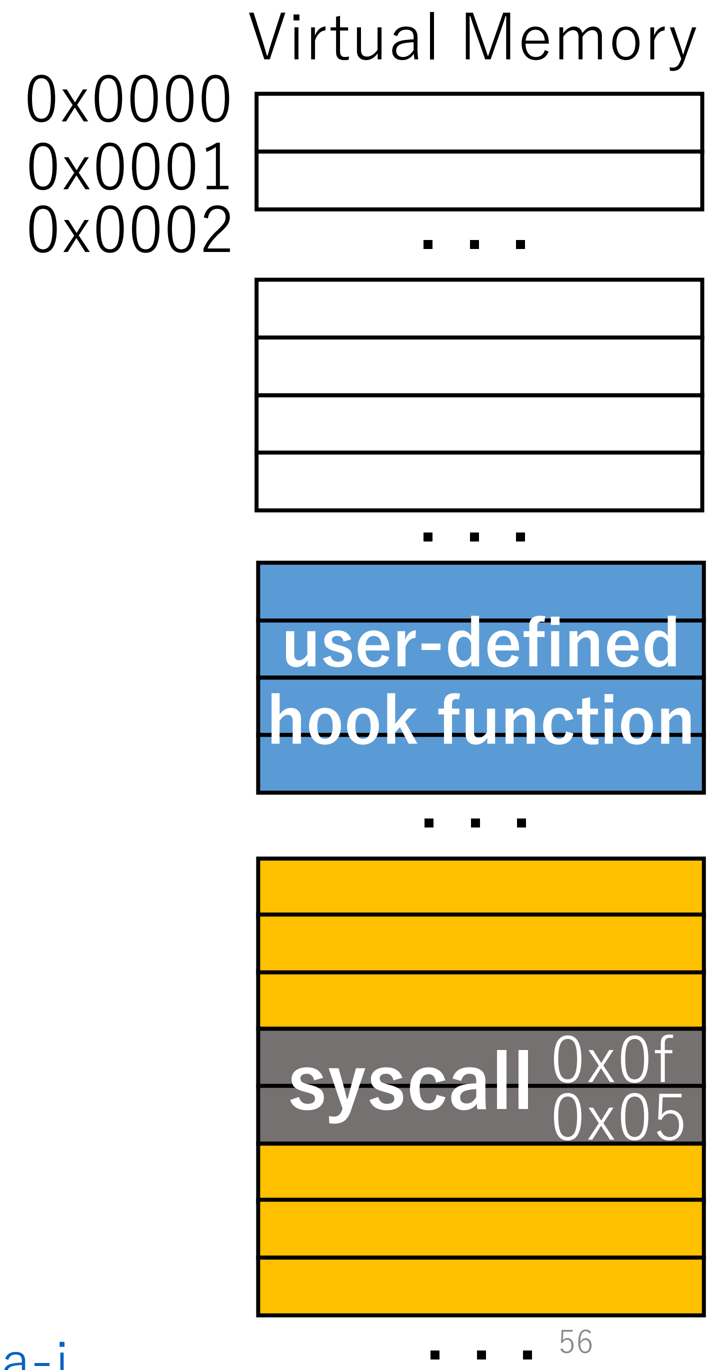
Calling Convention

- How to invoke a system call



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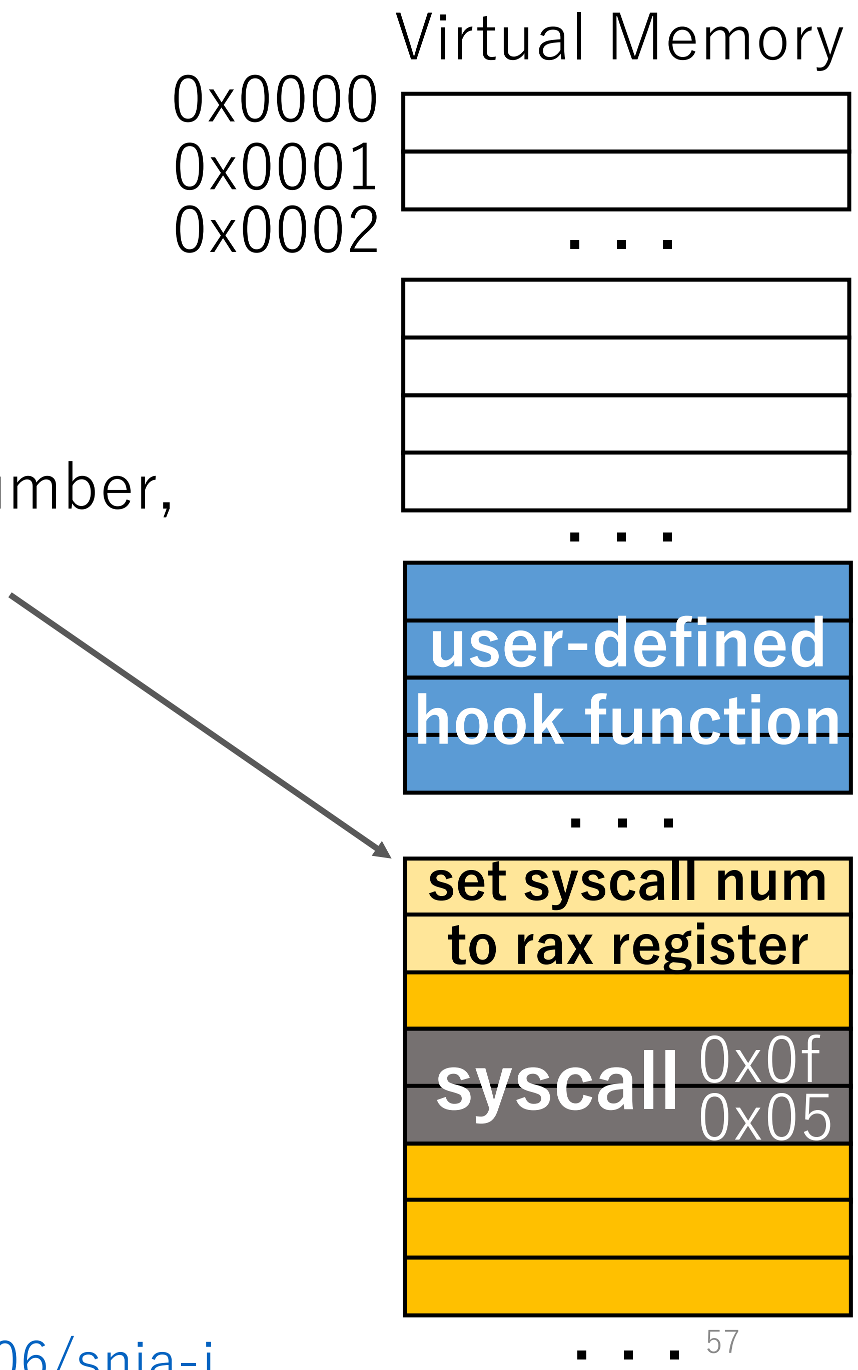

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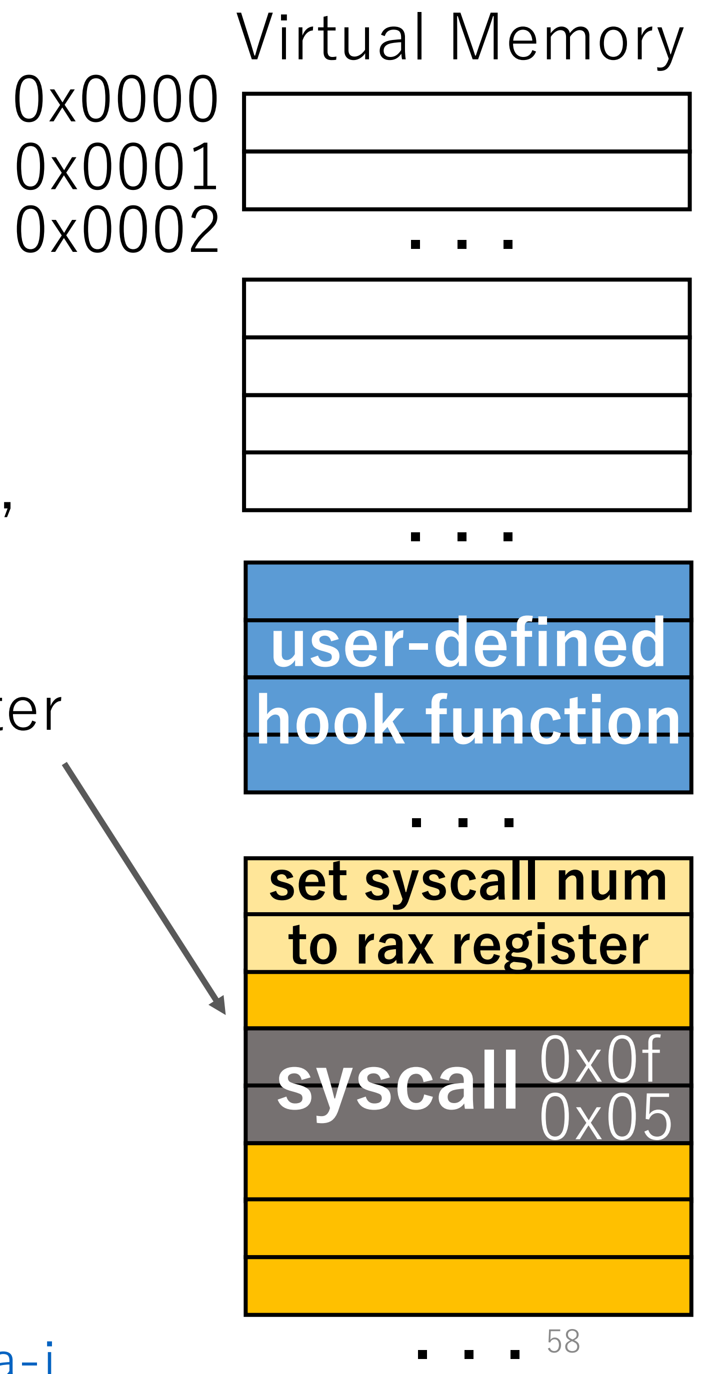

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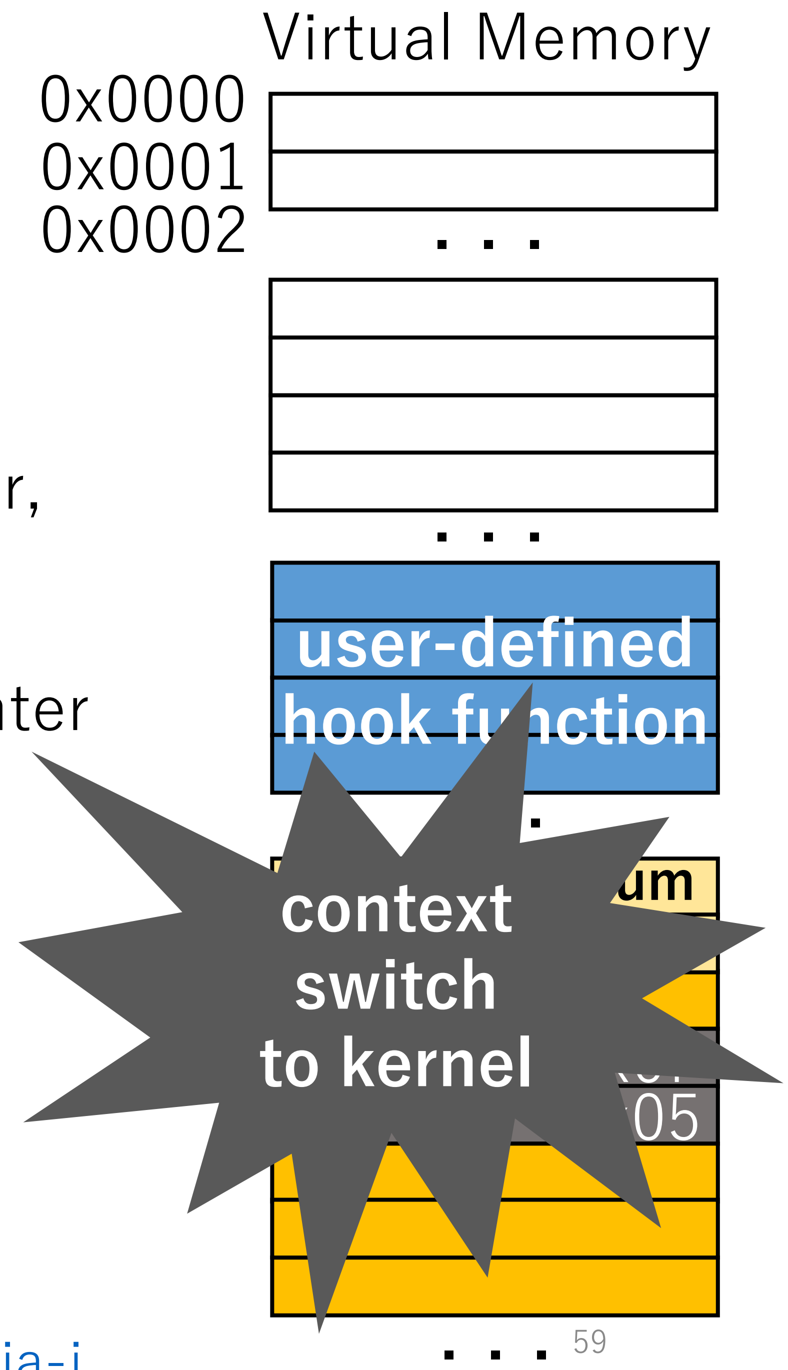

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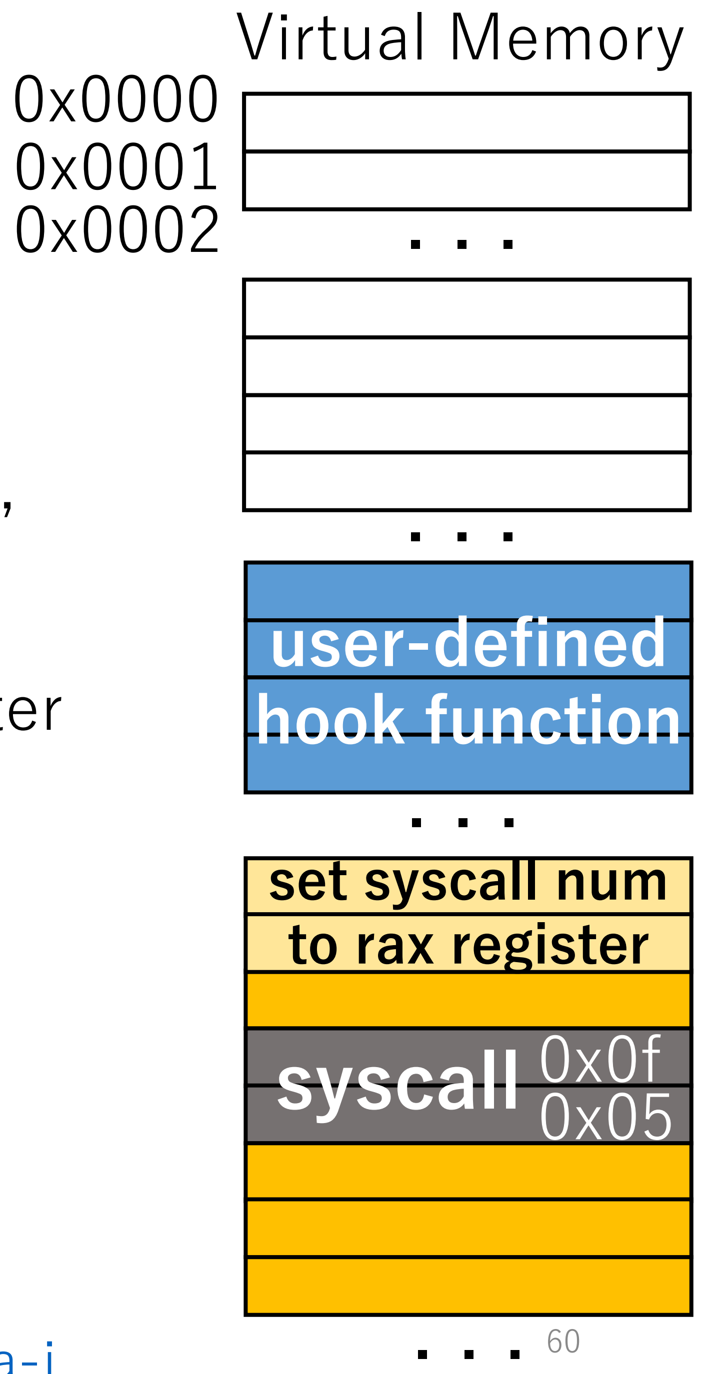
  - Kernel executes a system call specified through the system call number set to the **rax register**



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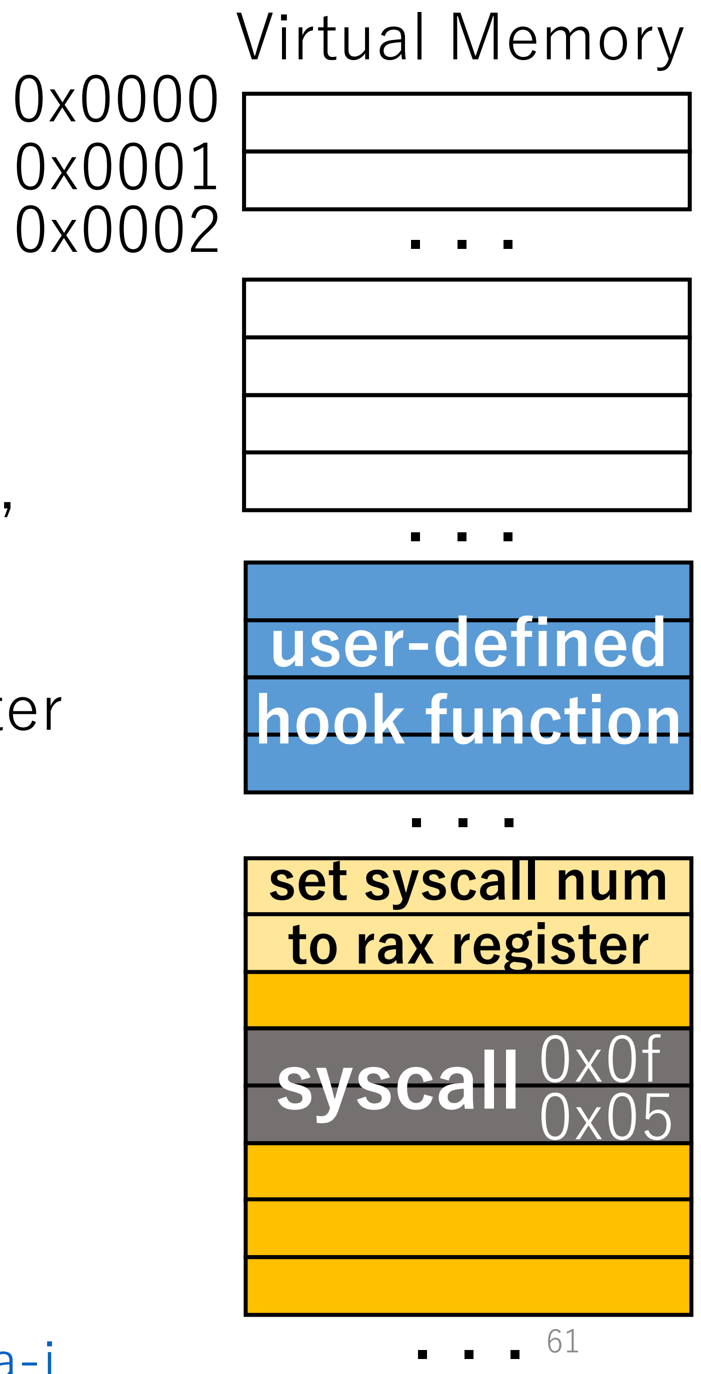
  - Kernel executes a system call specified through the system call number set to the **rax register**
    - if the rax register has 0, kernel executes read()
    - if the rax register has 1, kernel executes write()
    - if the rax register has 2, kernel executes open()



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<u>Point: Calling Convention</u>

When syscall/sysenter is executed,
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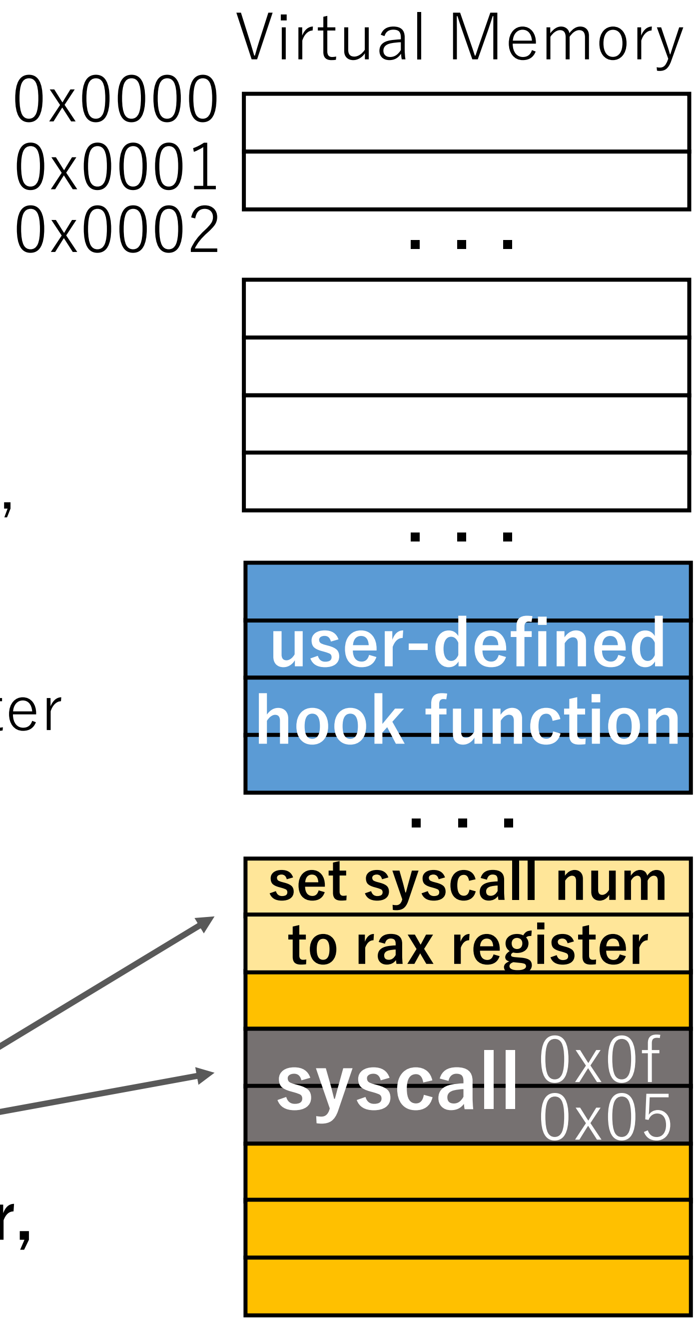

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When syscall/sysenter is executed,
the rax register always has a system call number,
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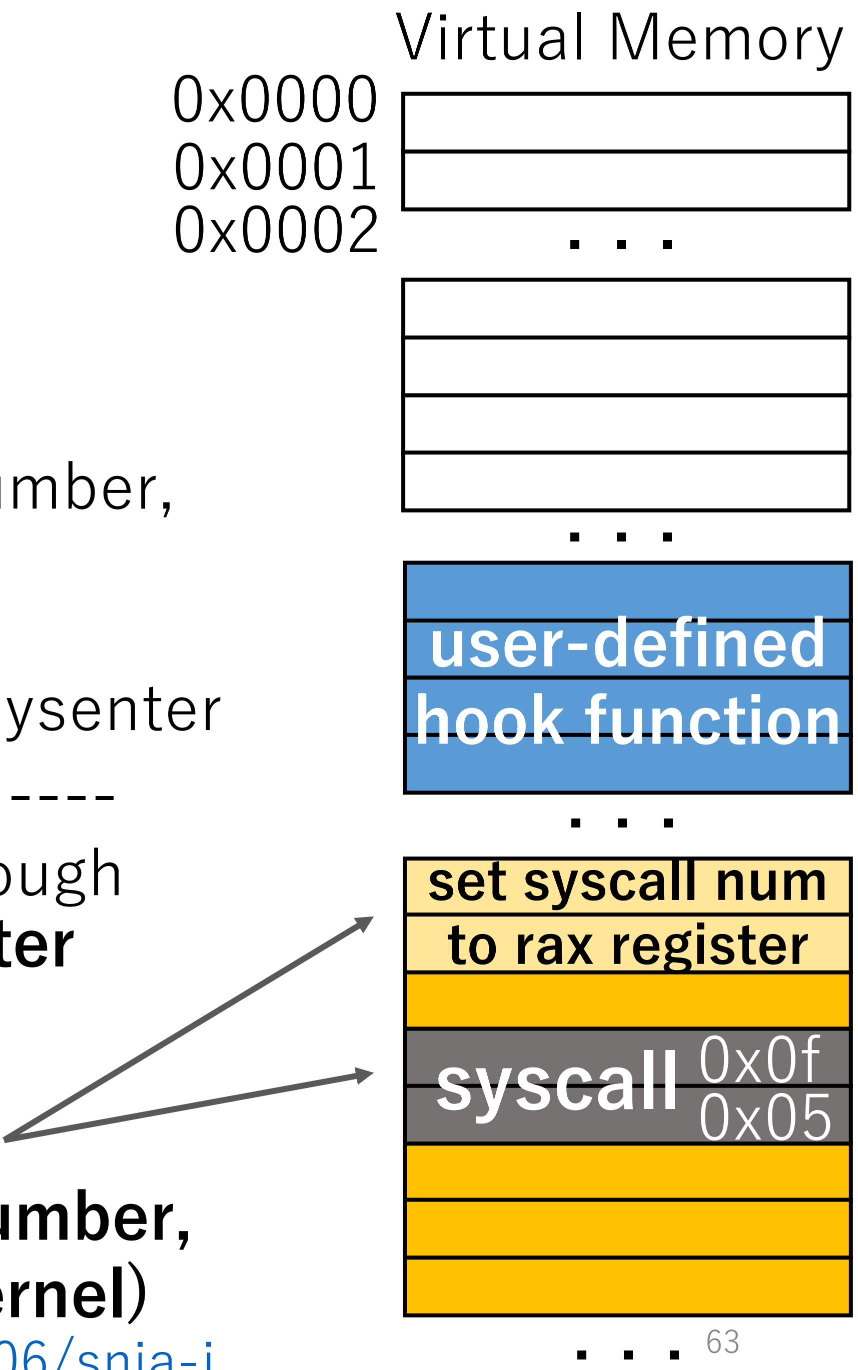

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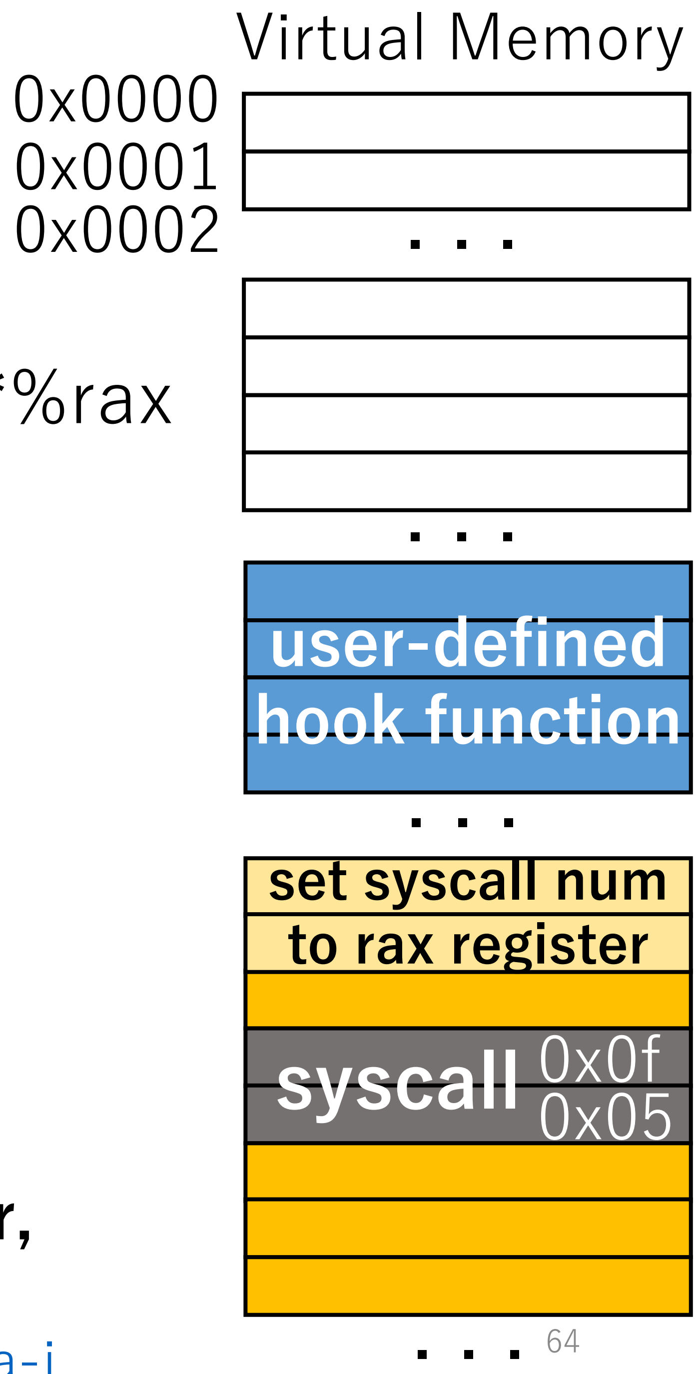

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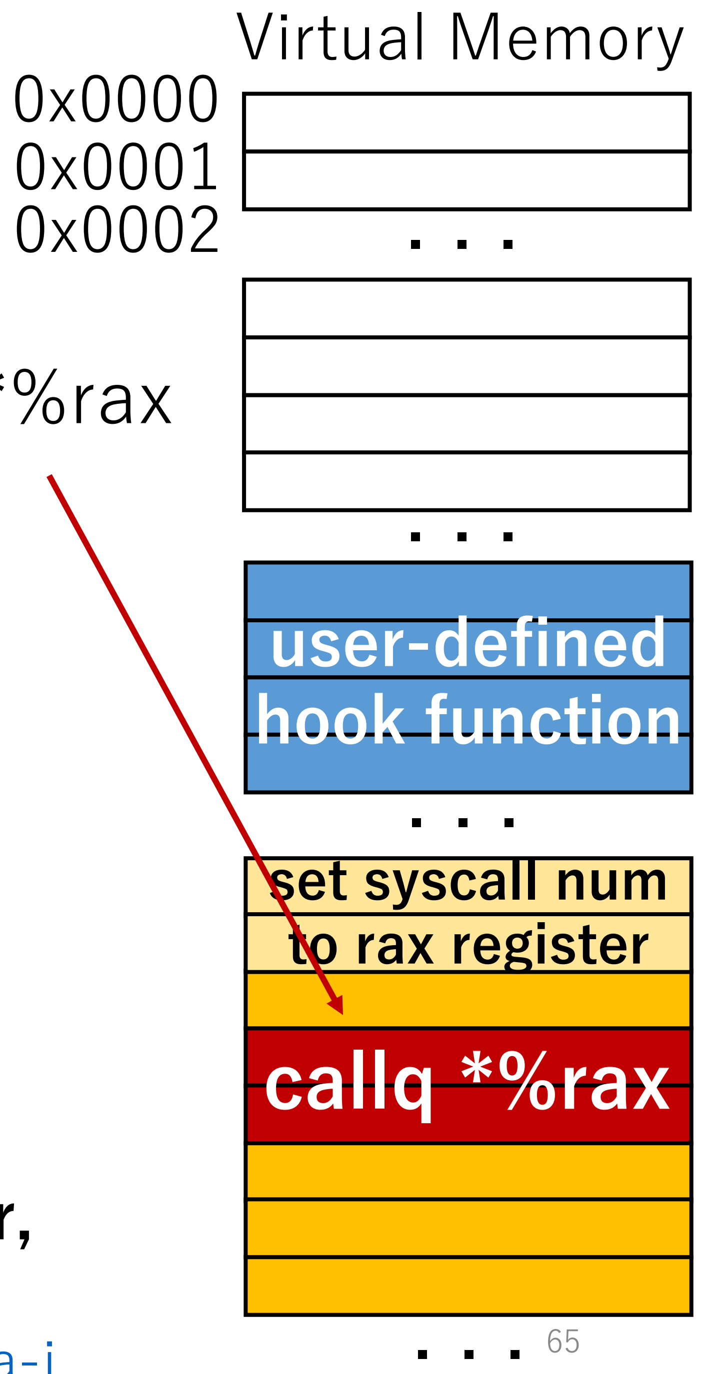

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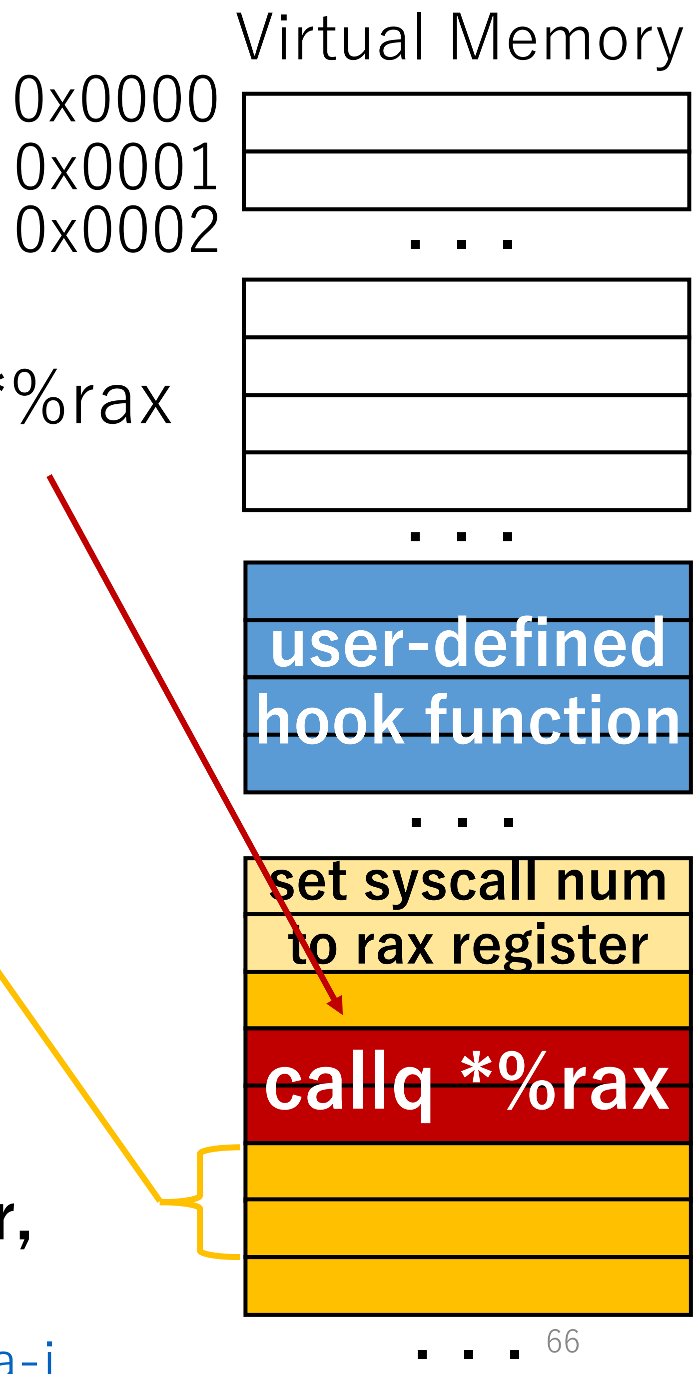

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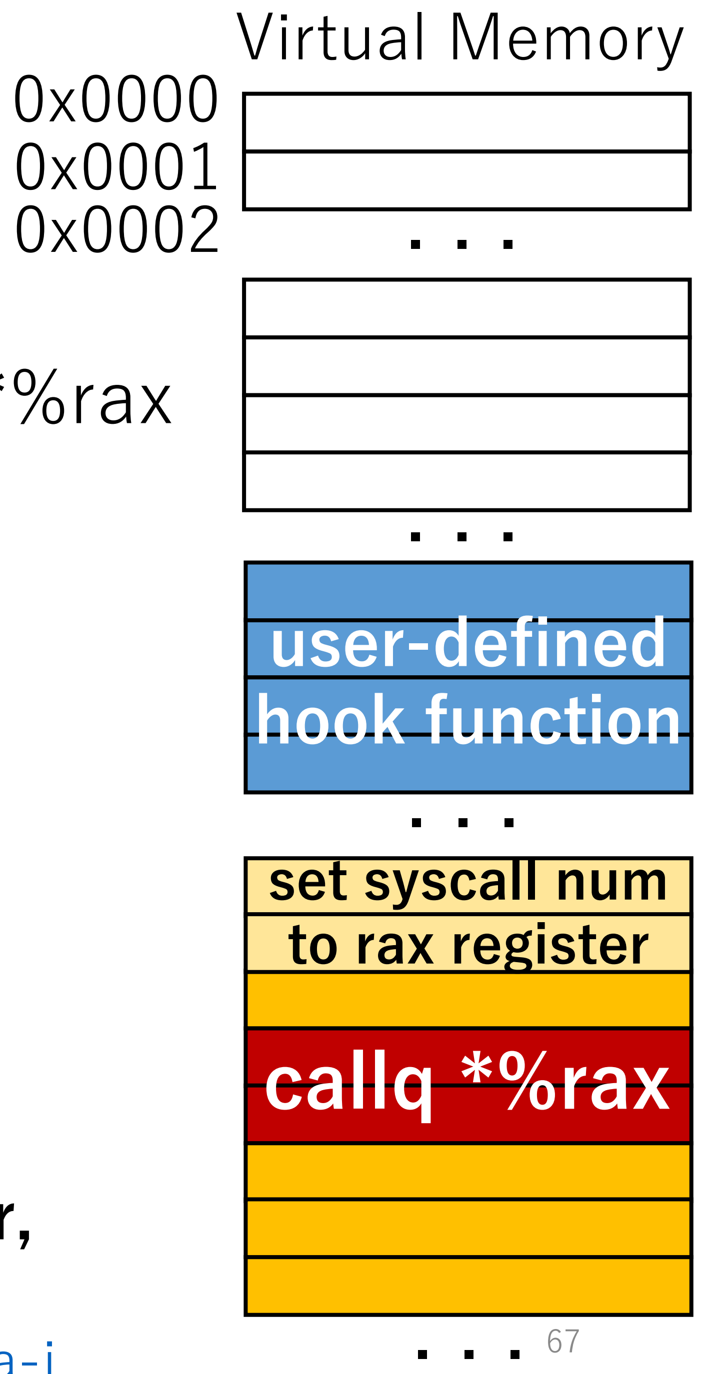

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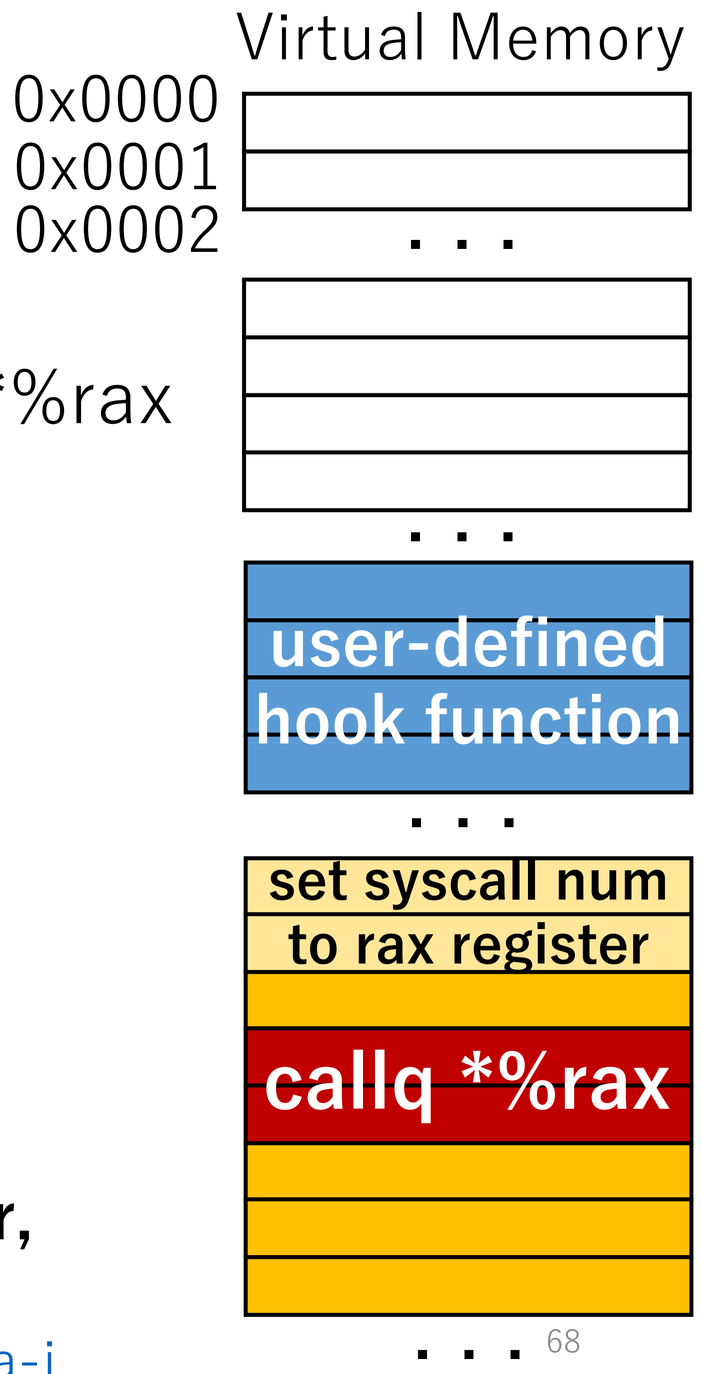

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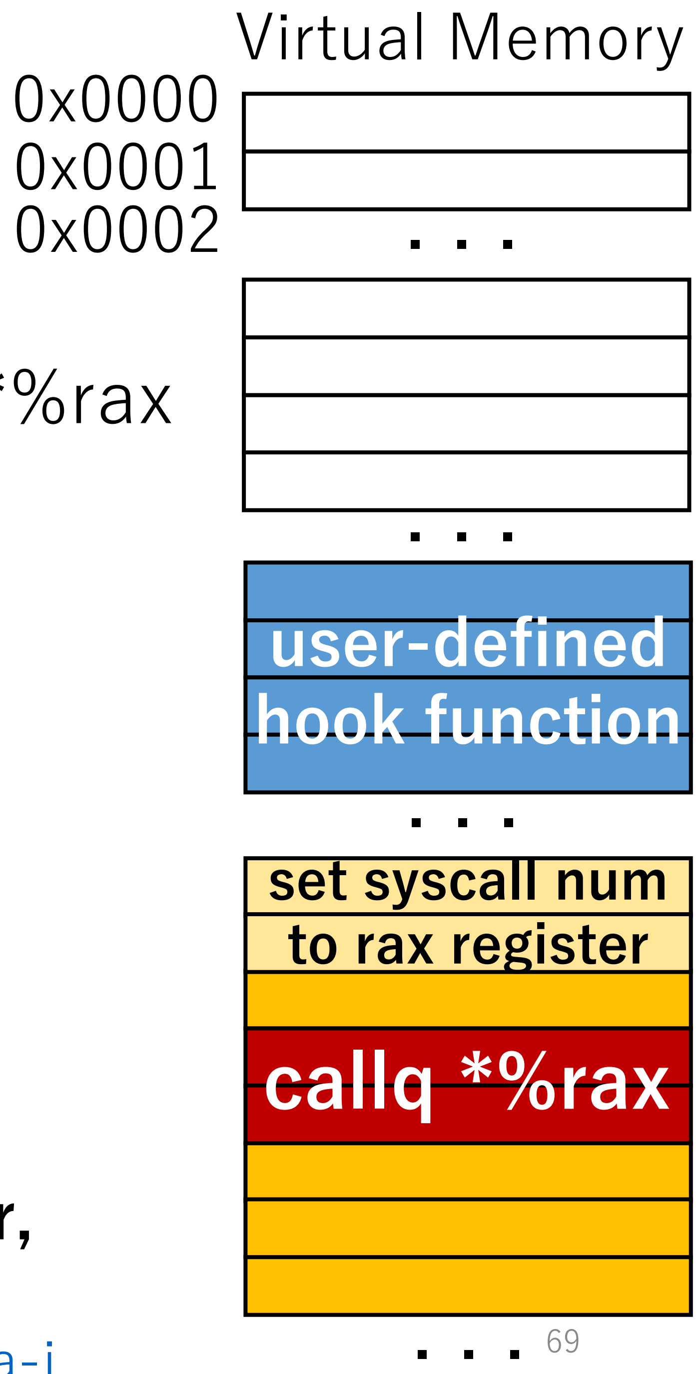

After the binary rewriting

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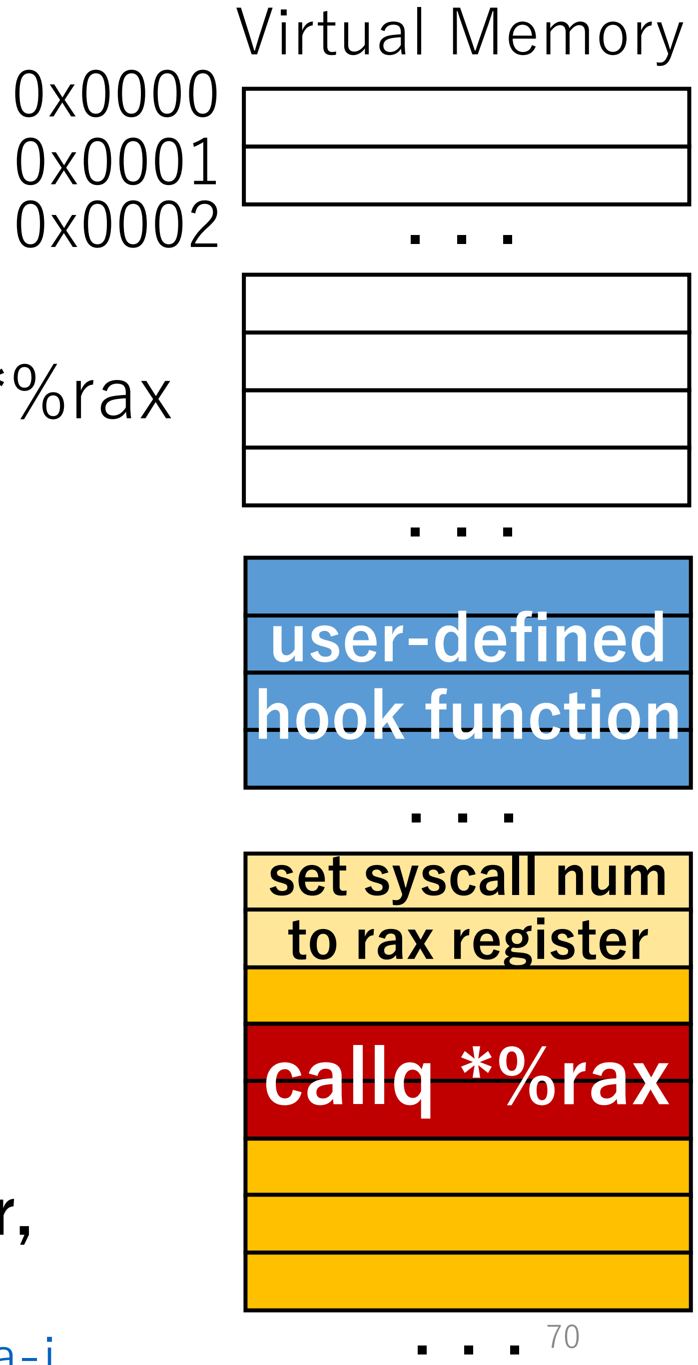

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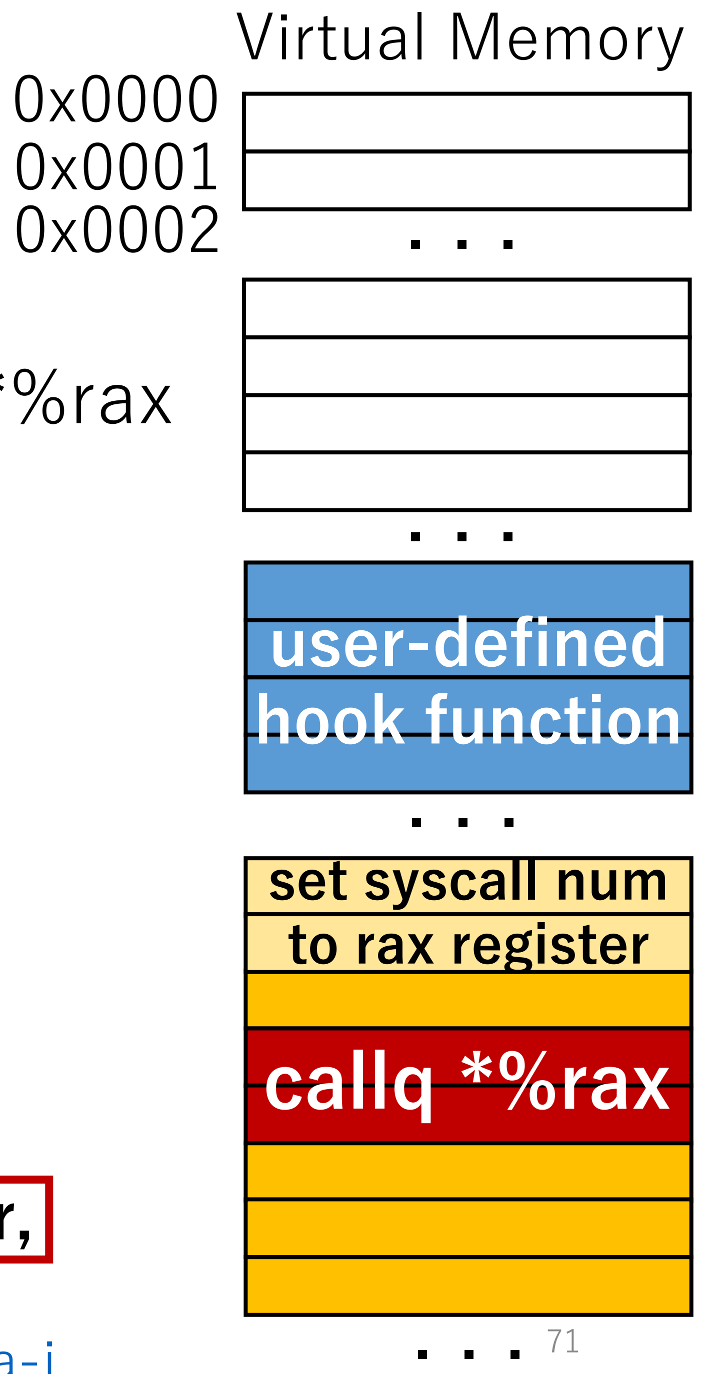

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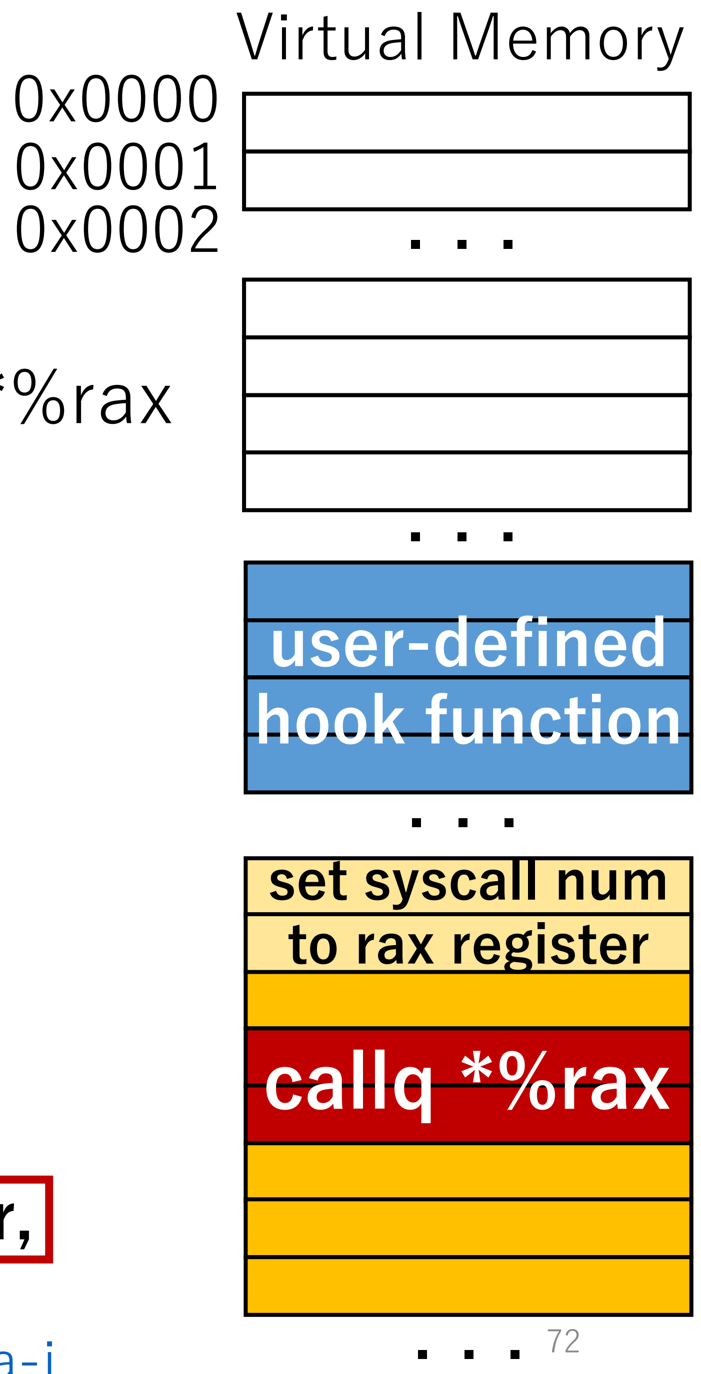

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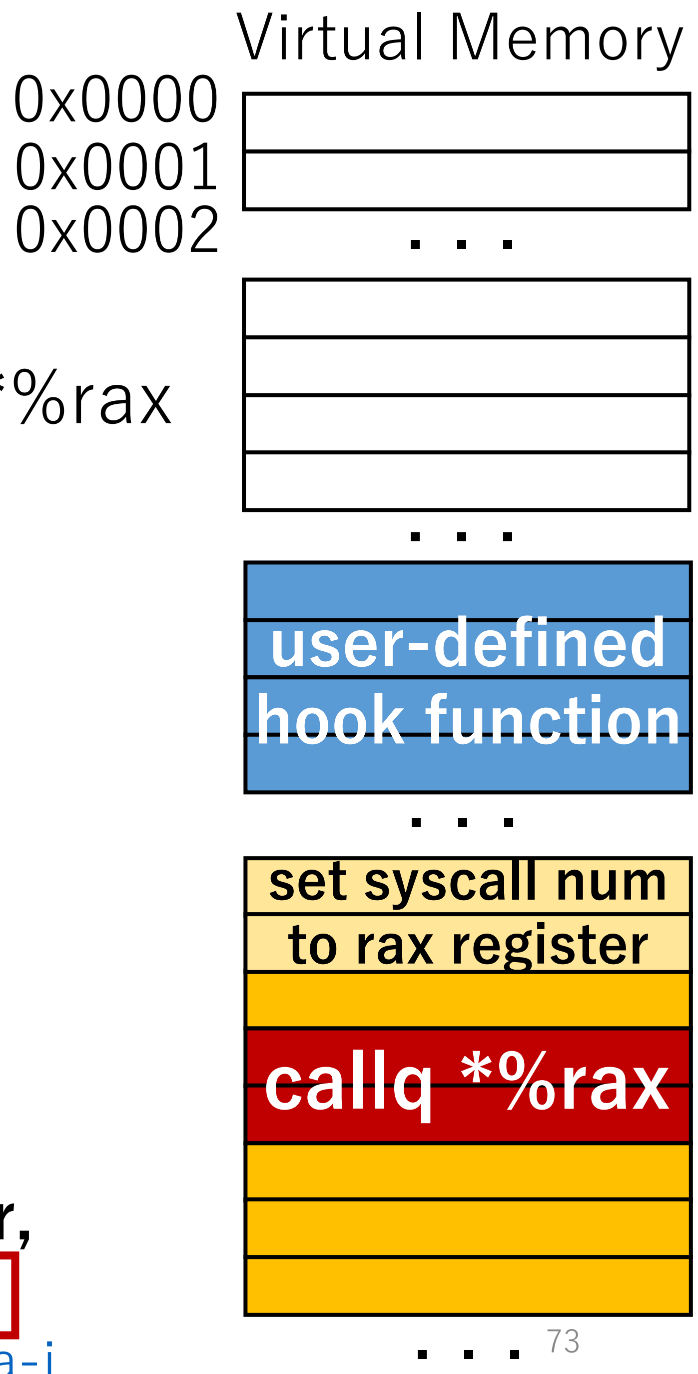

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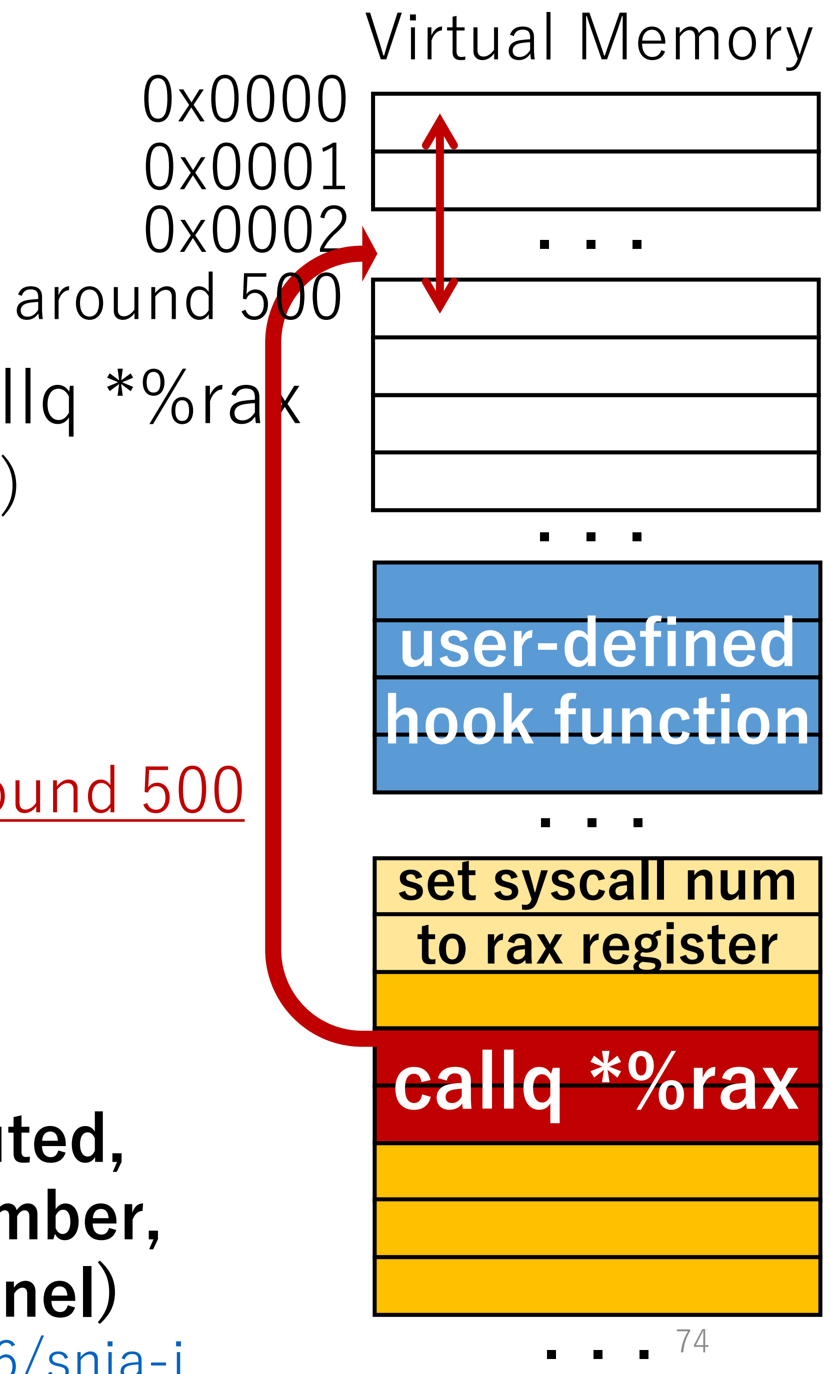

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zpoline

address range, potentially replaced "callq *%rax" jumps to
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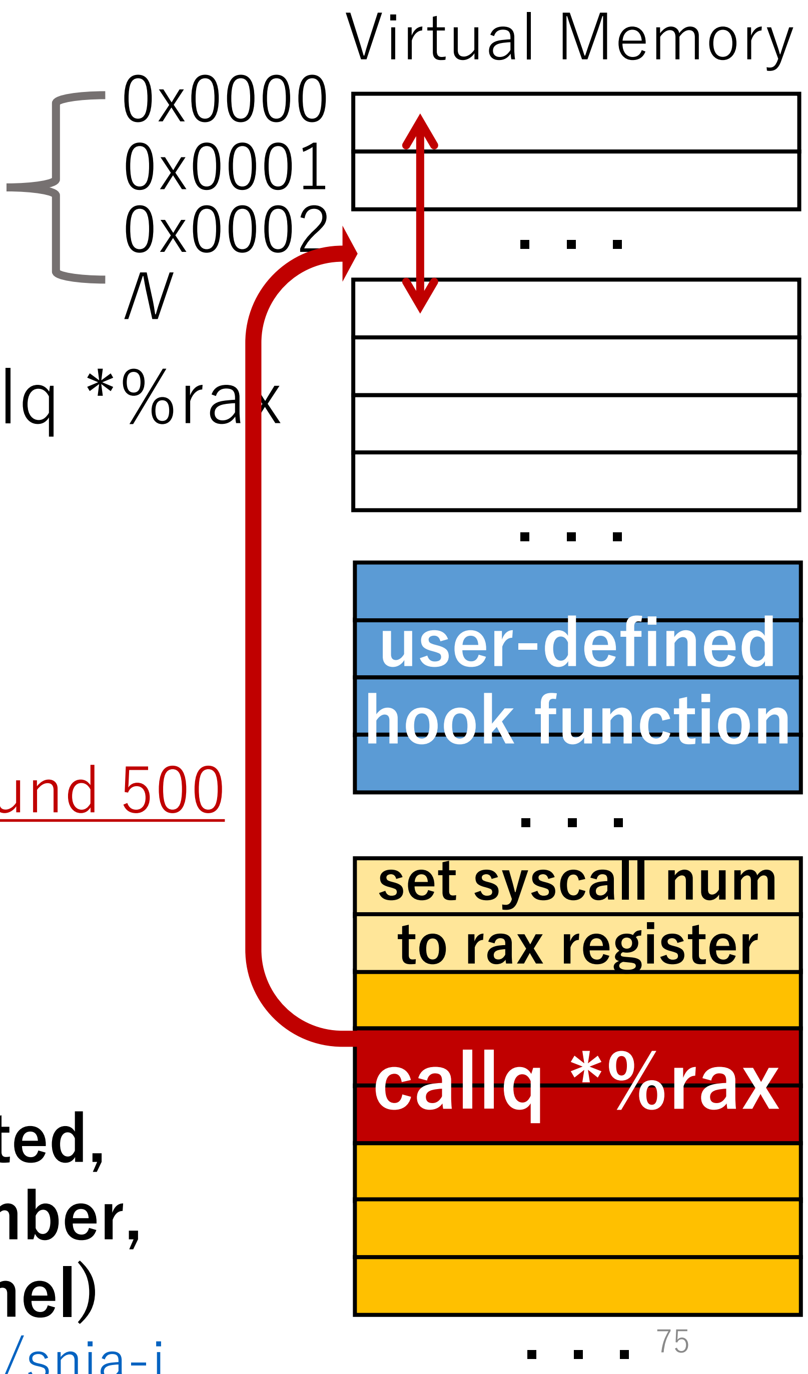

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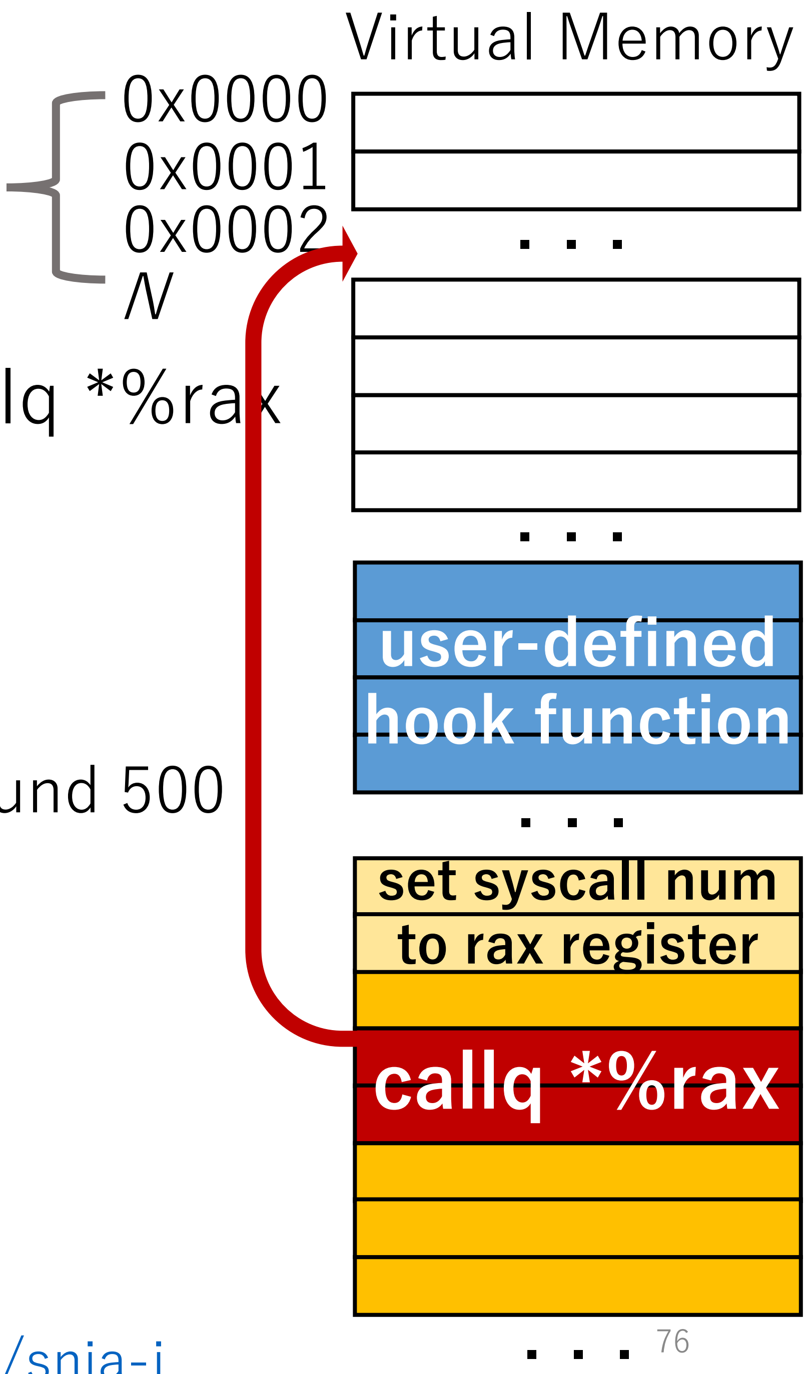

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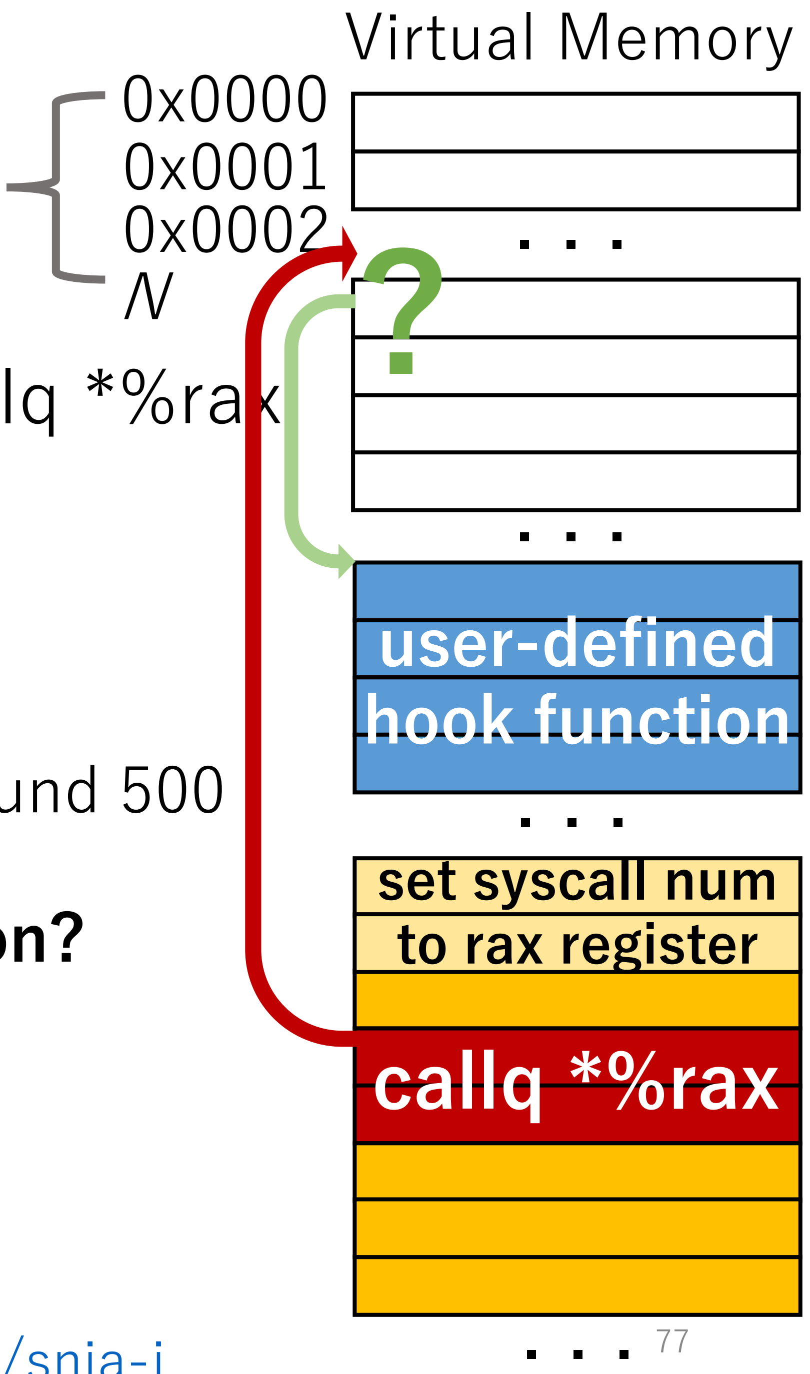

How to redirect to the user-defined hook function?

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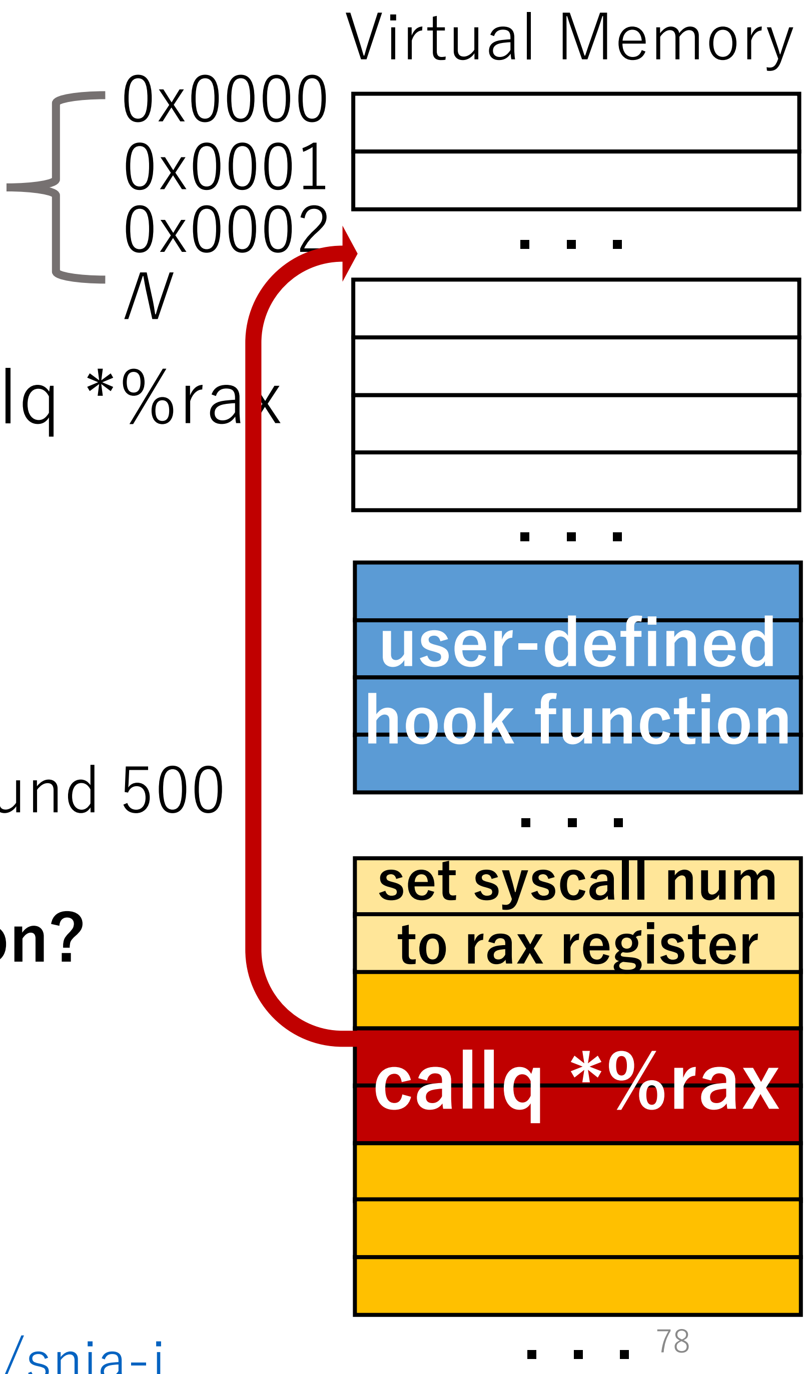

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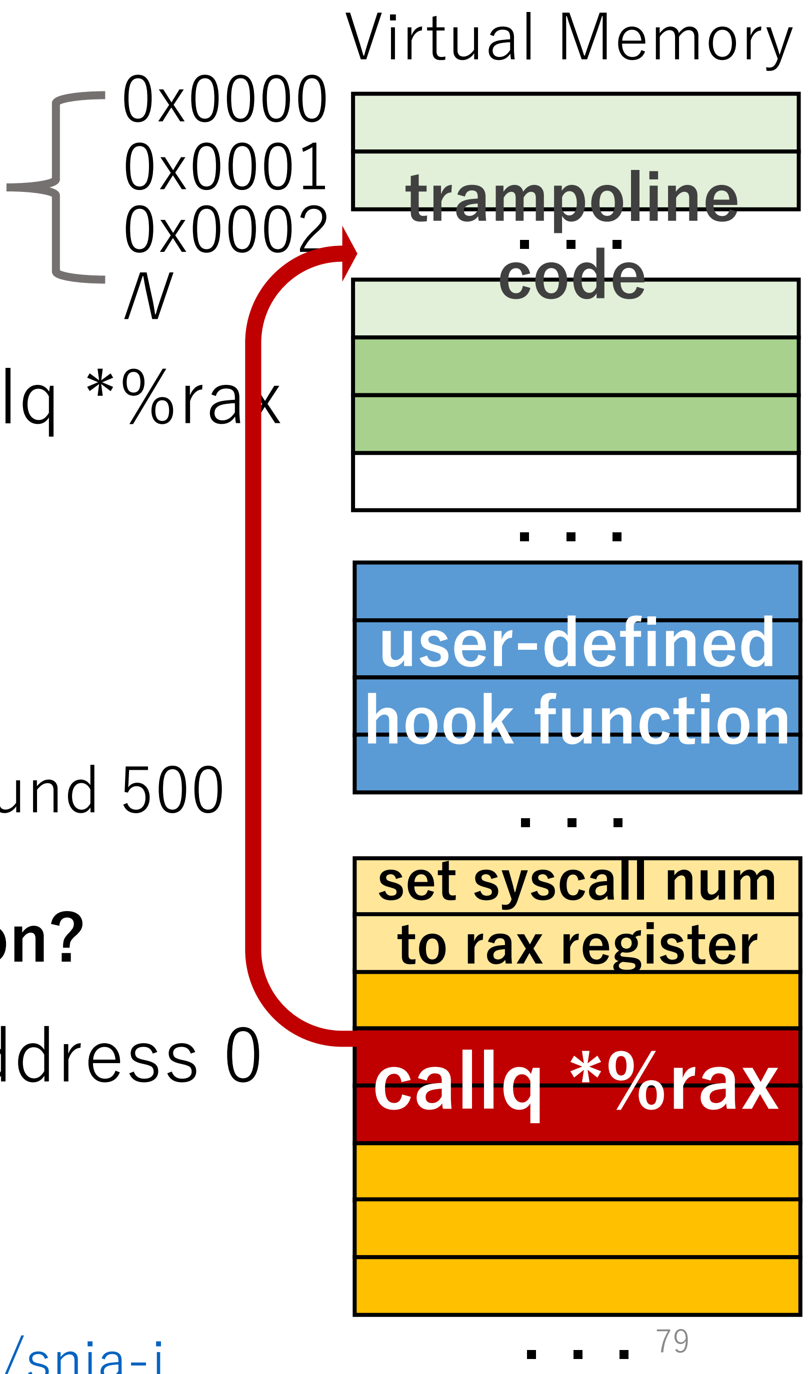
How to redirect to the user-defined hook function?

- zpoline instantiates trampoline code at address 0



https://github.com/yasukata/presentation/tree/gh-pages/2023/06/snia-j

zpoline

address range, potentially replaced "callq *%rax" jumps to
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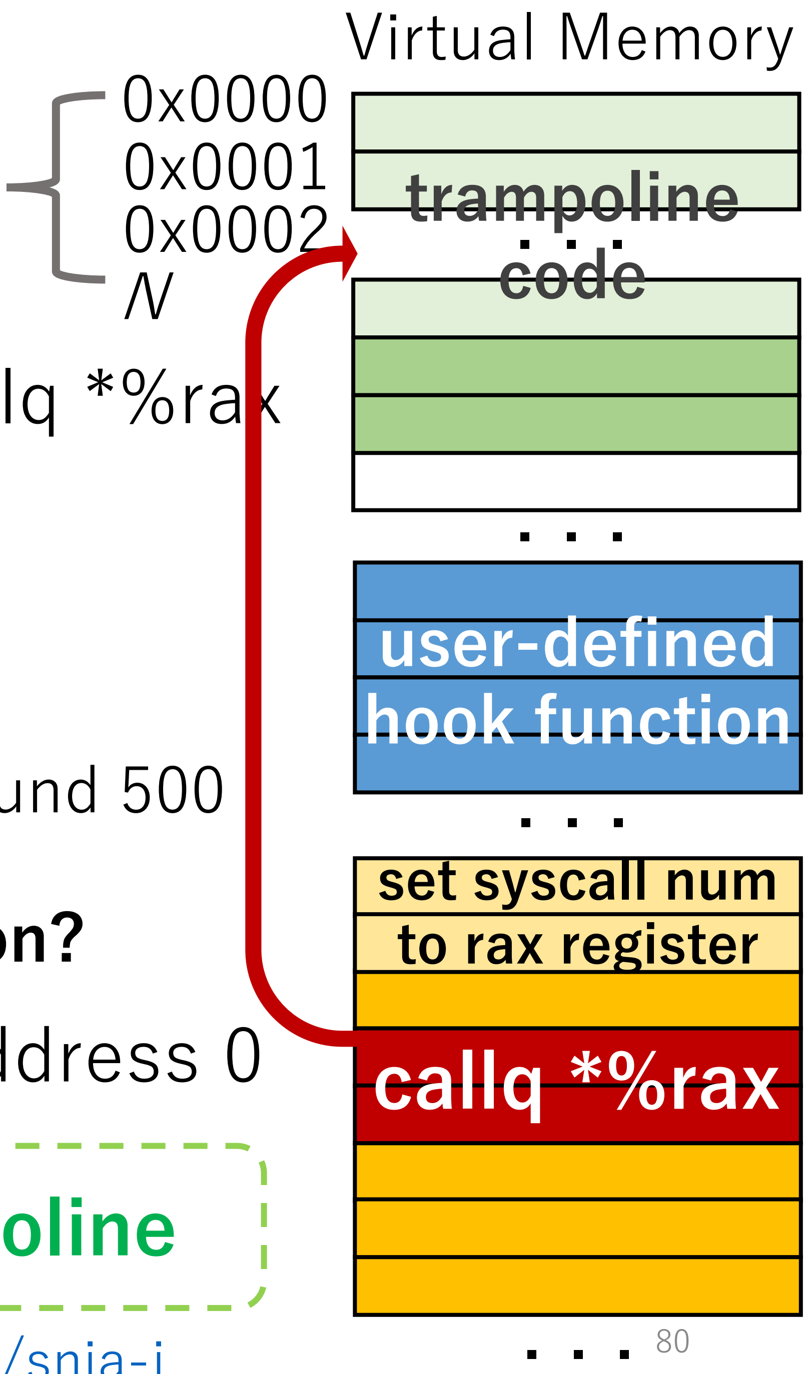

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Tram**poline** code at address 0 (**z**ero) ➔ **zpoline**

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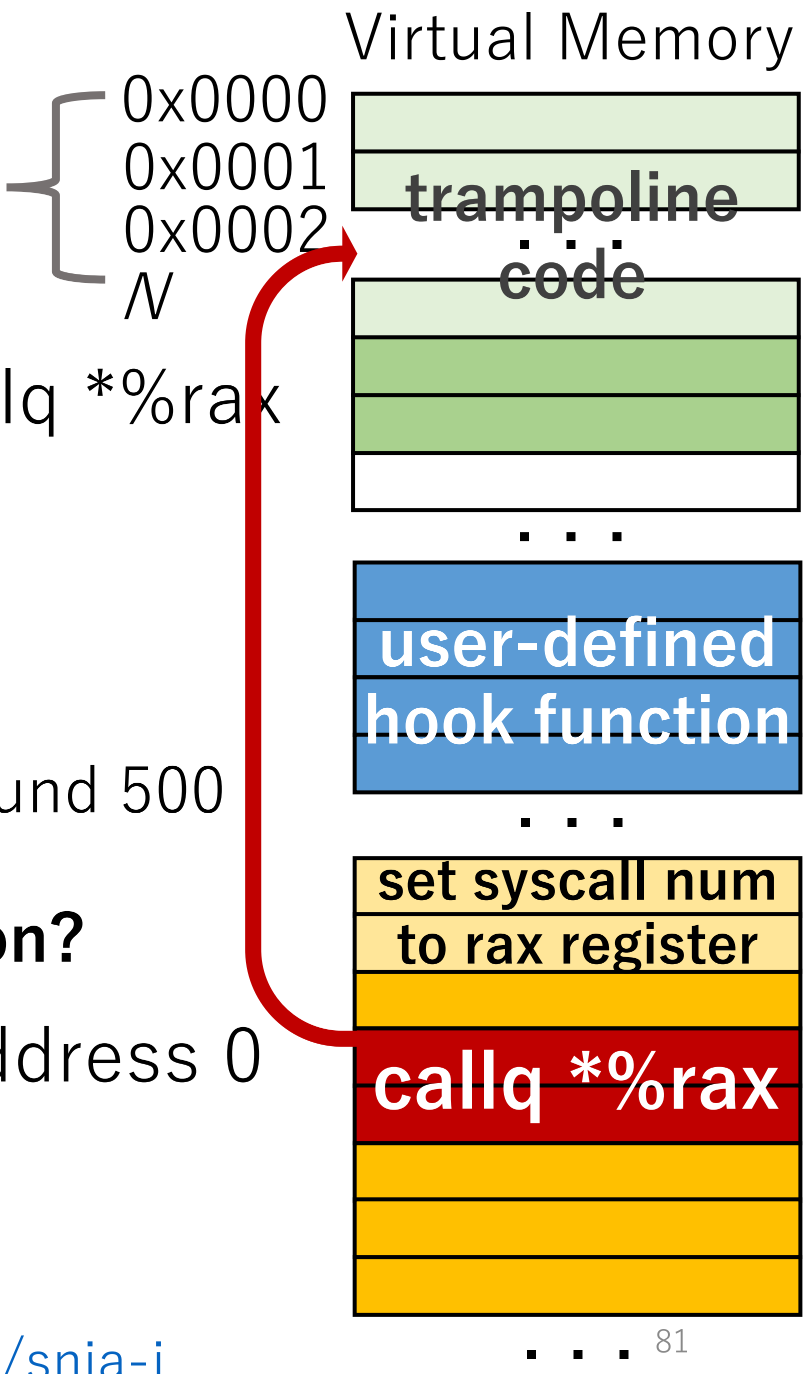

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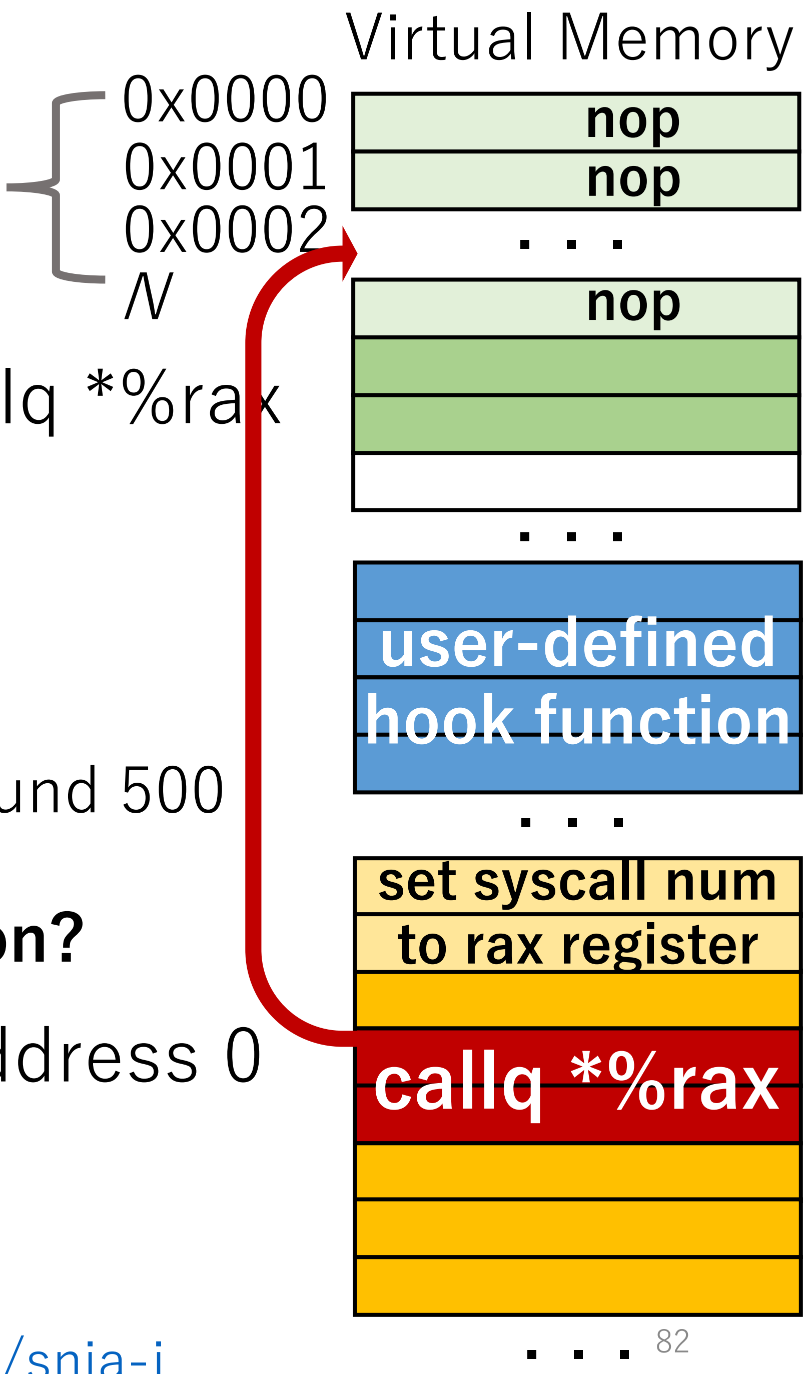

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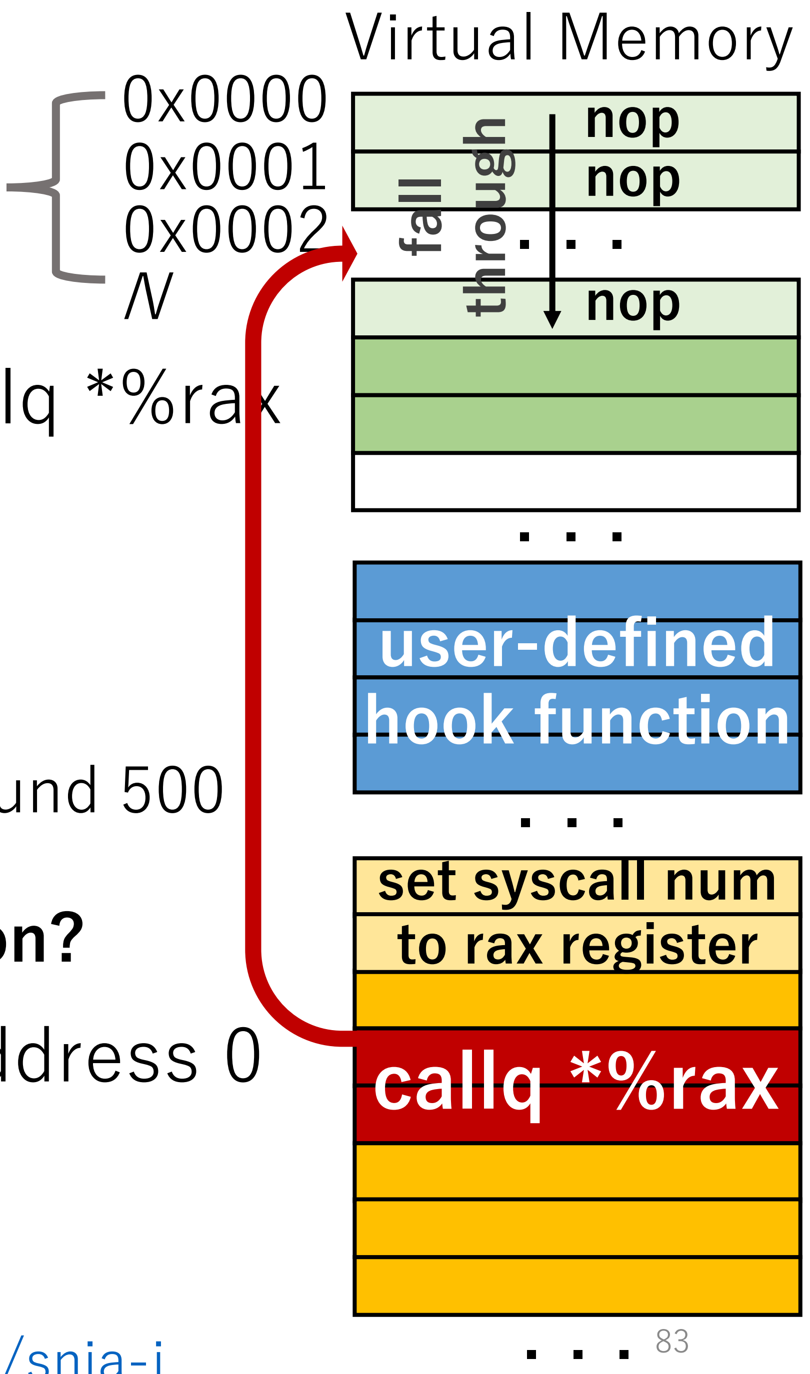

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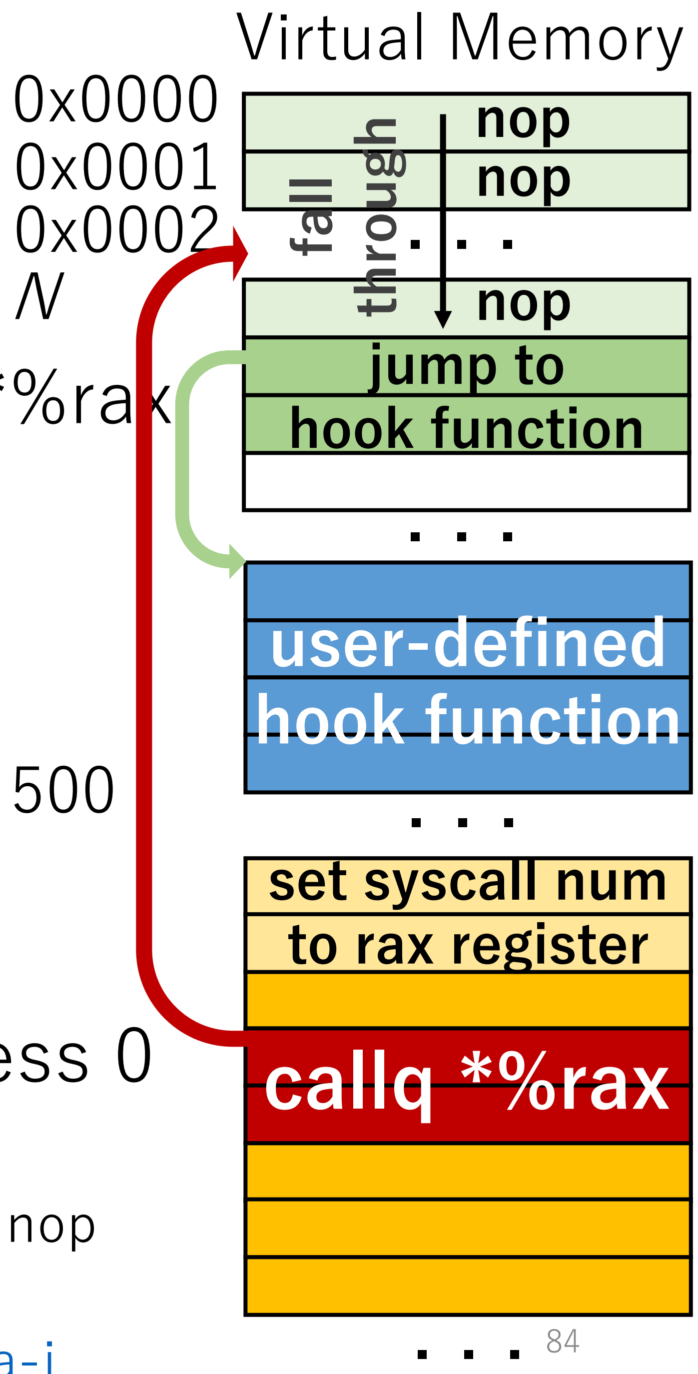

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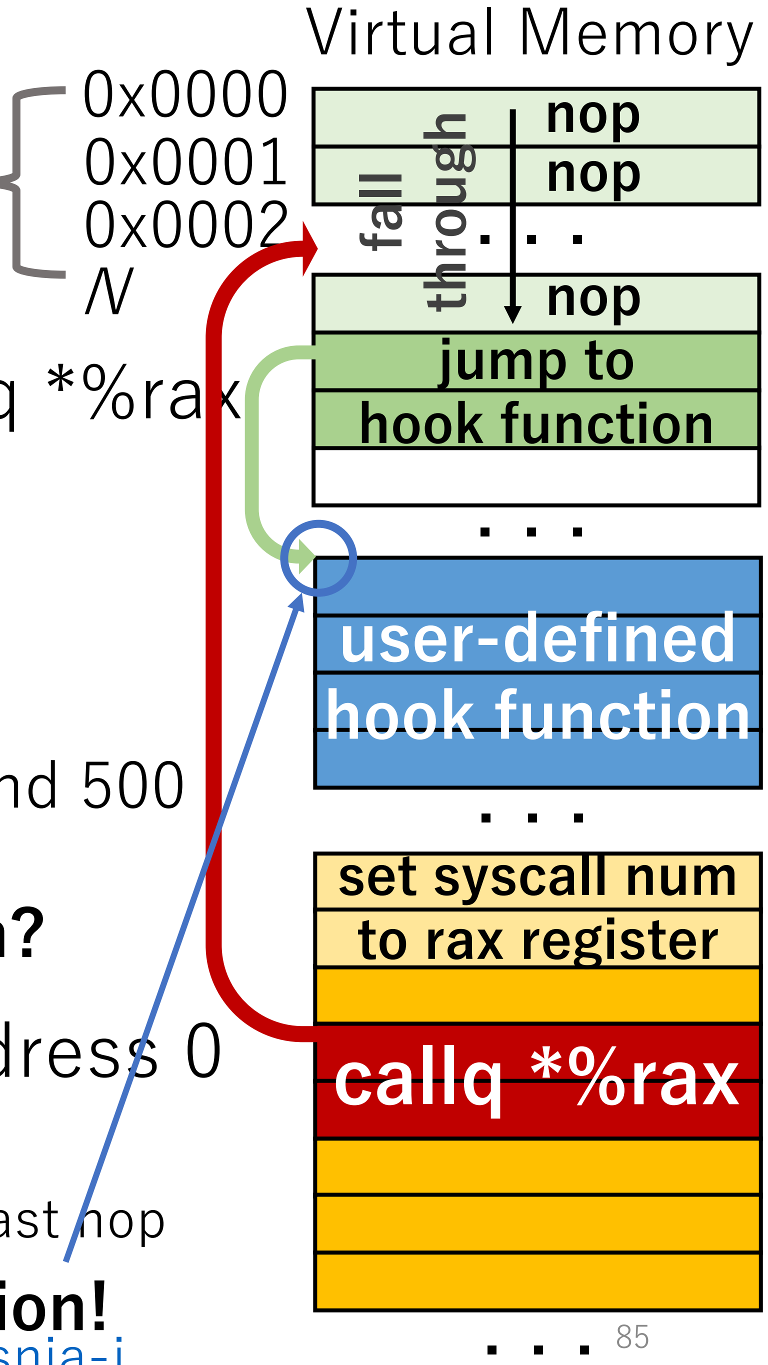

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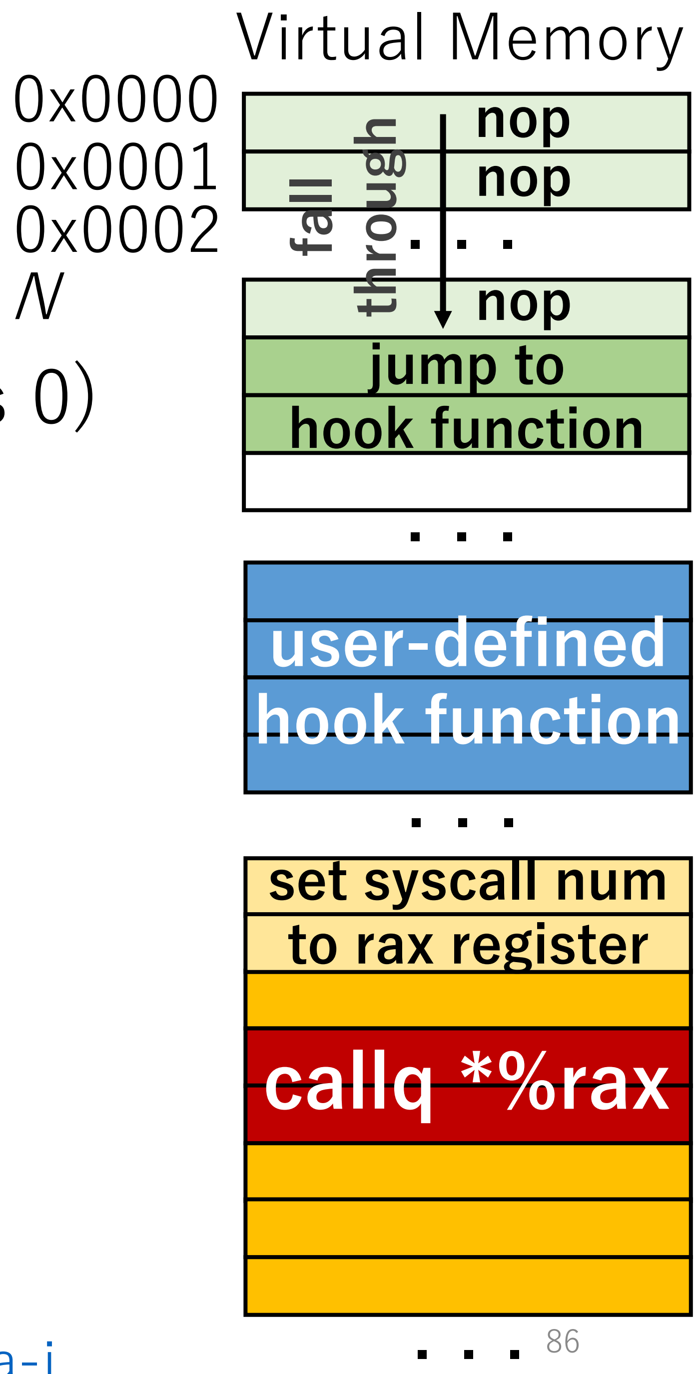
We could reach the user-defined hook function!

https://github.com/yasukata/presentation/tree/gh-pages/2023/06/snia-j

NULL Access Termination

- A buggy program may access NULL (address 0)



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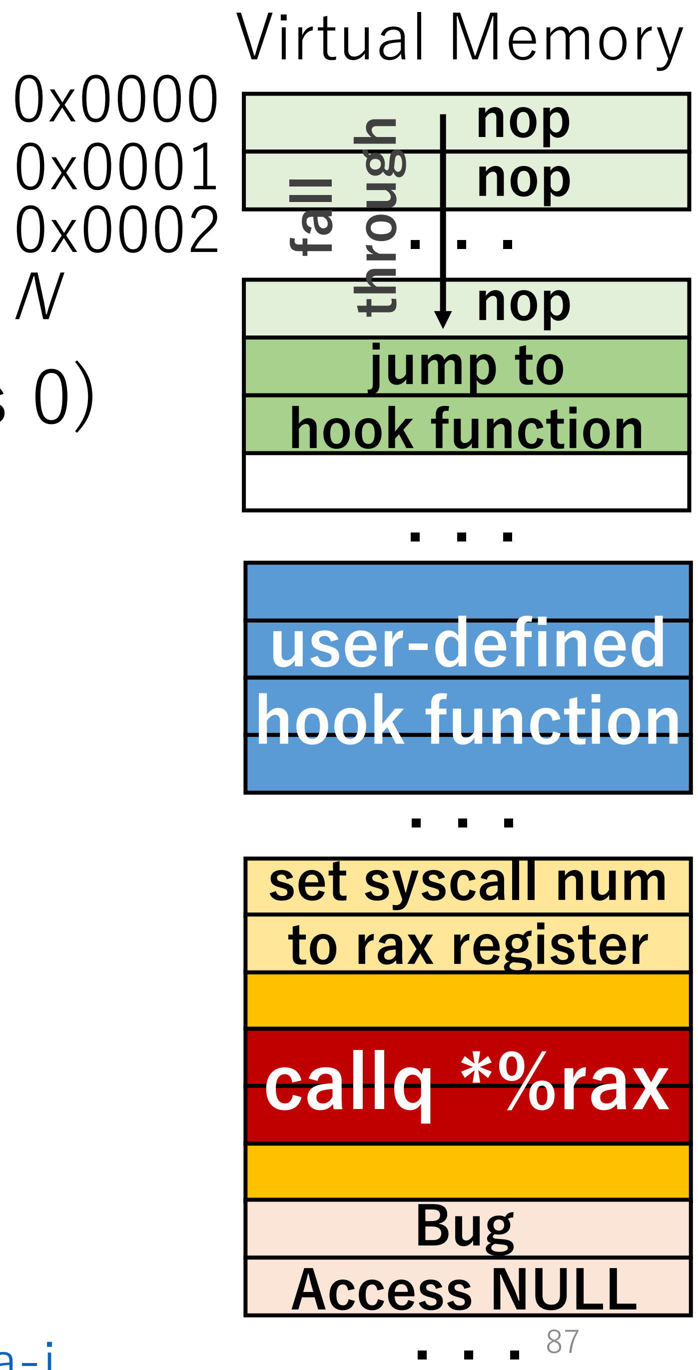

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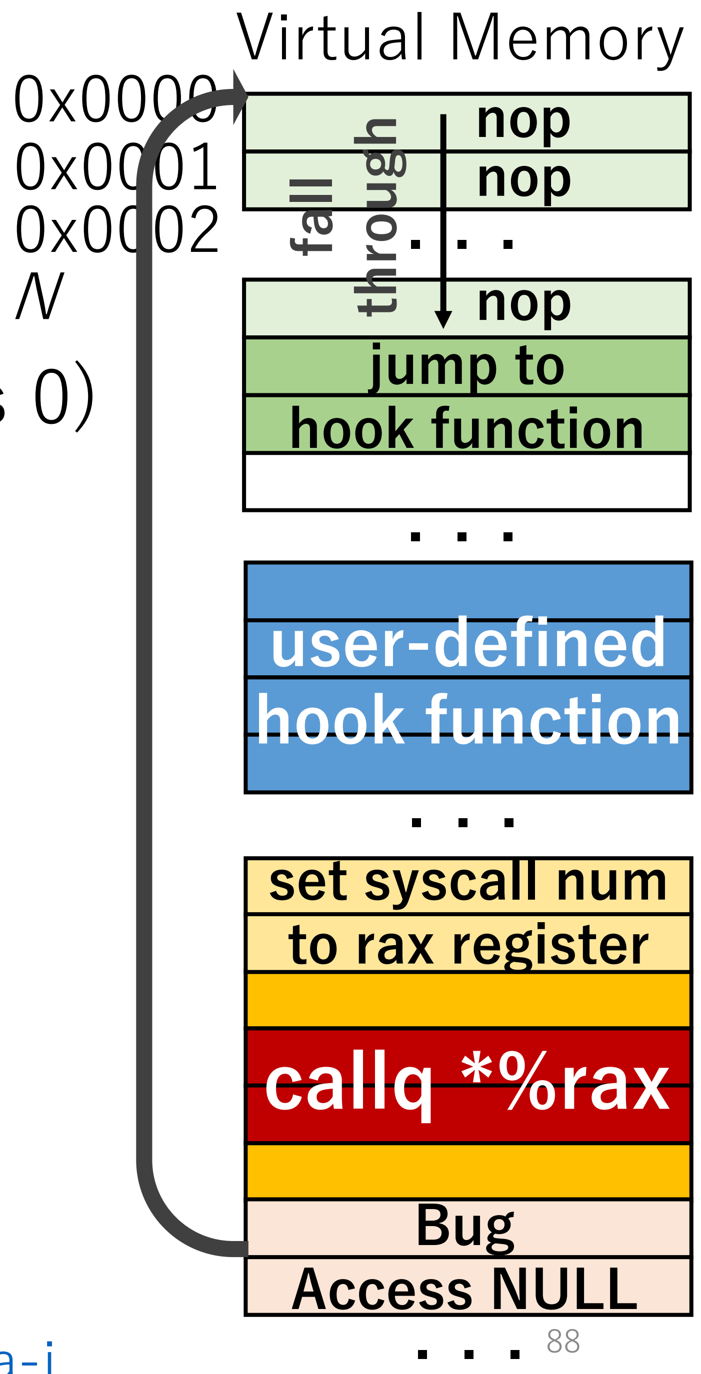

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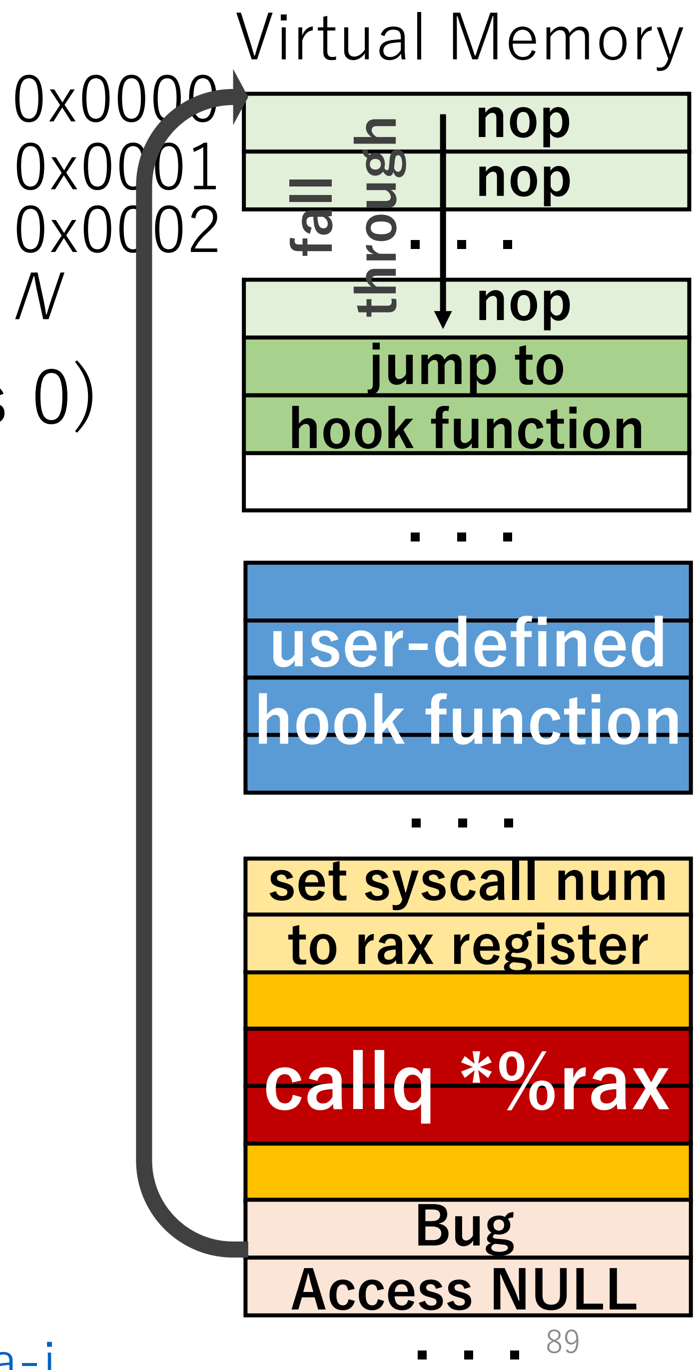

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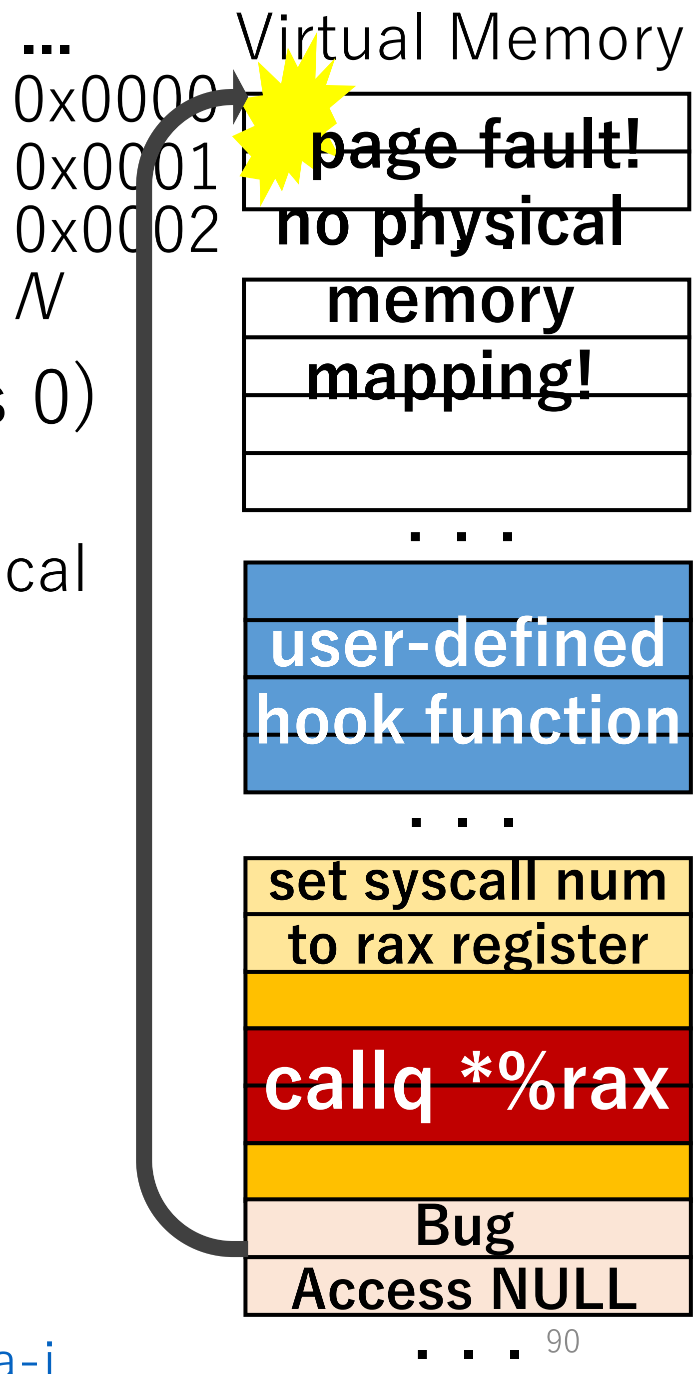
Normally, ...



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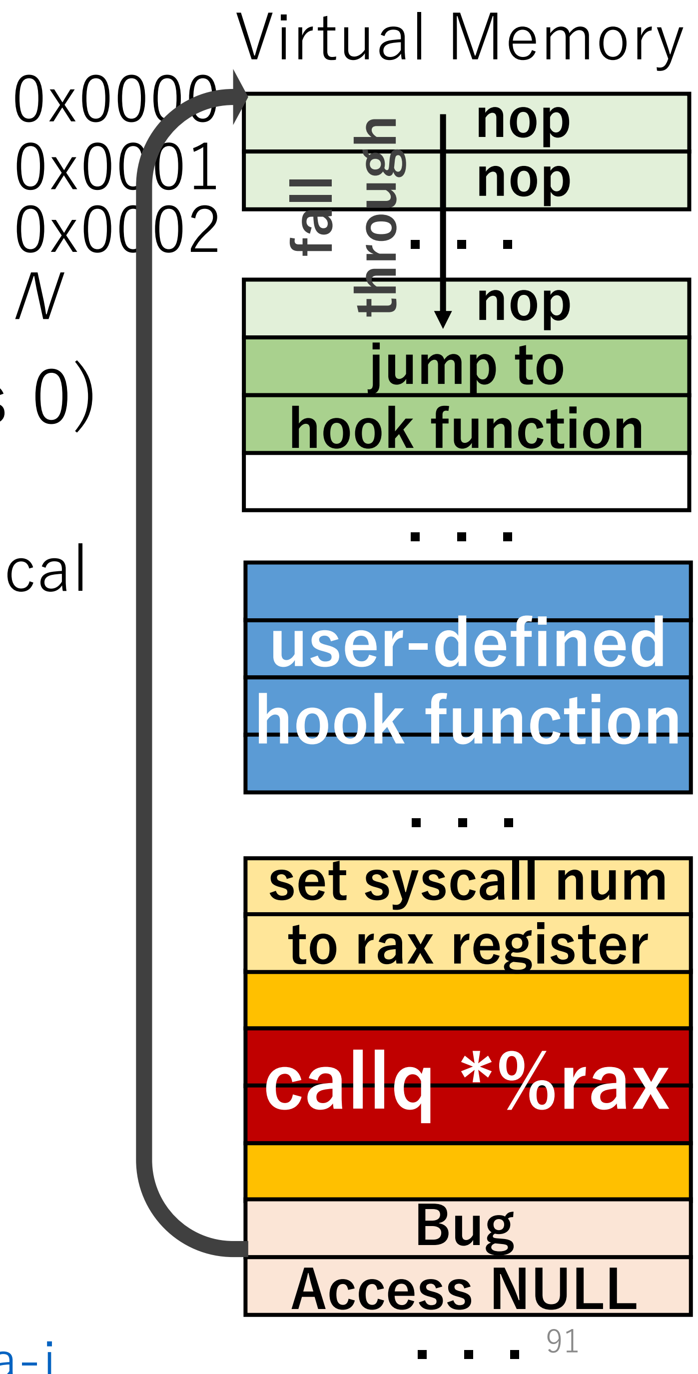

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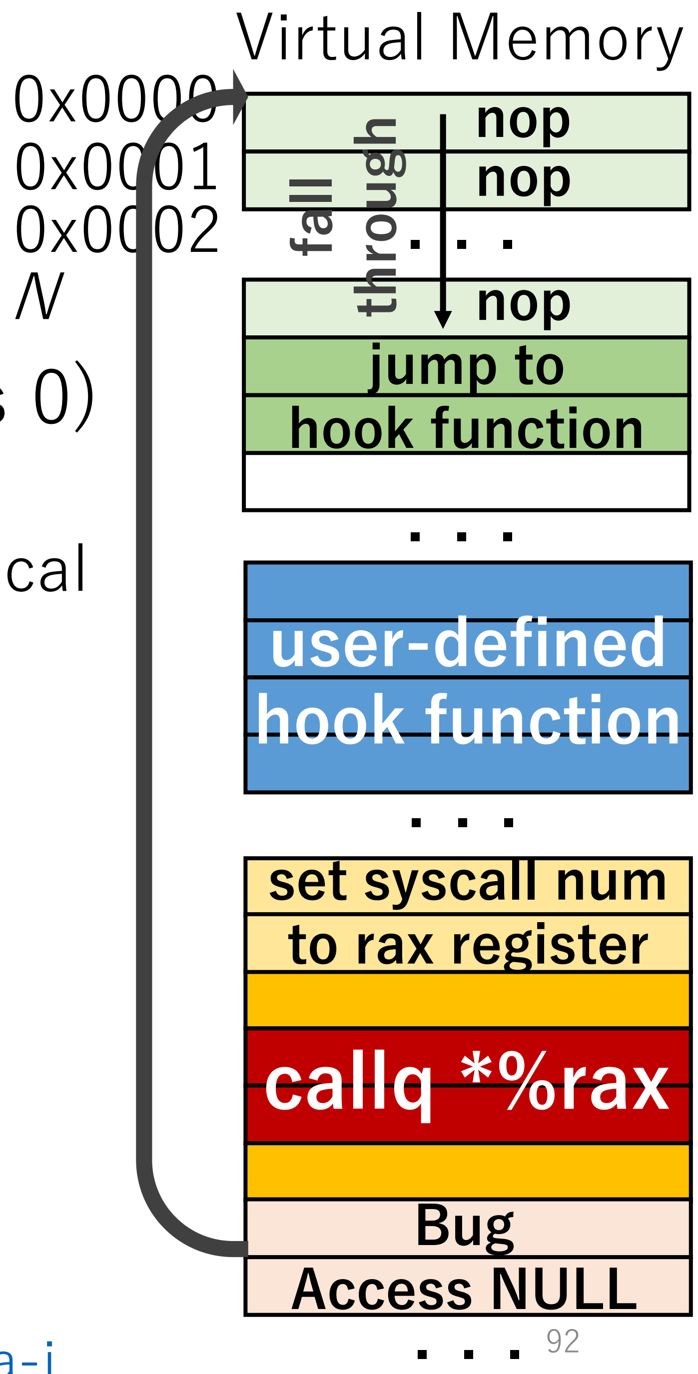

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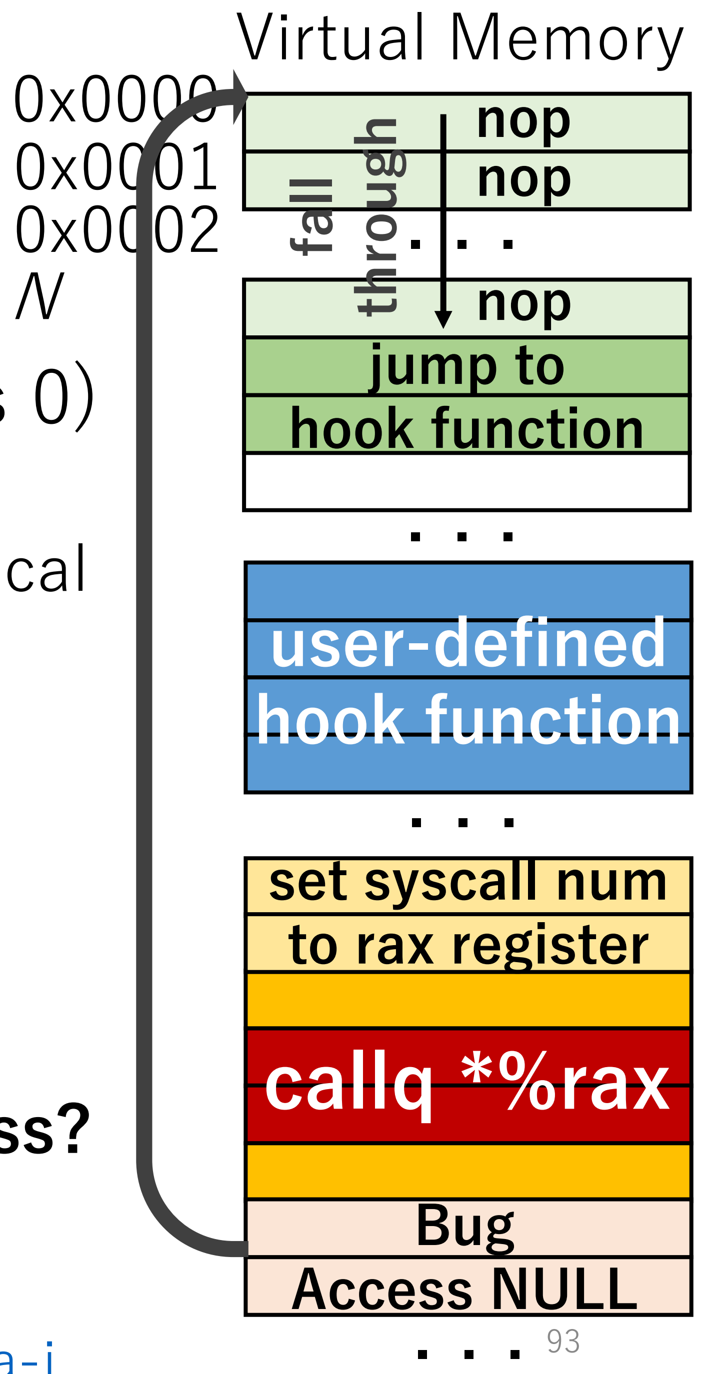
How can we detect and terminate a buggy NULL access?



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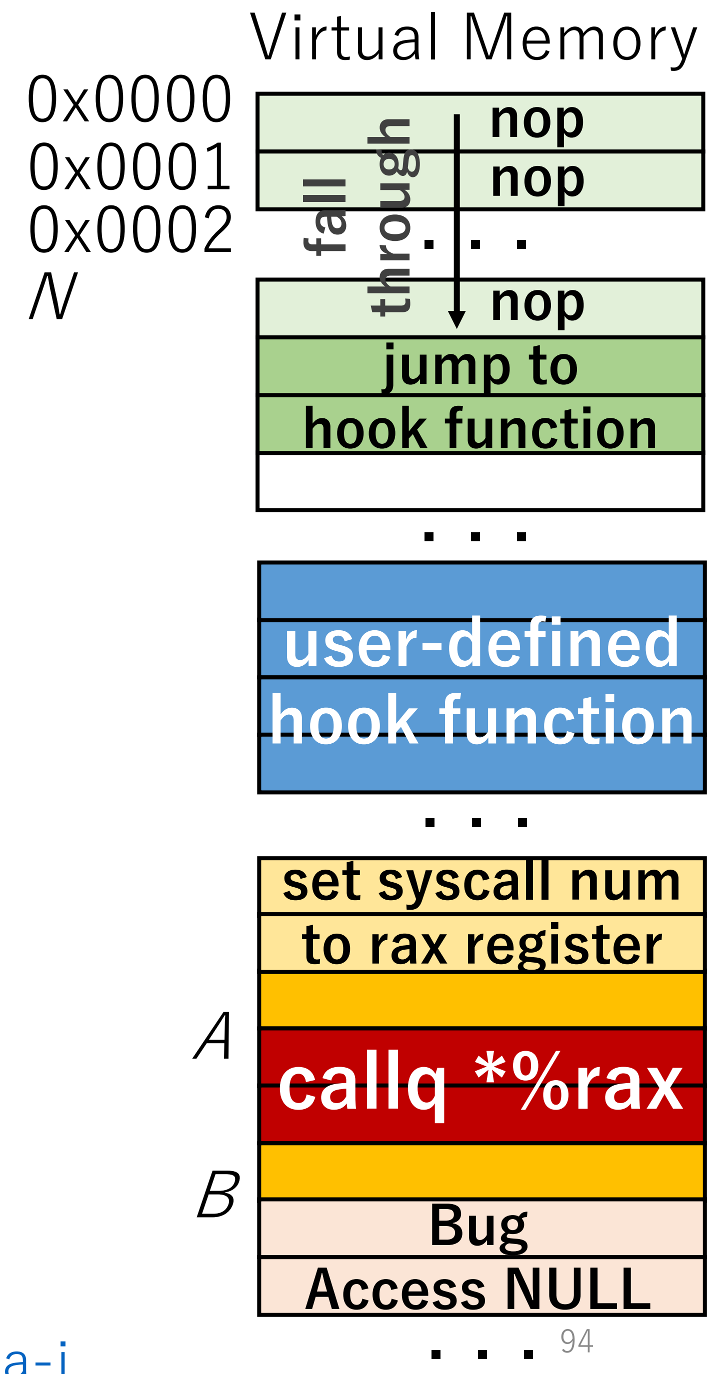
NULL Access Termination

- Memory access: read / write / execute



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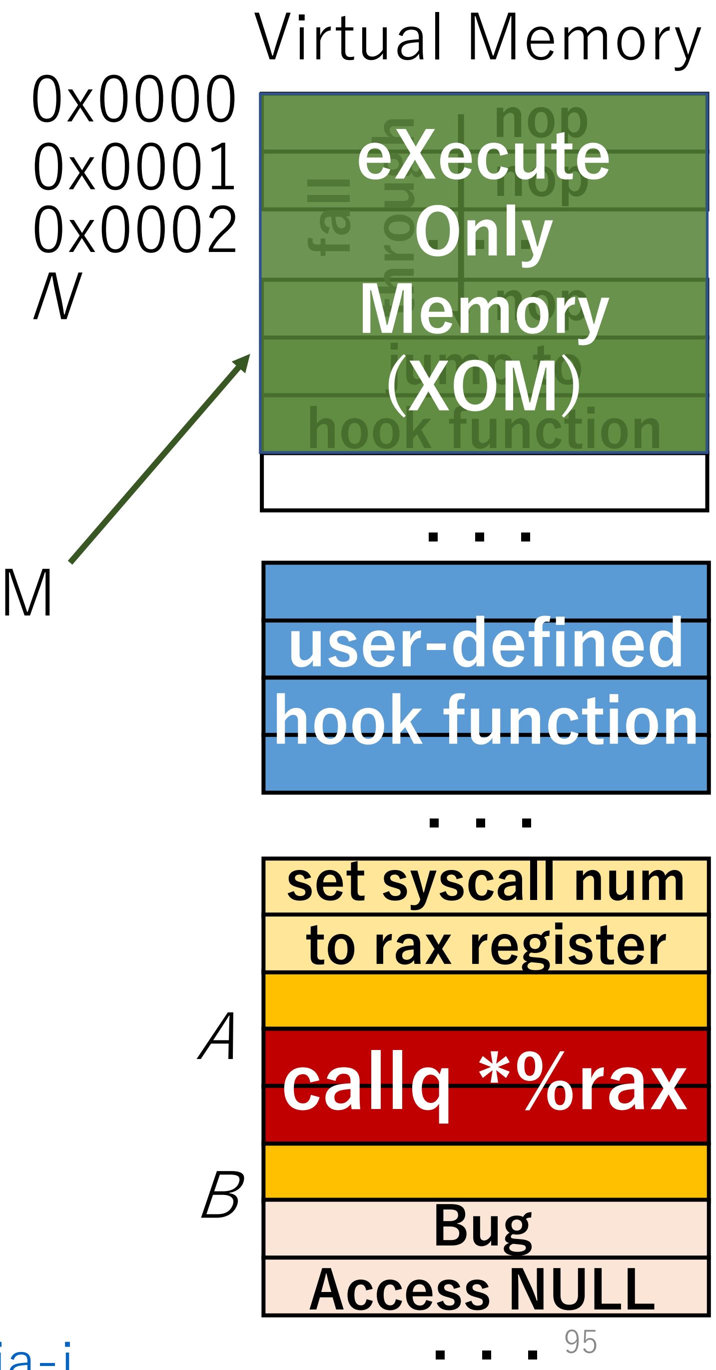
NULL Access Termination

- Memory access: read / write / execute
- Solution
  - read/write: configure the trampoline code as XOM



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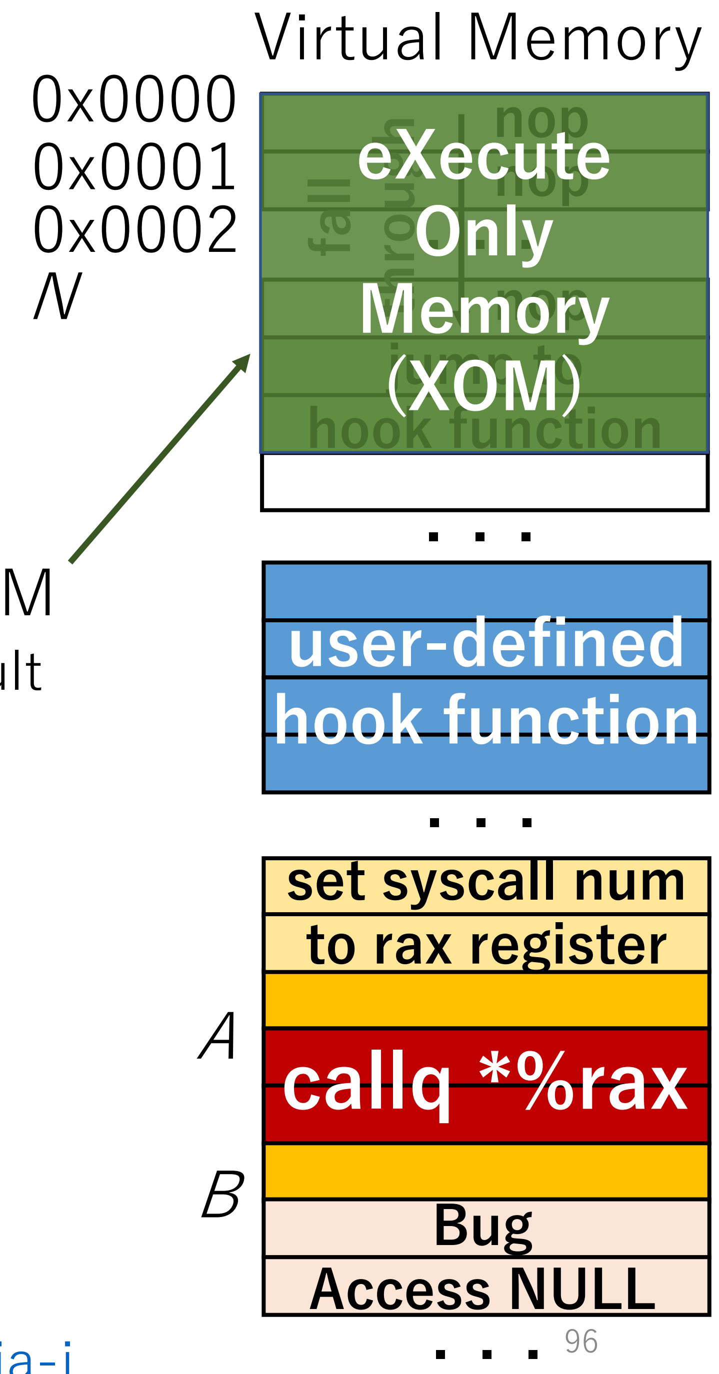

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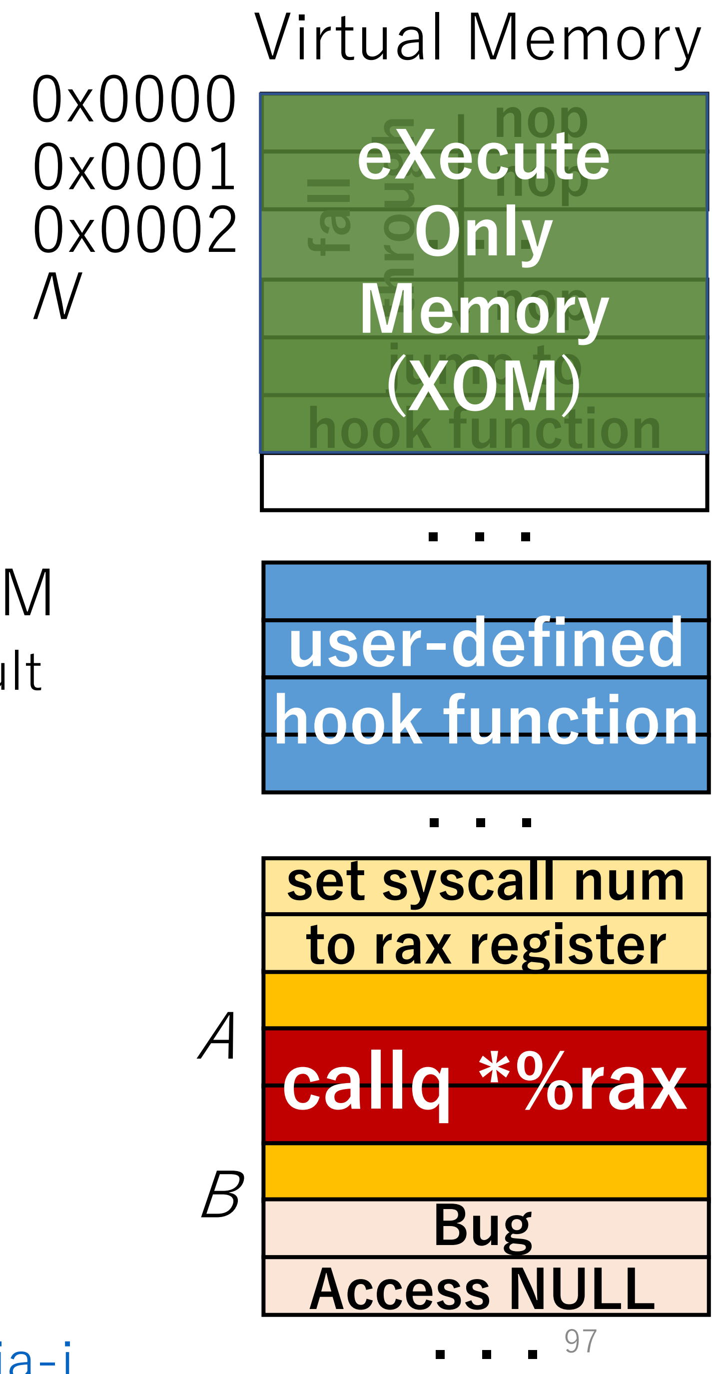

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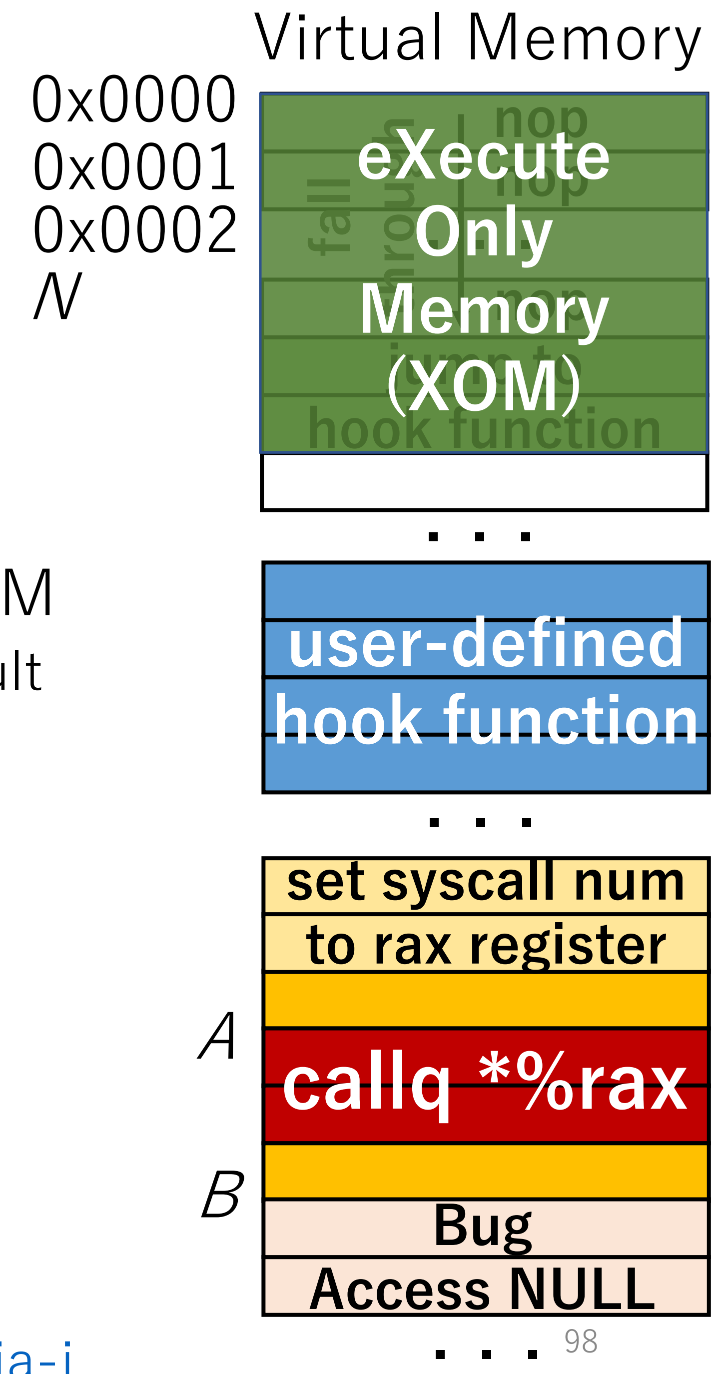

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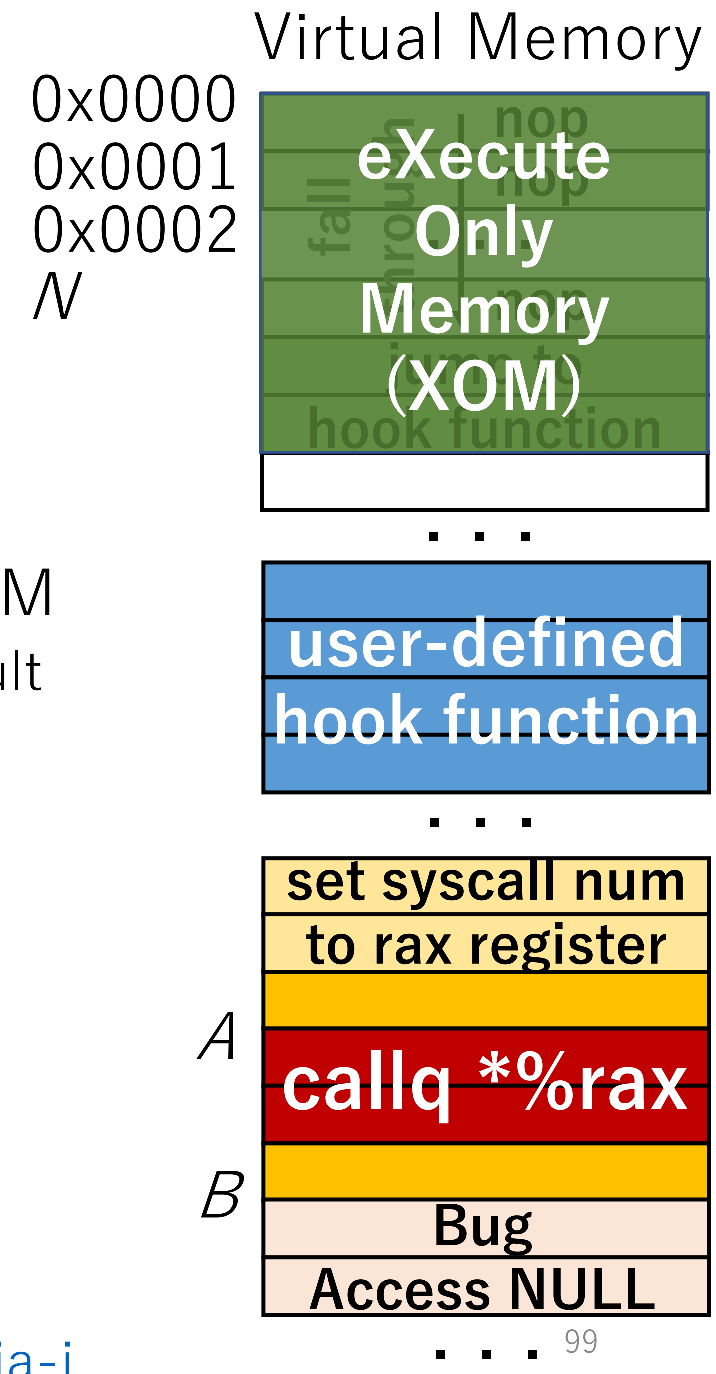
During binary rewriting phase …

List of replaced addresses : […]



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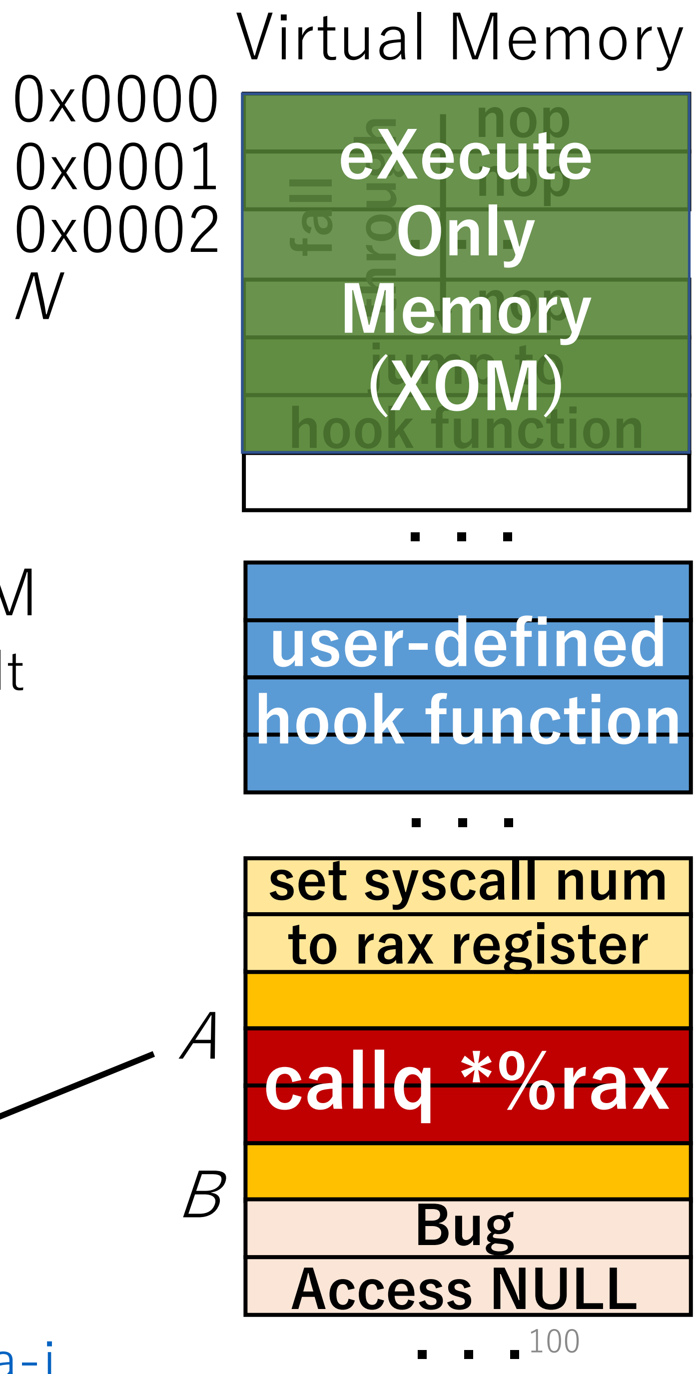

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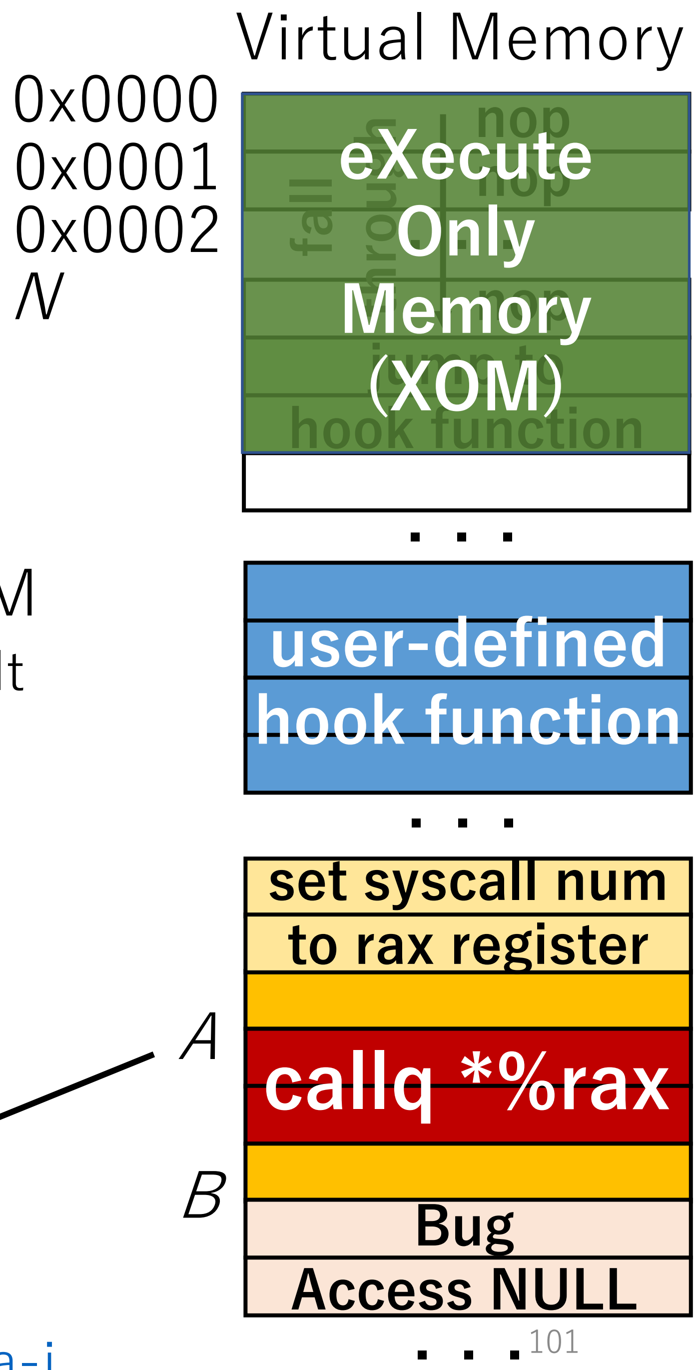

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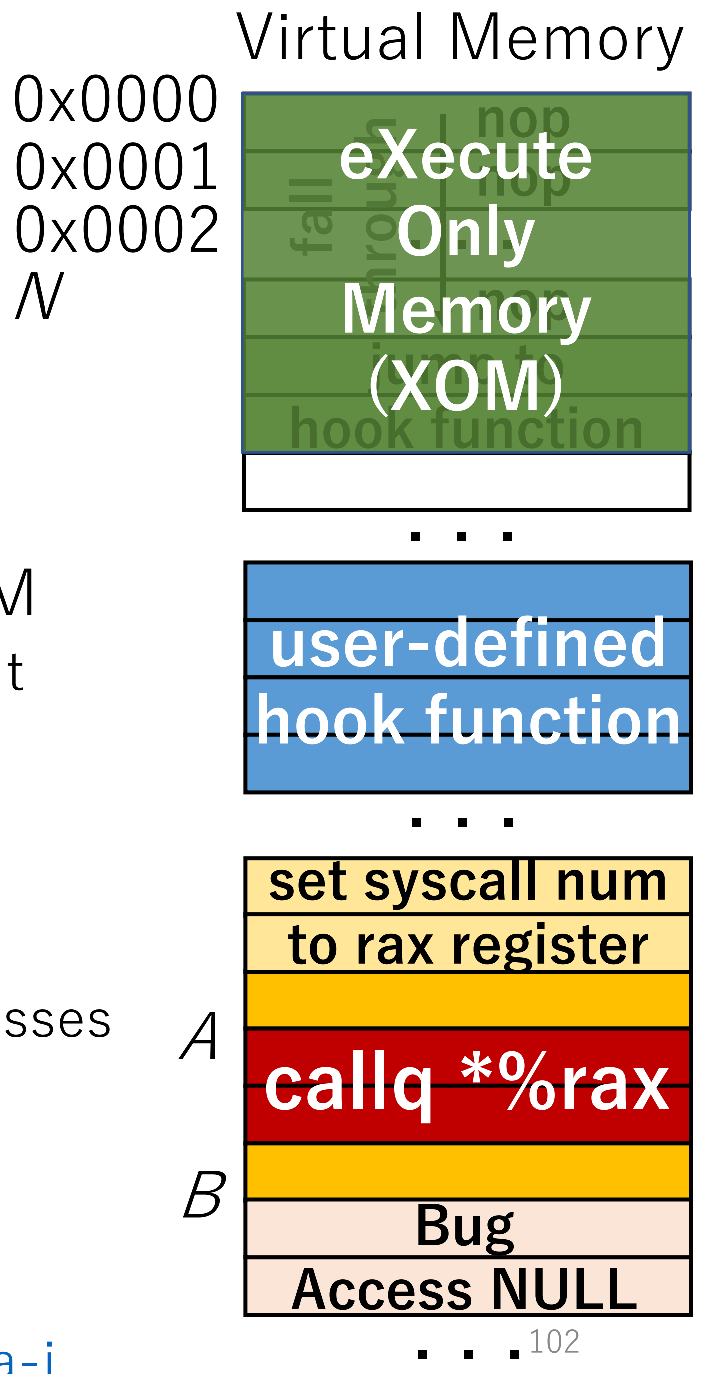

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NULL Access Termination

At runtime ...

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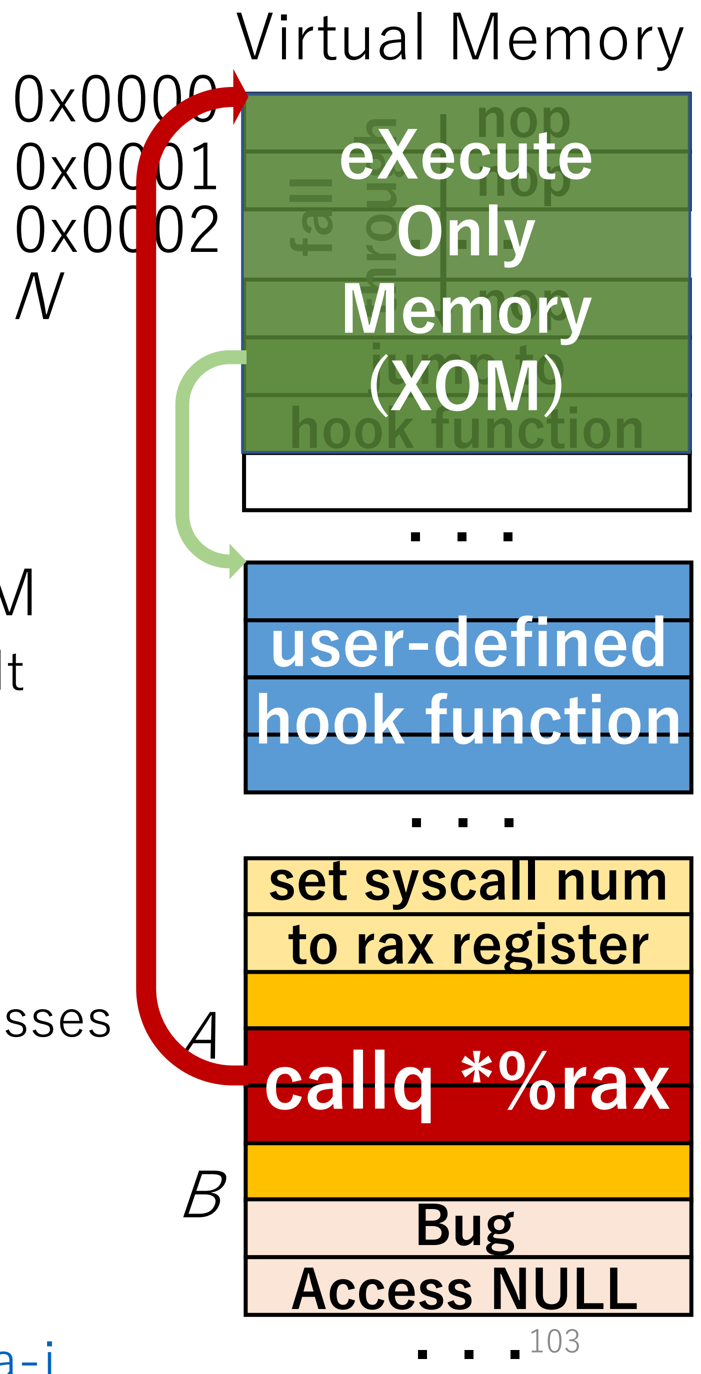

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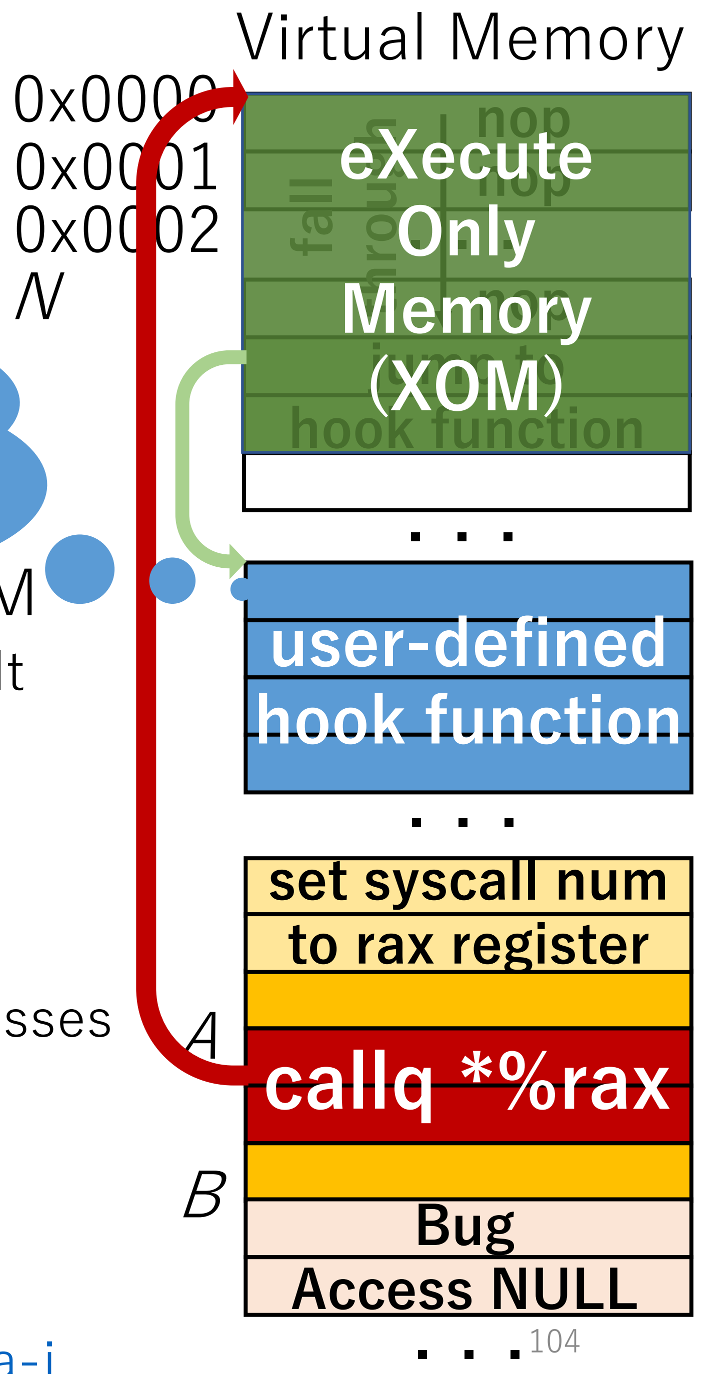
The caller address is *A*
***A* is in the list, so**
this is a valid access

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



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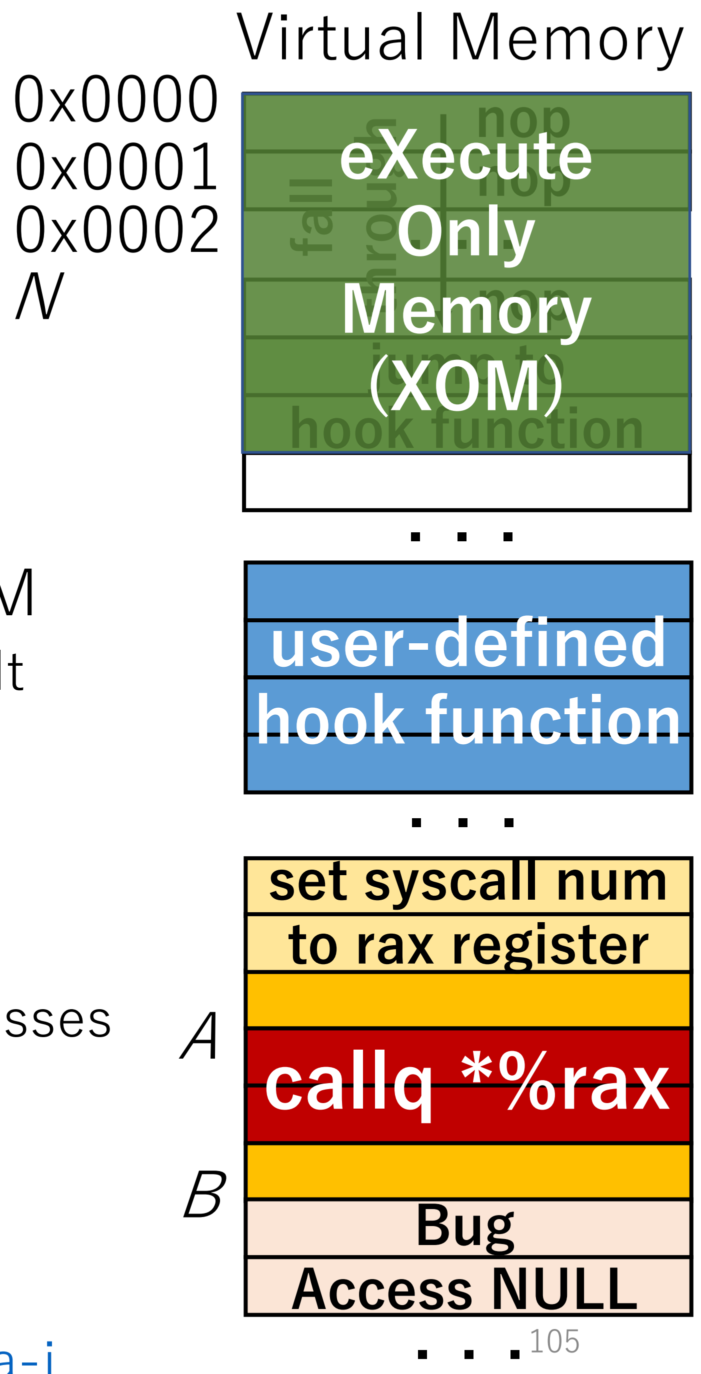

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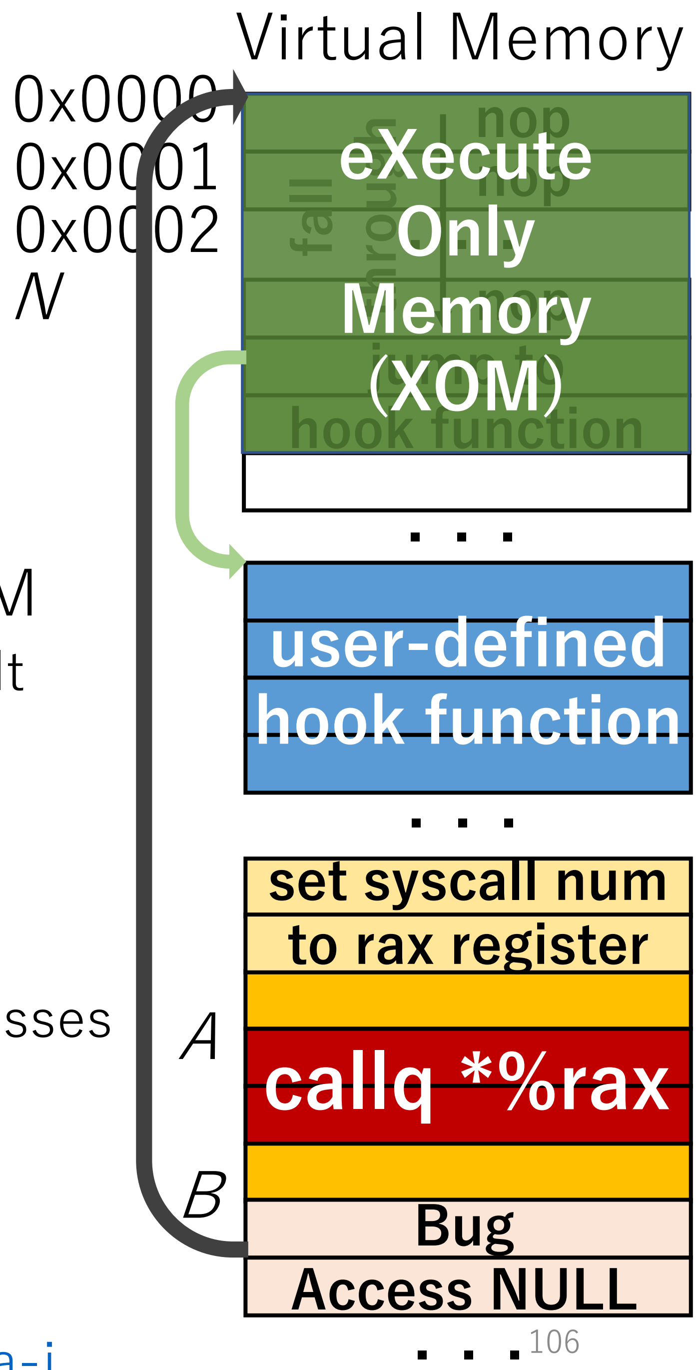

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The caller address is *B*
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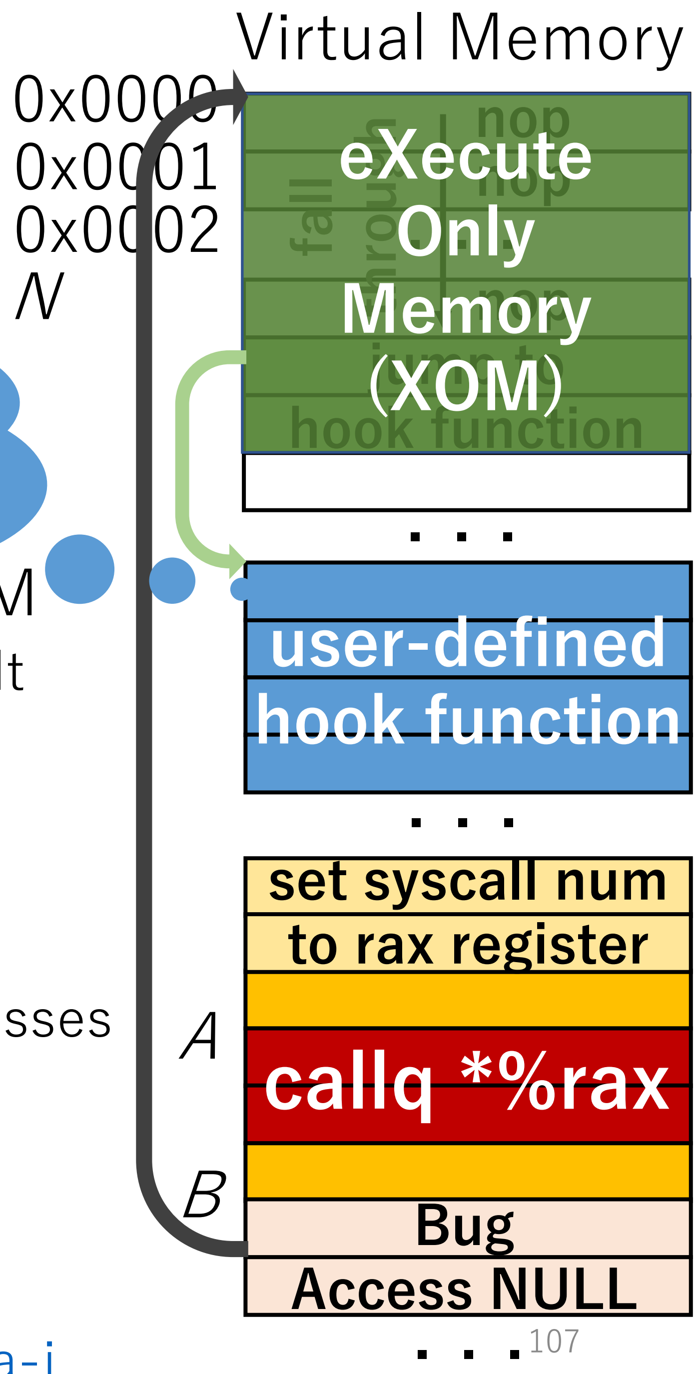

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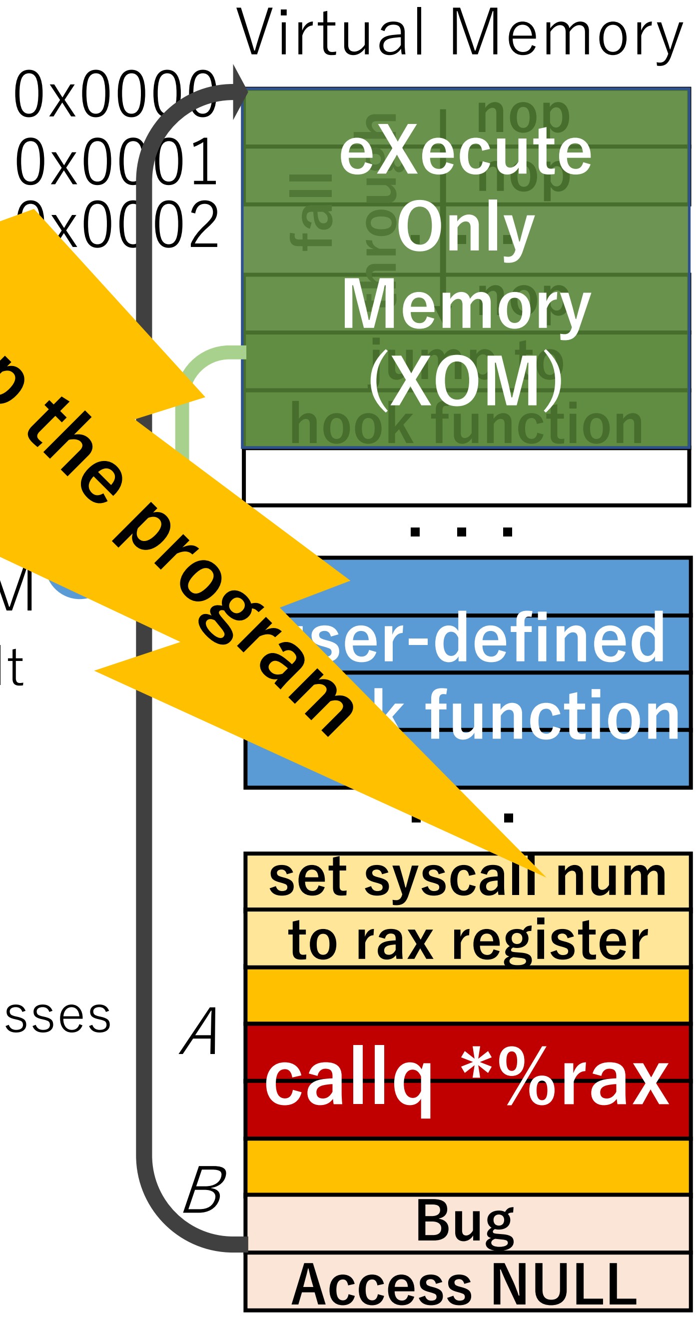

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       - Current prototype uses bitmap to implement this check

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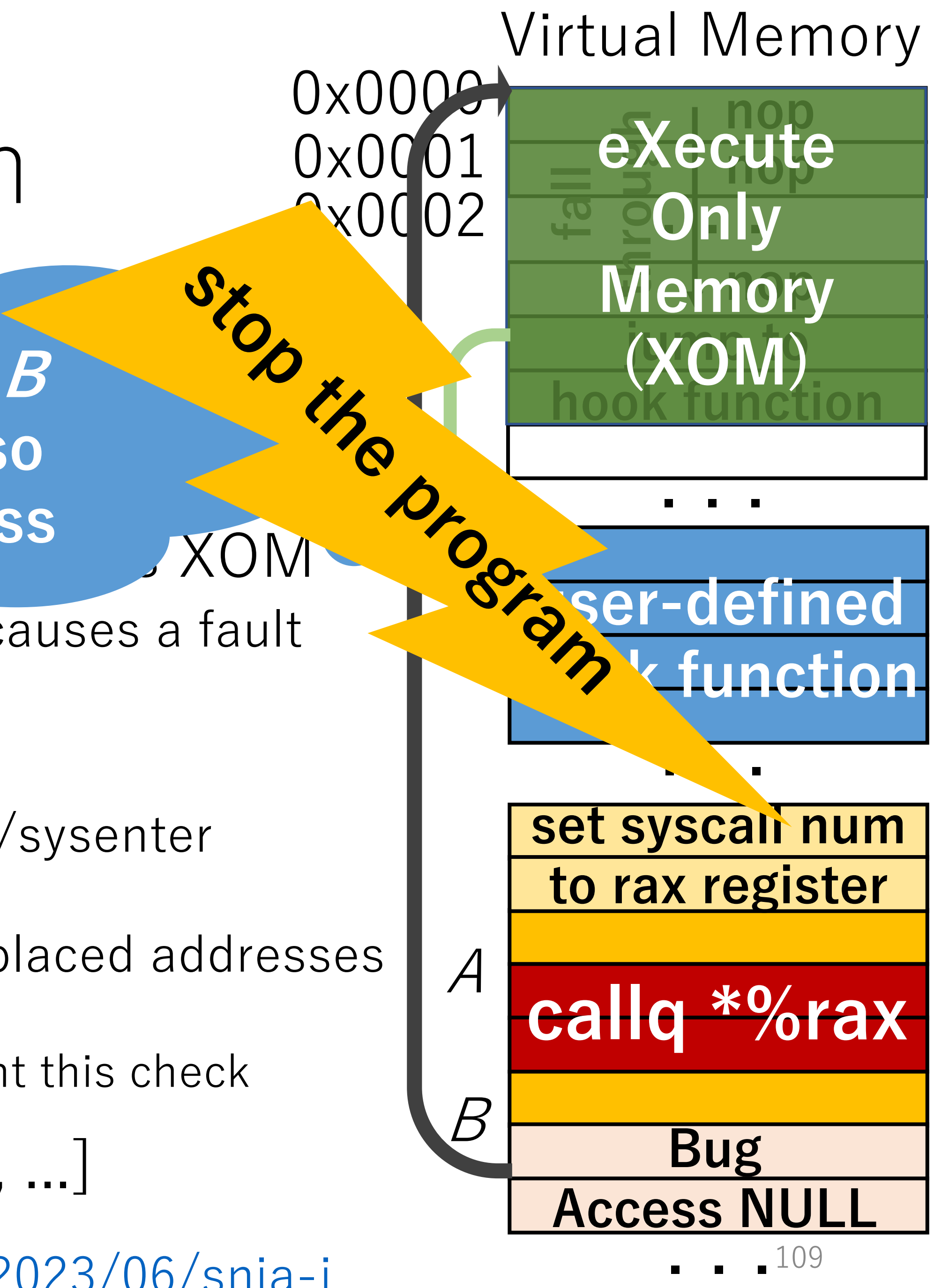

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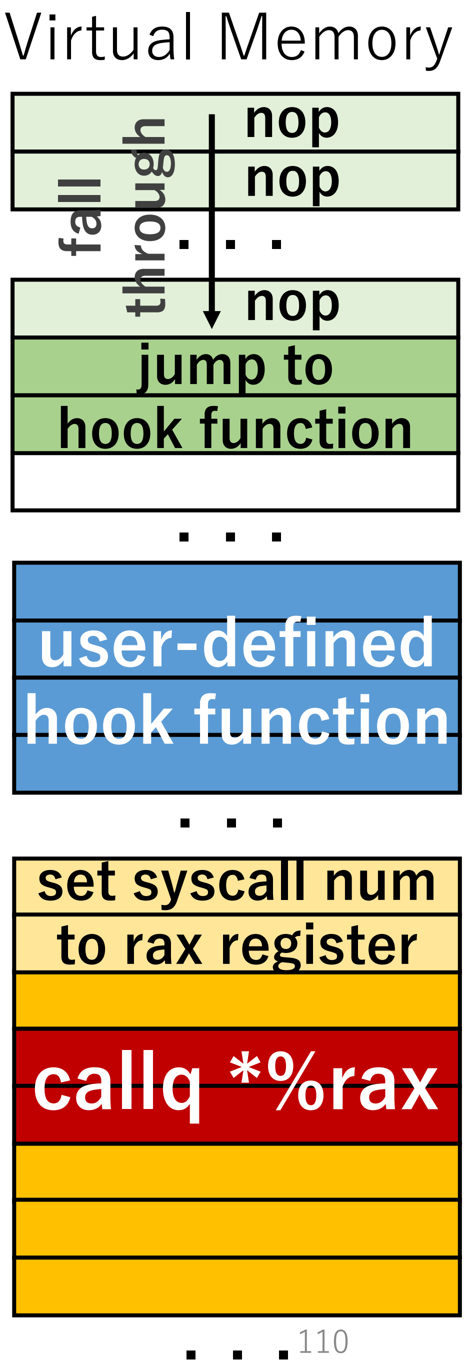
System Call Hook Overhead

- 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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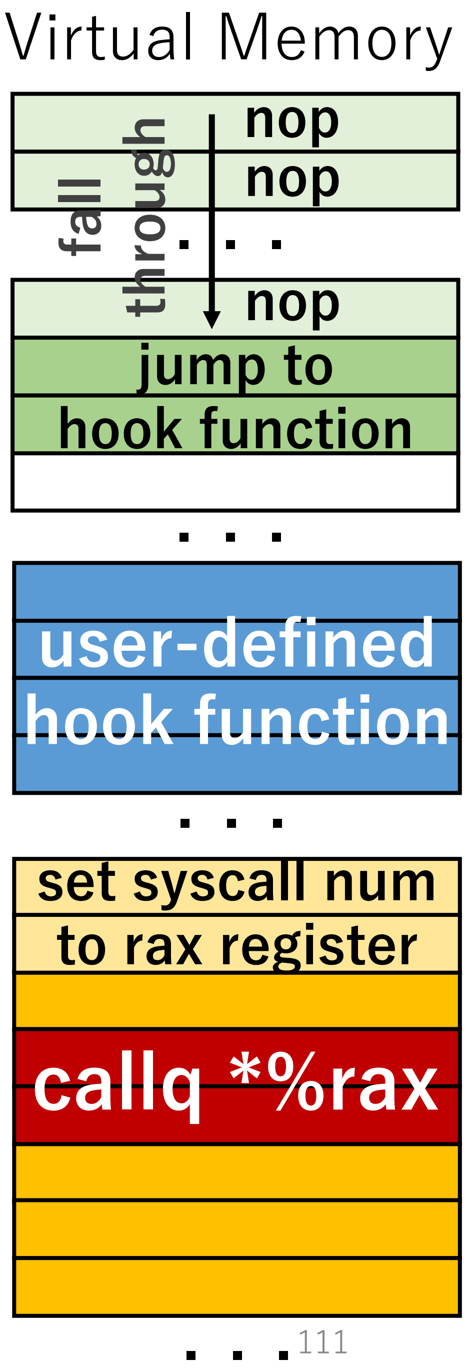
716x
32.7x
28.1x
improvement



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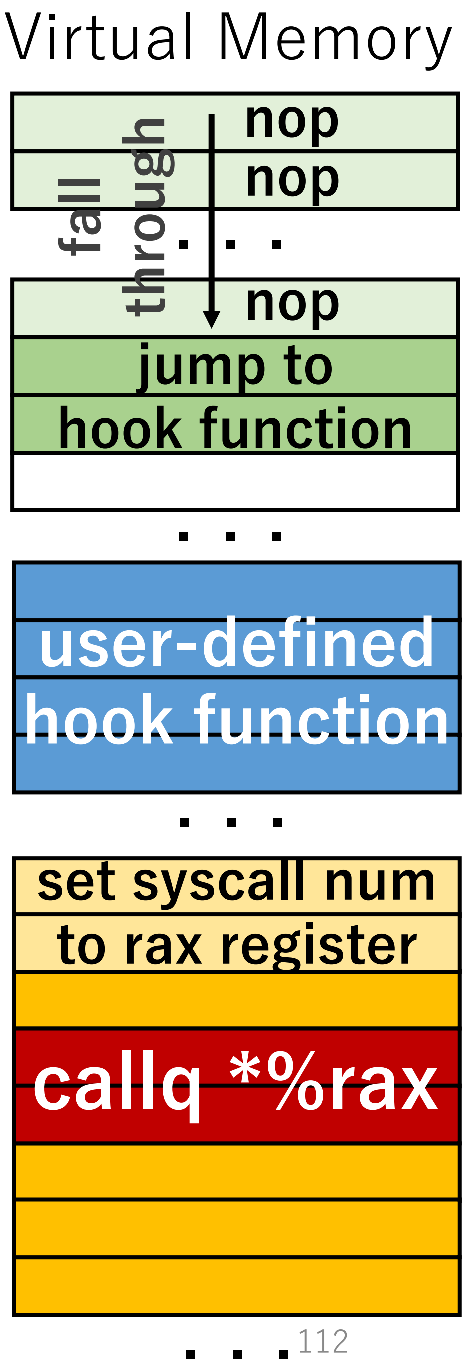

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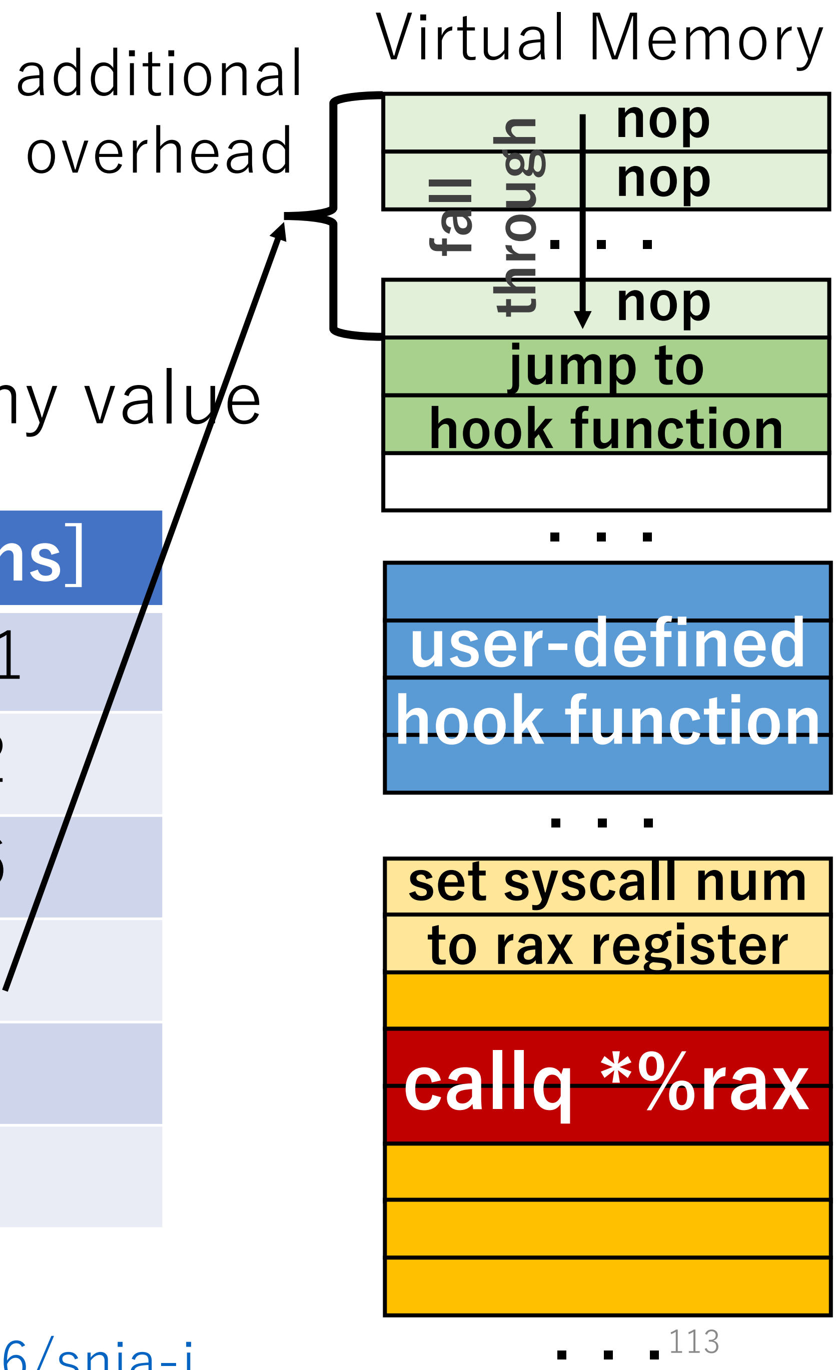
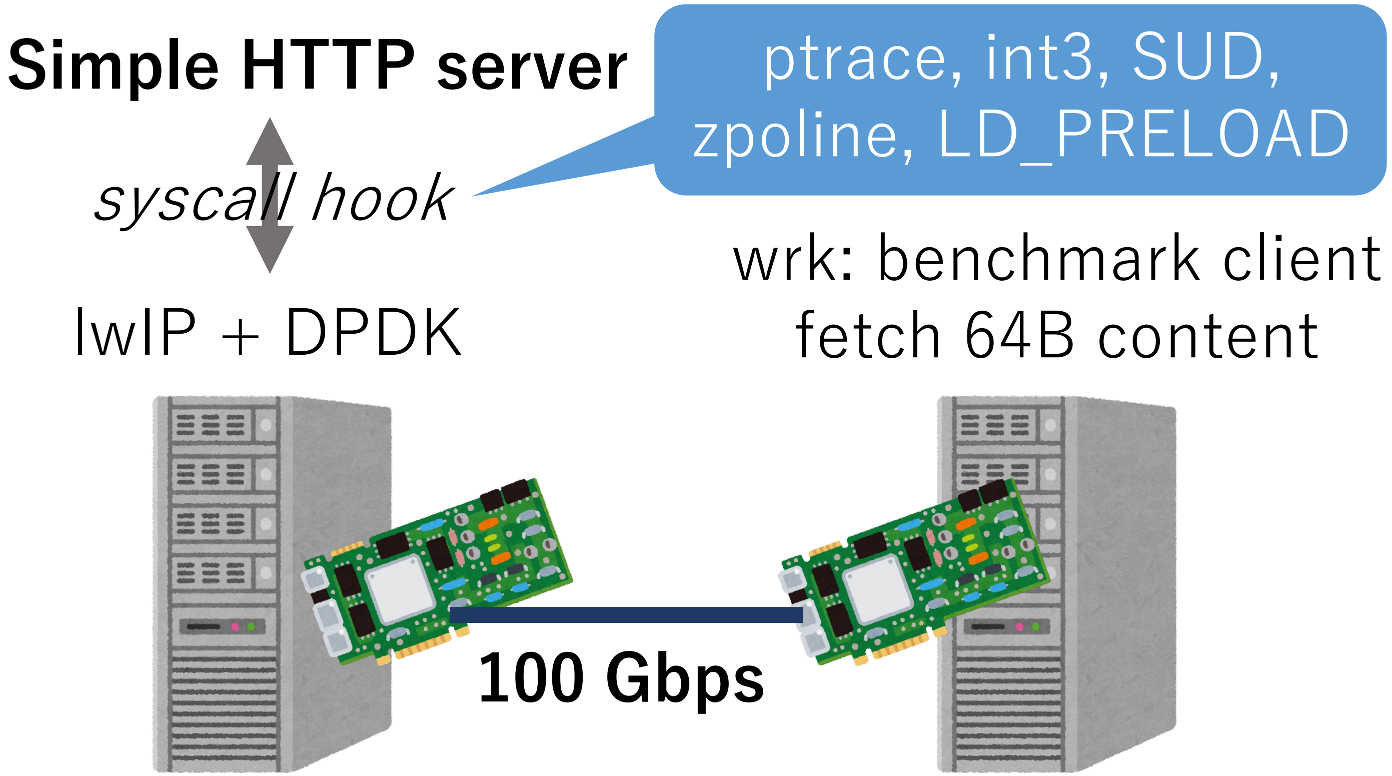
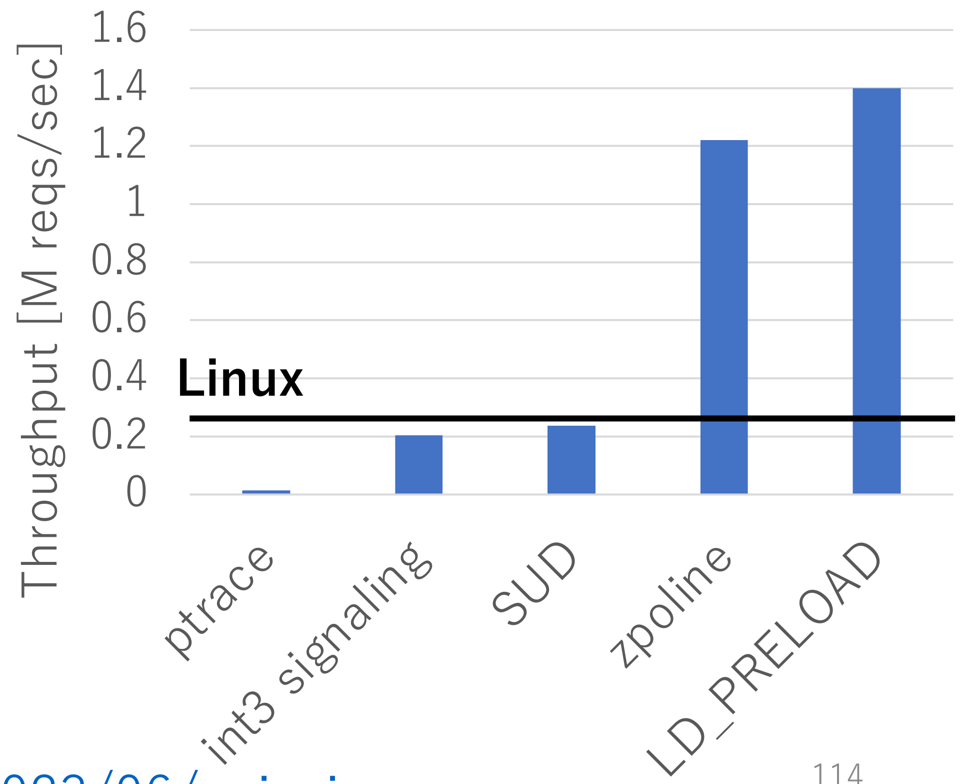


https://github.com/yasukata/presentation/tree/gh-pages/2023/06/snia-j

Application Performance

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





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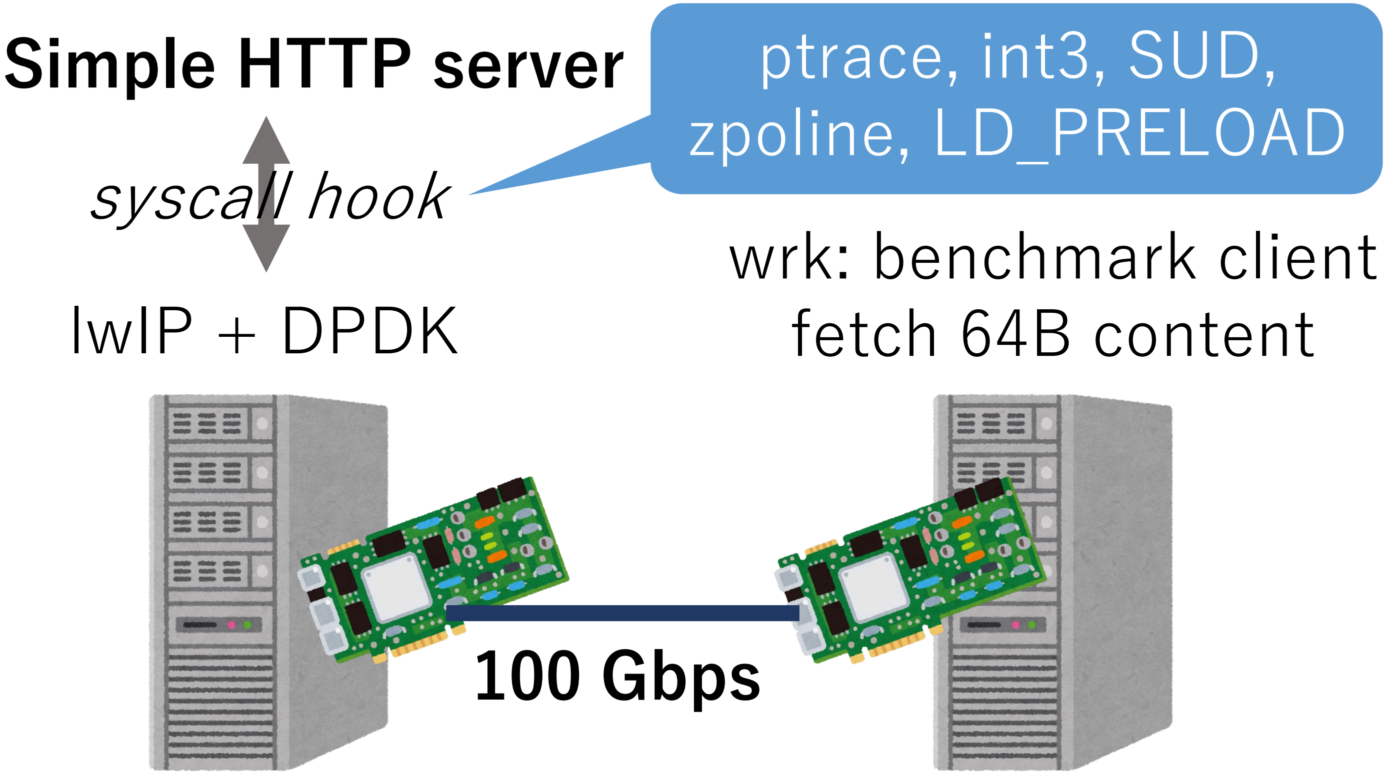

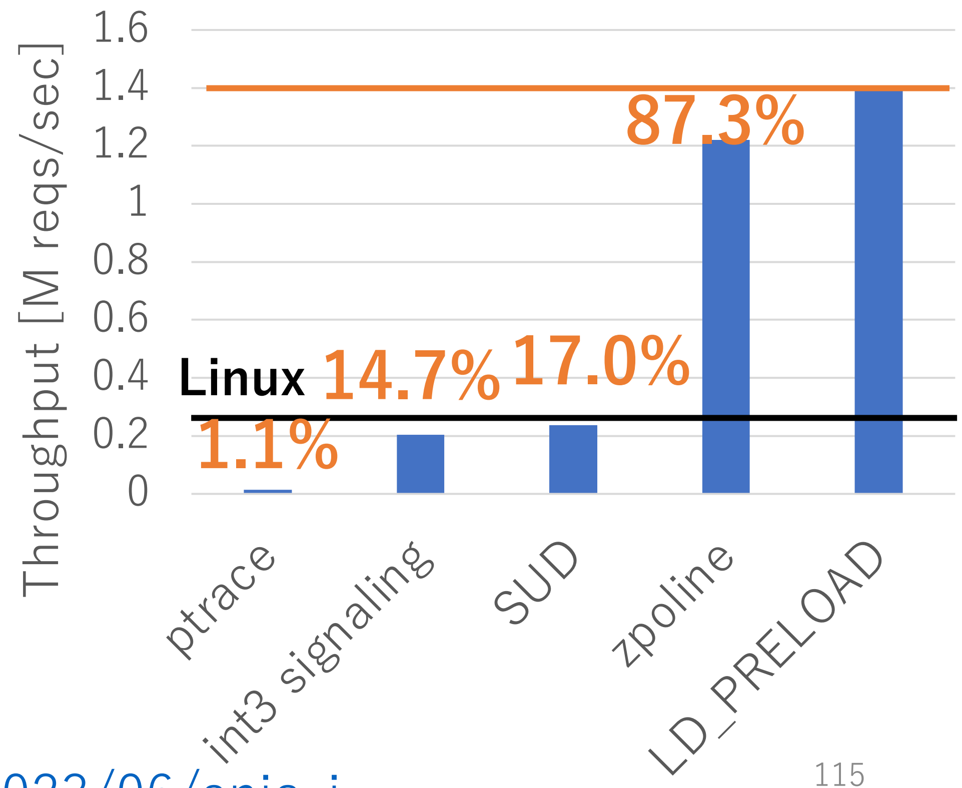

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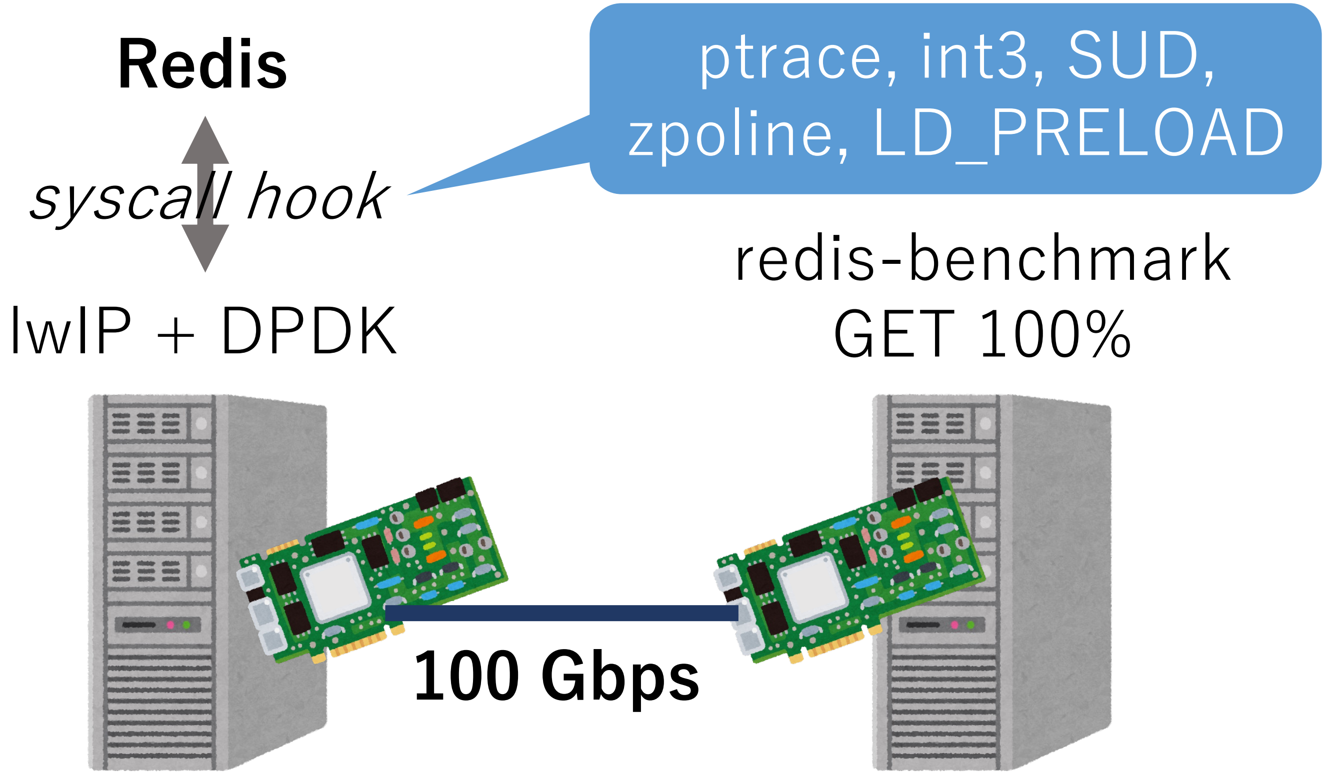

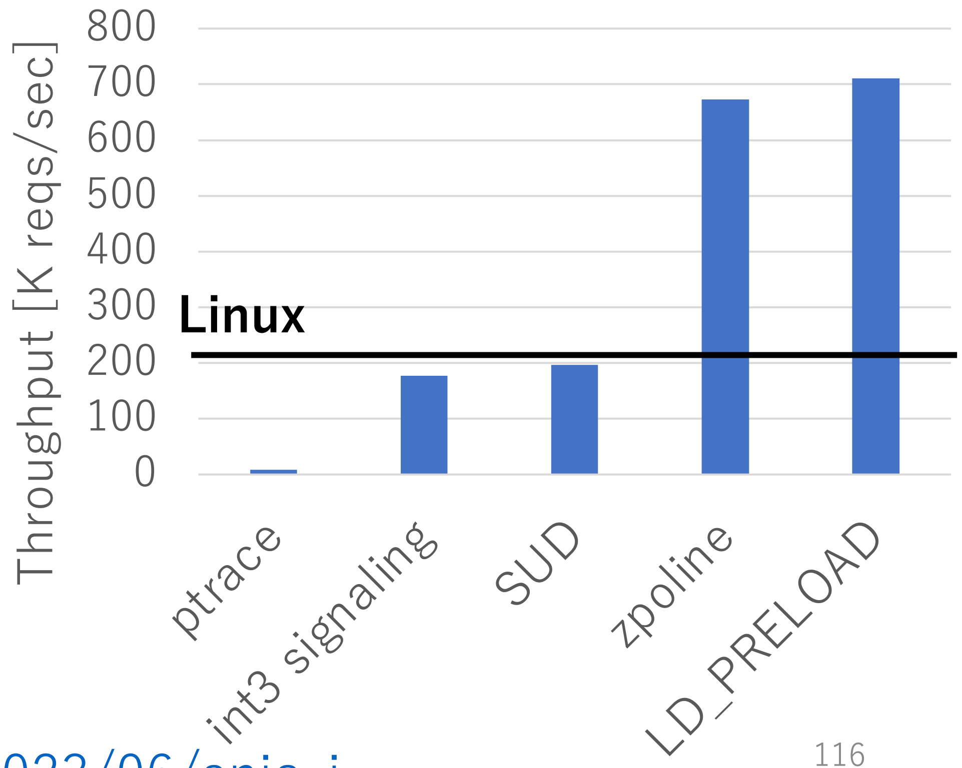

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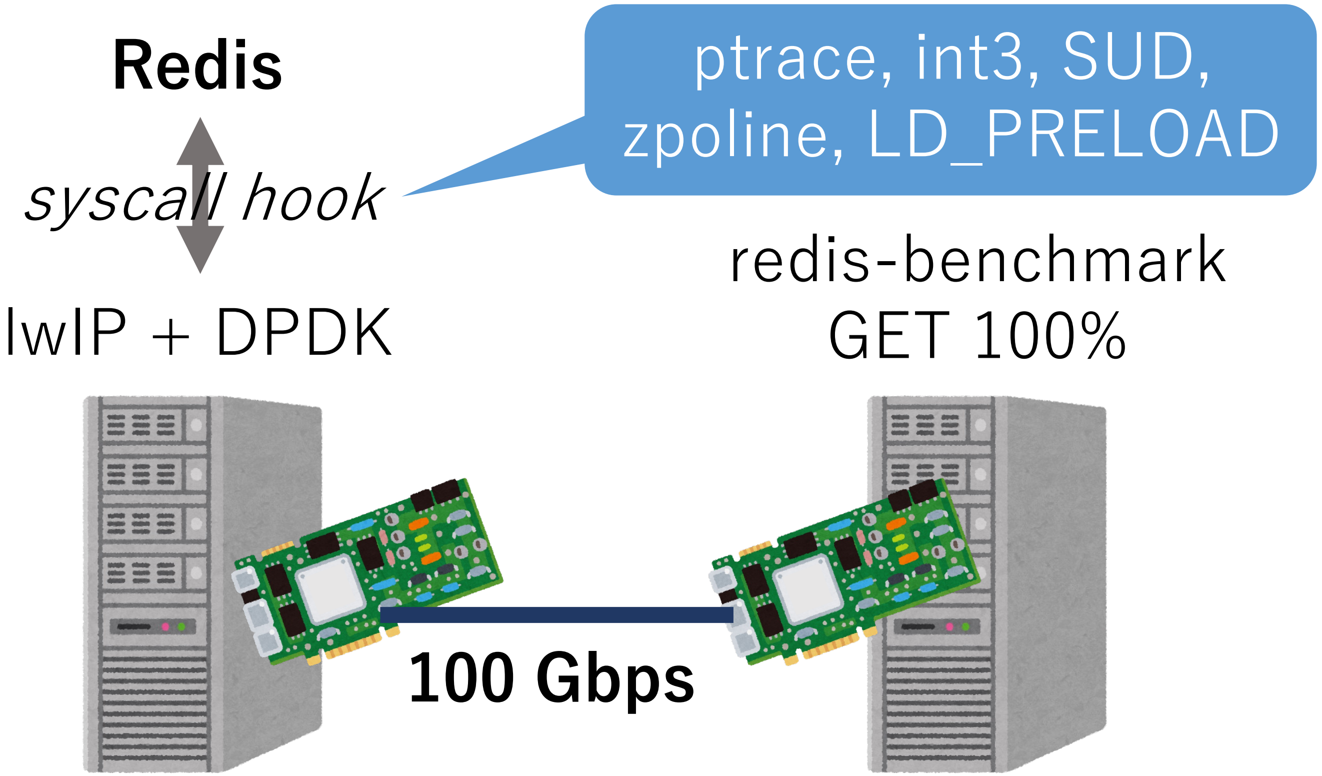
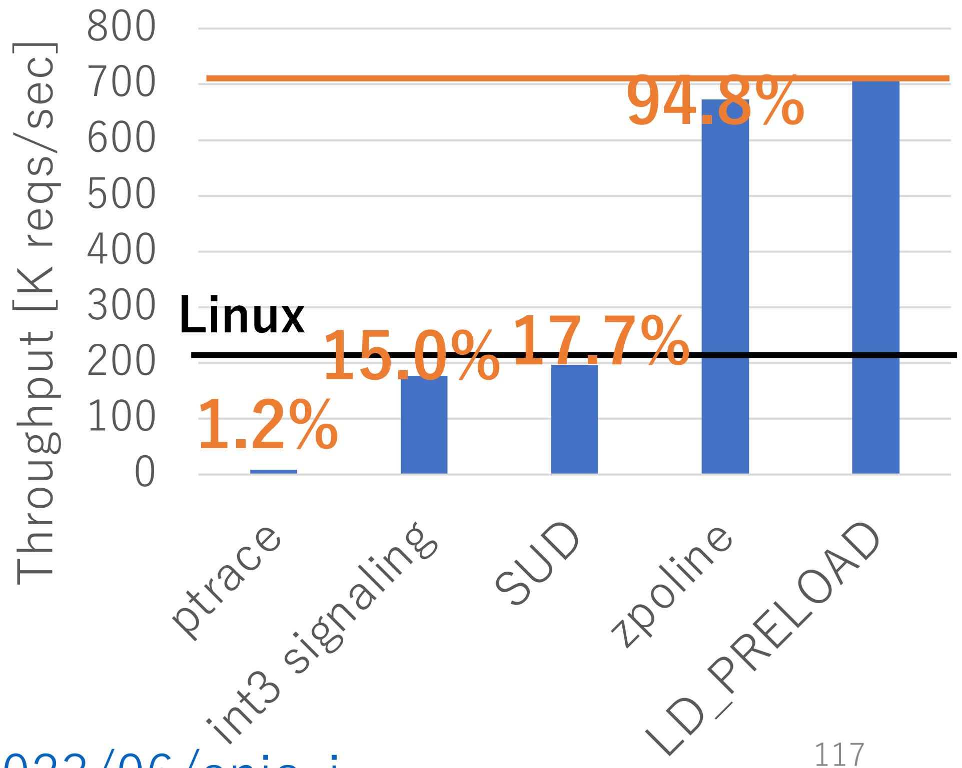




https://github.com/yasukata/presentation/tree/gh-pages/2023/06/snia-j

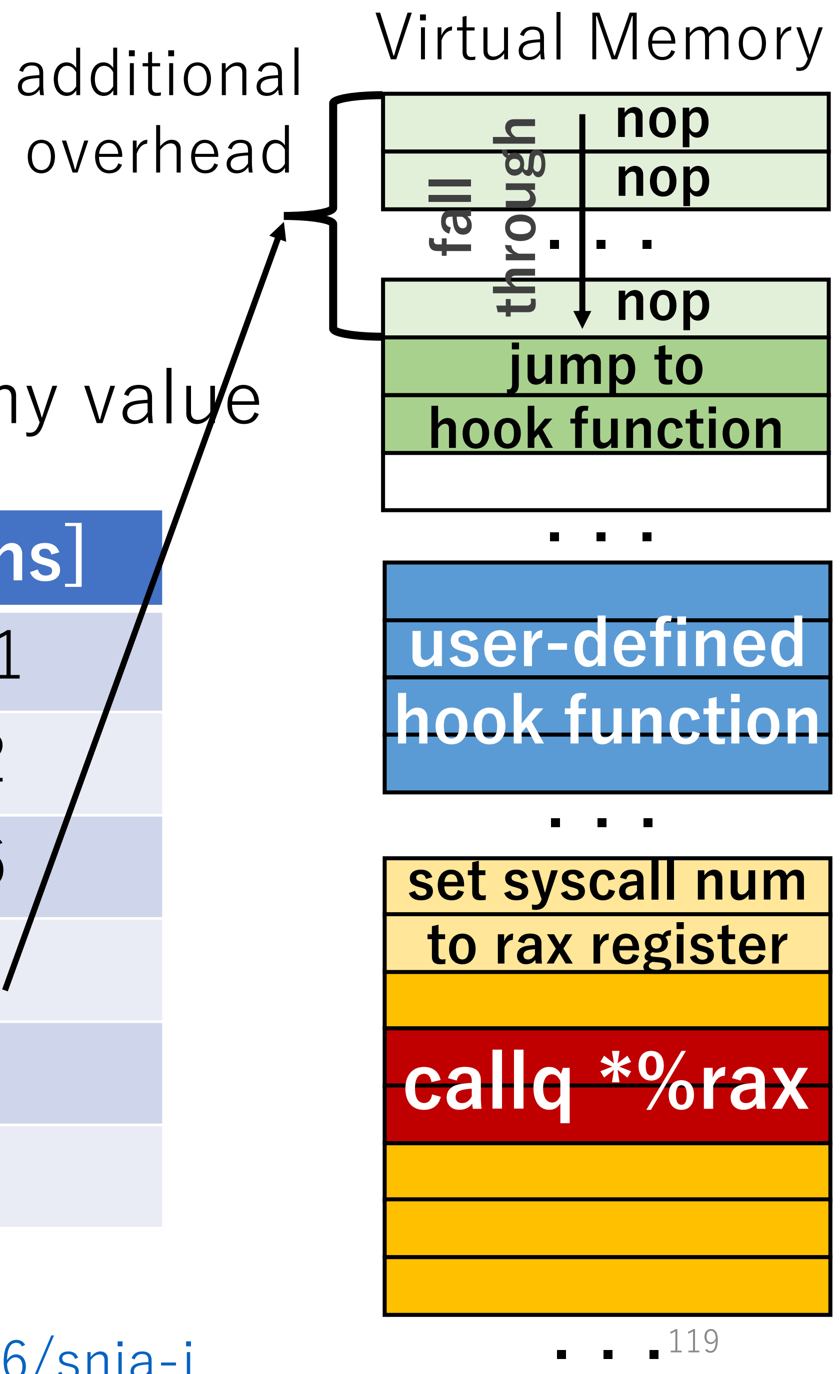
Summary

- zpoline: a system call hook mechanism
  - replaces syscall/sysenter with callq *%rax
  - instantiates the tram<u>poline</u> code at virtual address 0 (<u>z</u>ero)
- 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

最適化

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

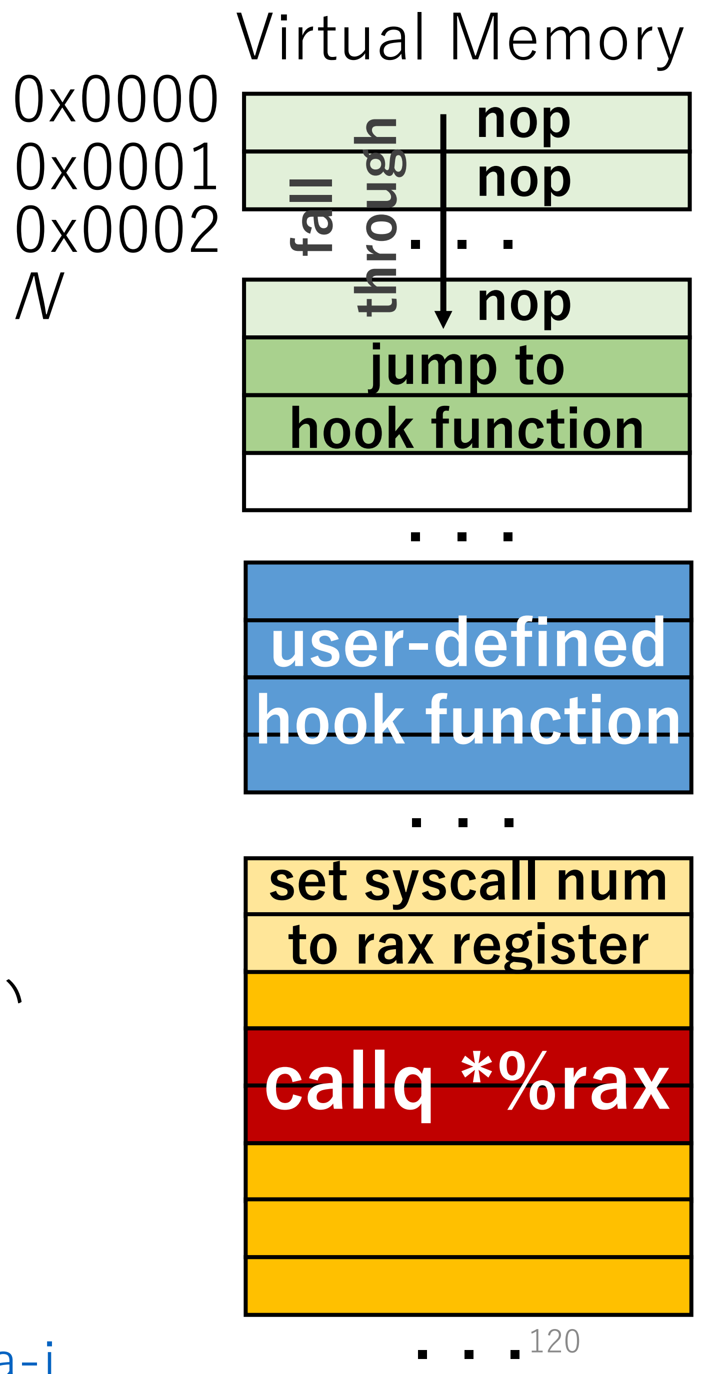
Mechanism	Time [ns]
ptrace	31201
int3 signaling	1342
SUD	1156
zpoline	41
zpoline (w/o NULL exec check)	40
LD_PRELOAD	6



https://github.com/yasukata/presentation/tree/gh-pages/2023/06/snia-j

最適化

- nop を敷き詰めている理由
  - jump してきたアドレスを命令の先頭と解釈する
- 目標
  - 0 ~ N どこに jump してもフック関数を呼び出すコードへ辿り着けるようにしたい
  - nop のように逐一実行する必要がなければなお良い



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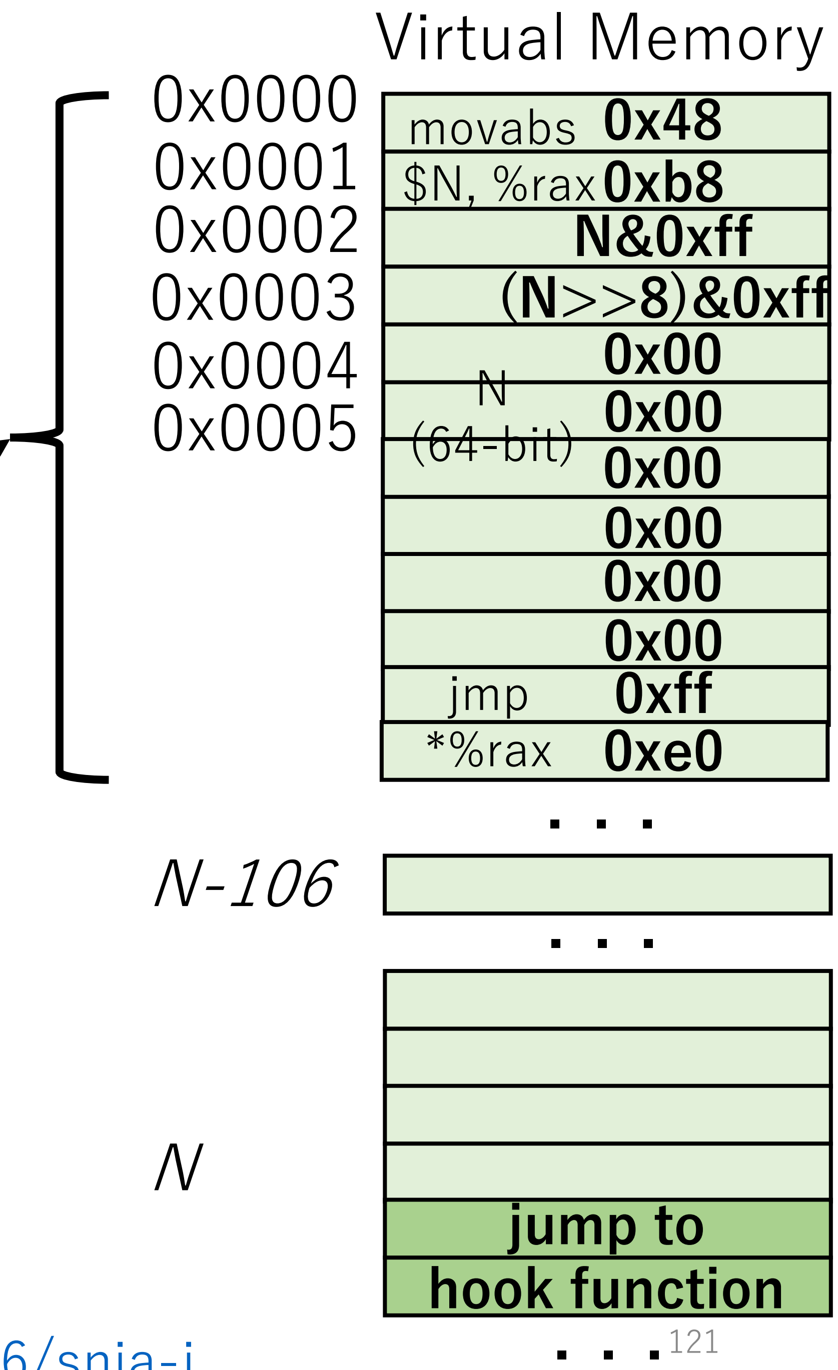
面倒なポイント

- 例えば、
  - rax に N を入れて
    - N < 512 として見てください
  - rax の値をアドレスとして jump

```
movabs $N, %rax
jmp *%rax
```



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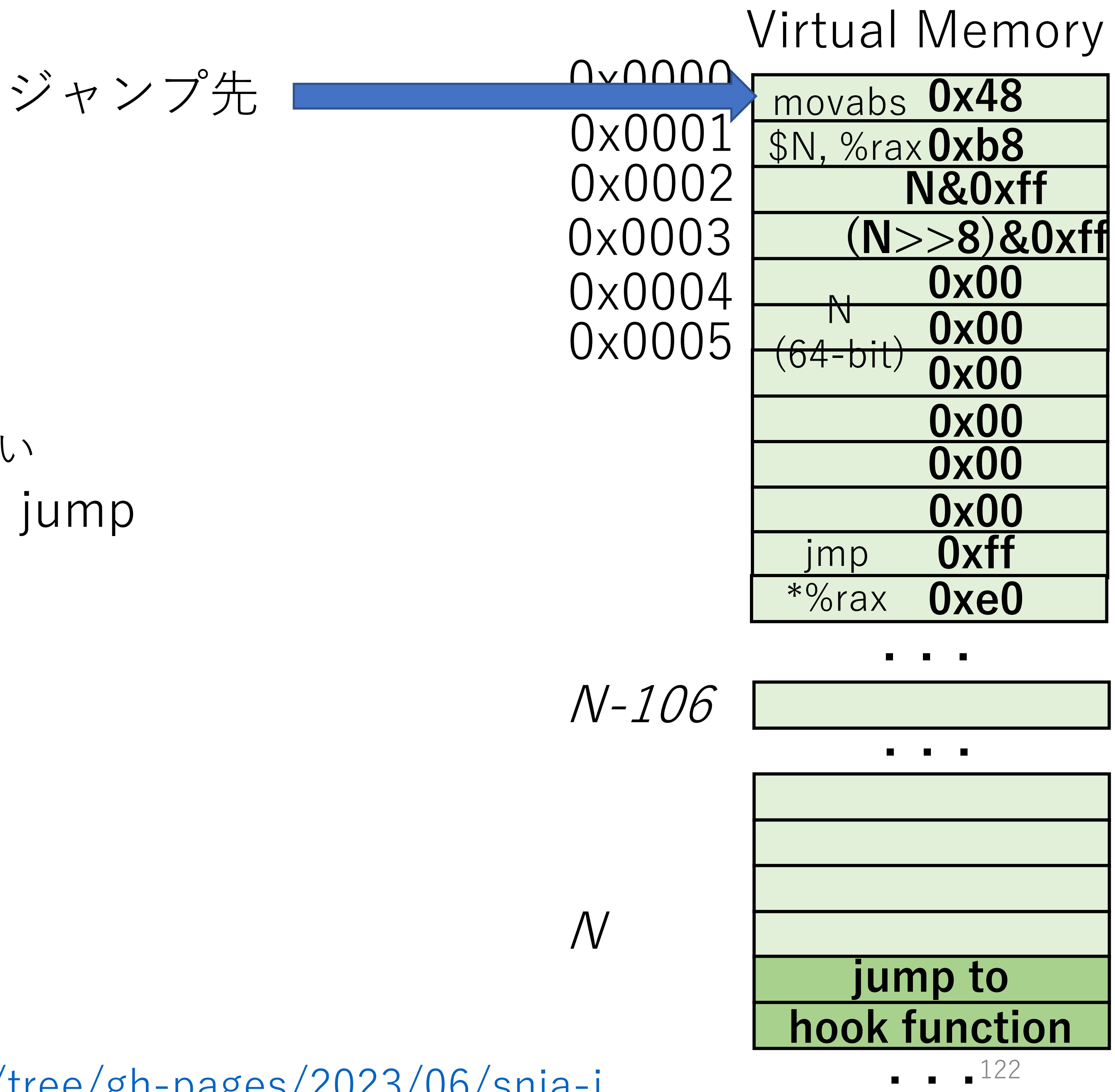

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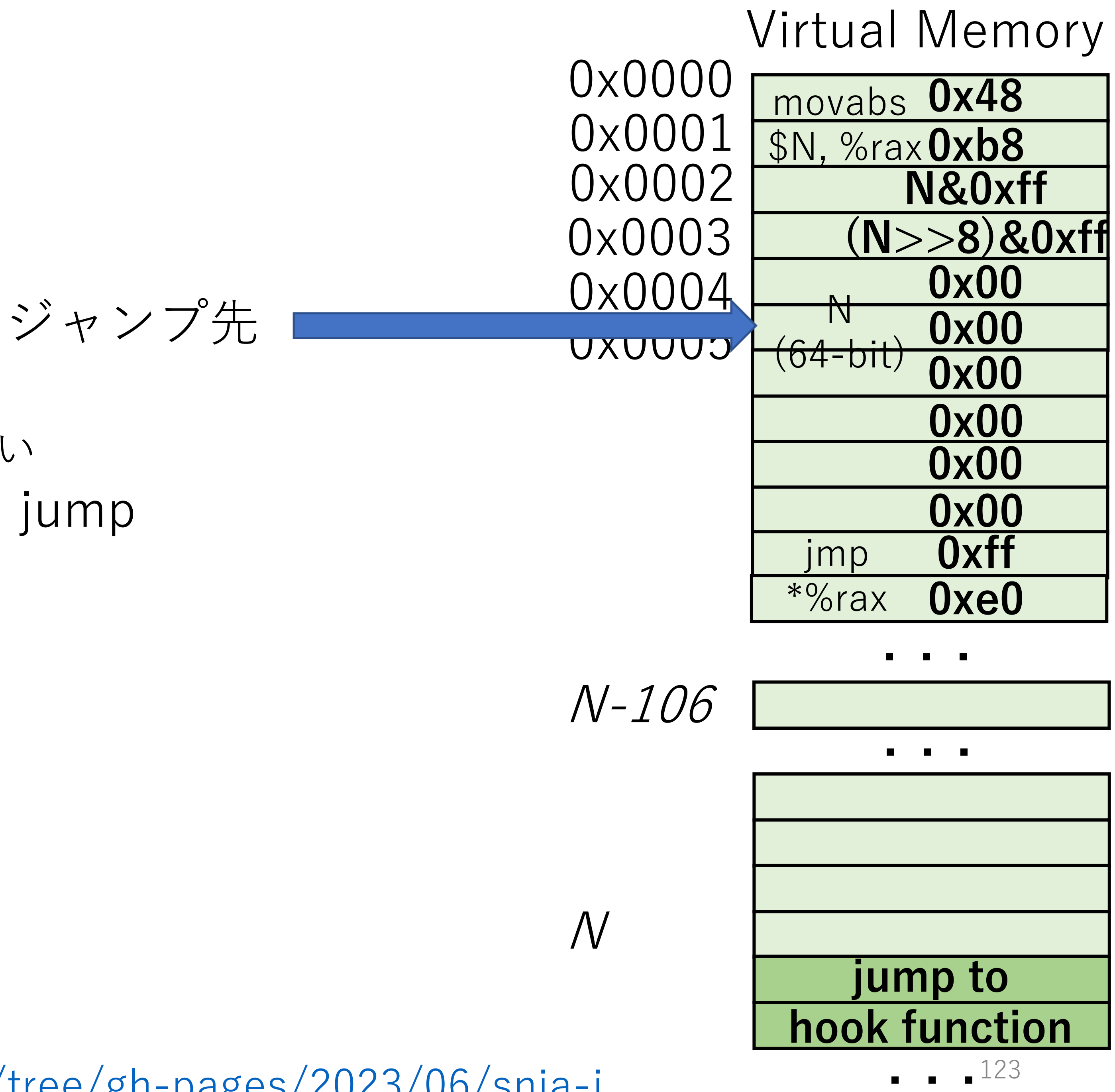

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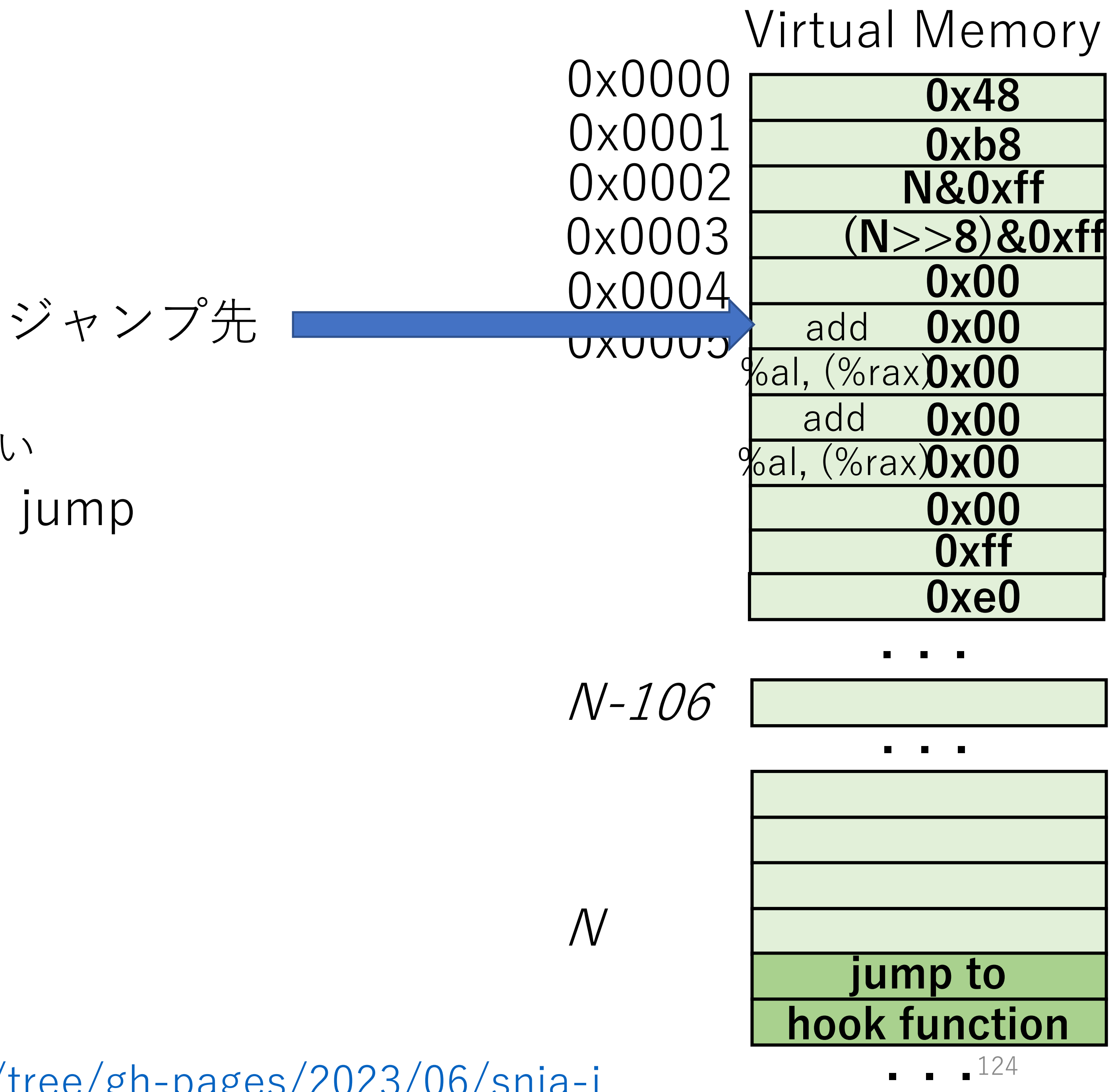
add %al, (%rax)



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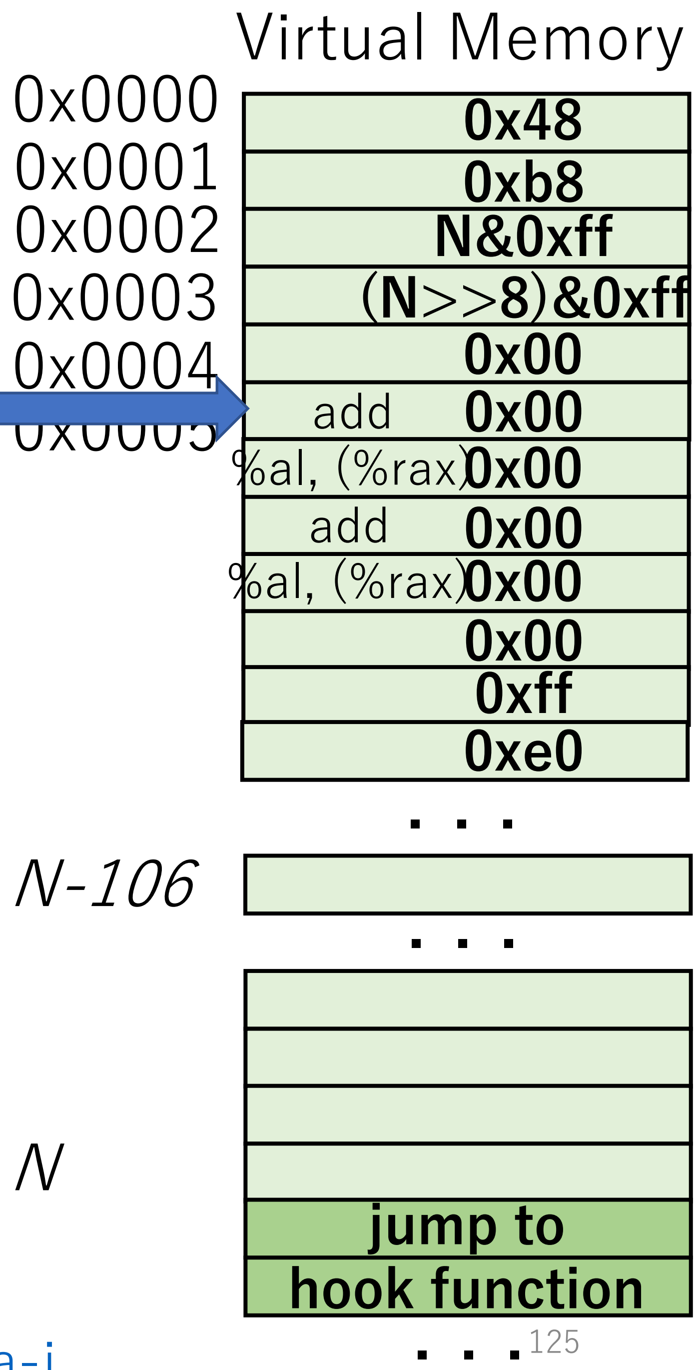
ジャンプ先



add %al, (%rax)

<u>ジャンプ先のアドレスが命令の先頭と解釈される</u>

https://github.com/yasukata/presentation/tree/gh-pages/2023/06/snia-j

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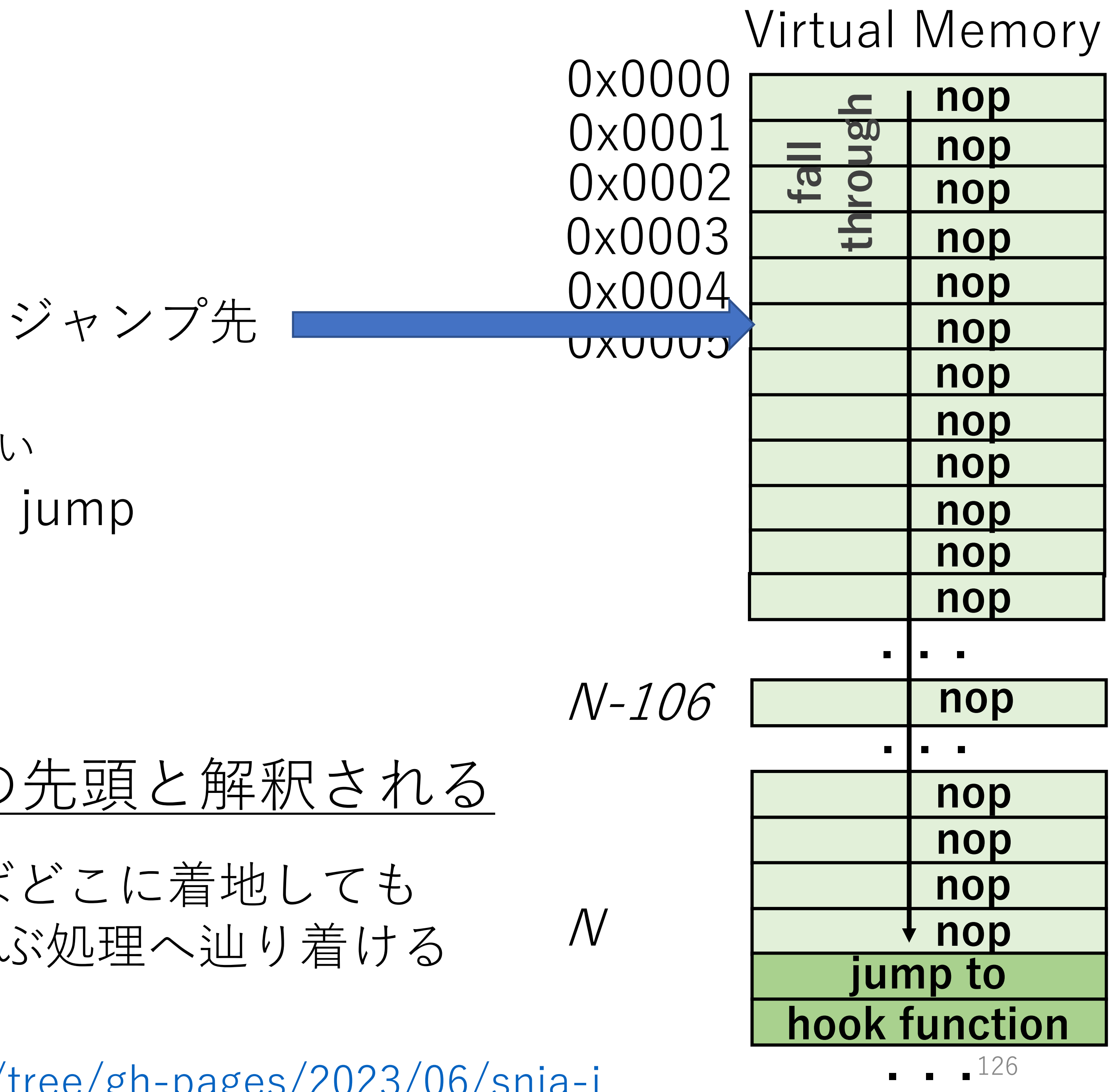


add %al, (%rax)

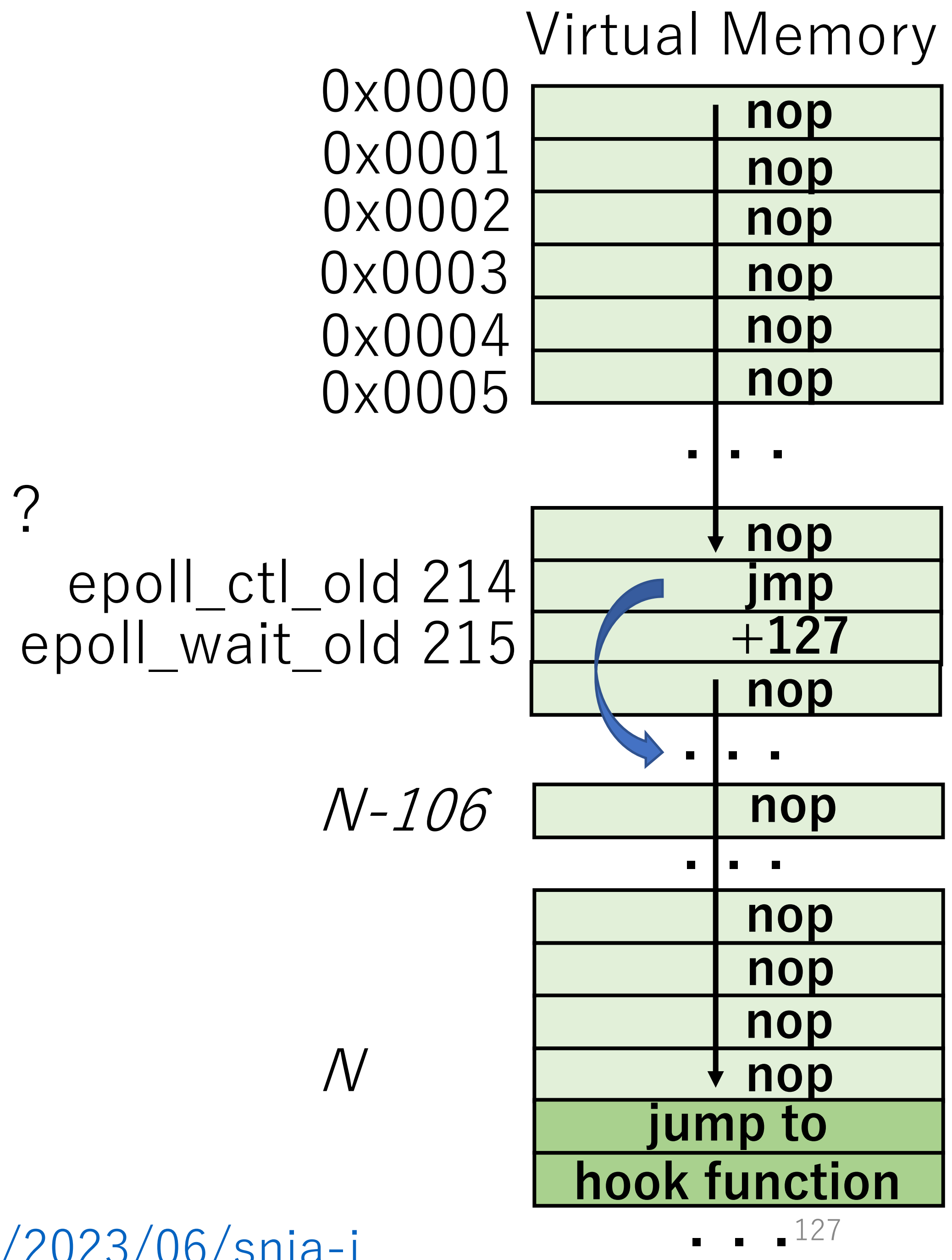
<u>ジャンプ先のアドレスが命令の先頭と解釈される</u>

1 byte の nop 命令で埋めておけばどこに着地しても
同じ命令と解釈され、フックへ飛ぶ処理へ辿り着ける

https://github.com/yasukata/presentation/tree/gh-pages/2023/06/snia-j

最適化 v1

- 匿名レビュアー C
  - 使われていないシステムコール番号に short jump 命令を入れたら良いのでは？
    - 0xeb 127 : +127 バイトジャンプ



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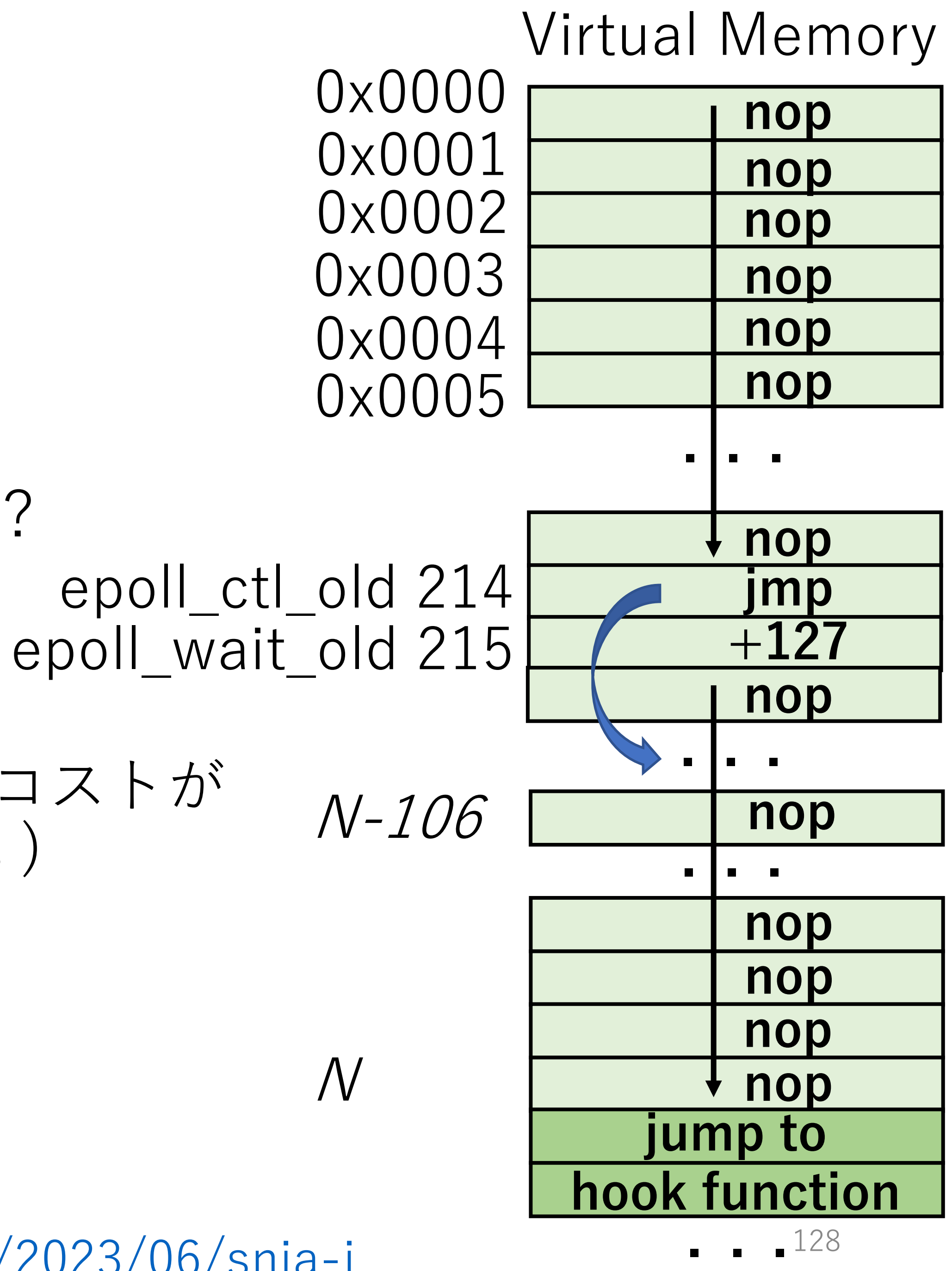
    - 0xeb 127 : +127 バイトジャンプ
  - epoll_ctl_old / epoll_wait_old に
    short jump 命令を埋め込むとフックのコストが
    31 ns まで削減できた（これまで 41 ns）

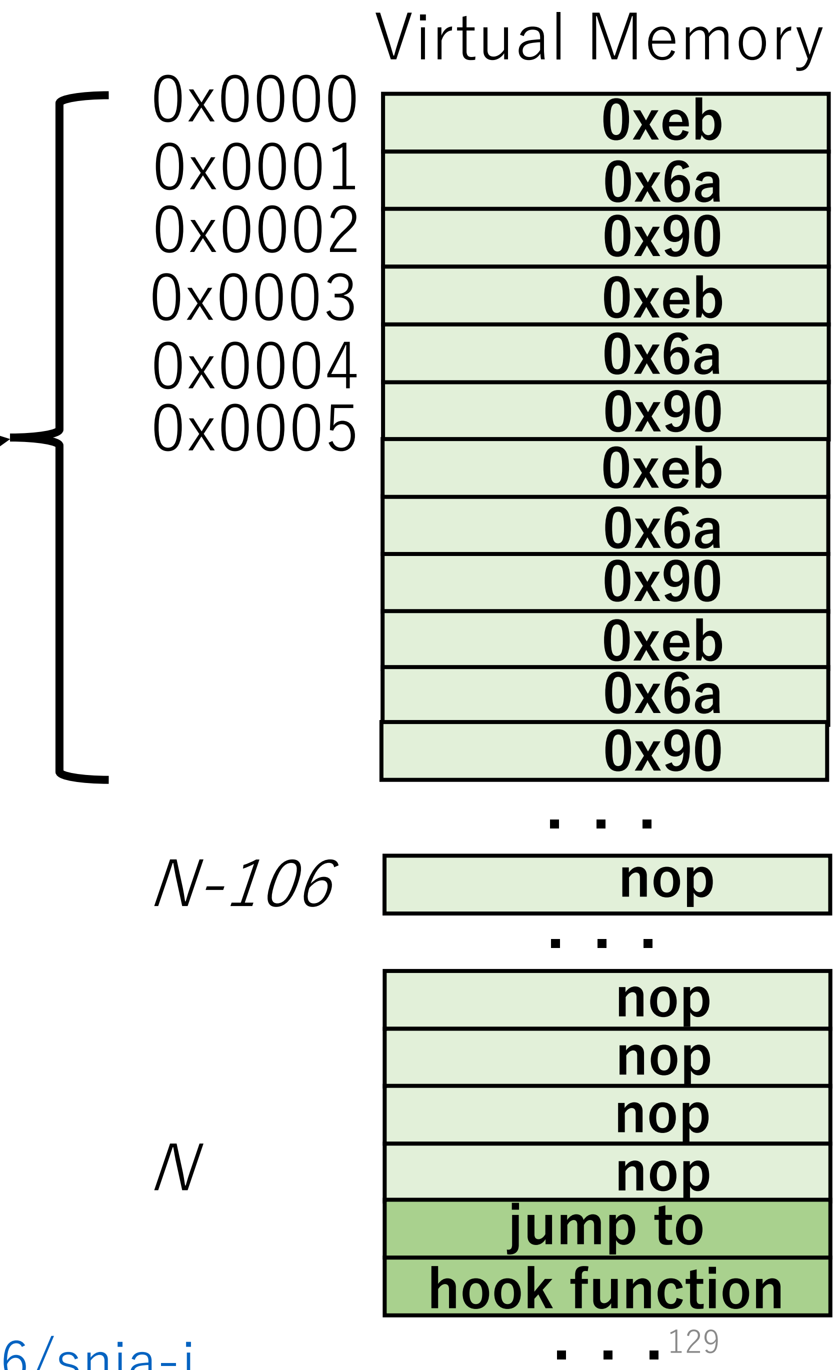


https://github.com/yasukata/presentation/tree/gh-pages/2023/06/snia-j

最適化 v2

- もうちょっとたくさん飛びたい

0xeb 0x6a 0x90
を繰り返す



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- この場合、命令の解釈は３通り
  - n * 3 + 0 : 0xeb 0x6a 0x90
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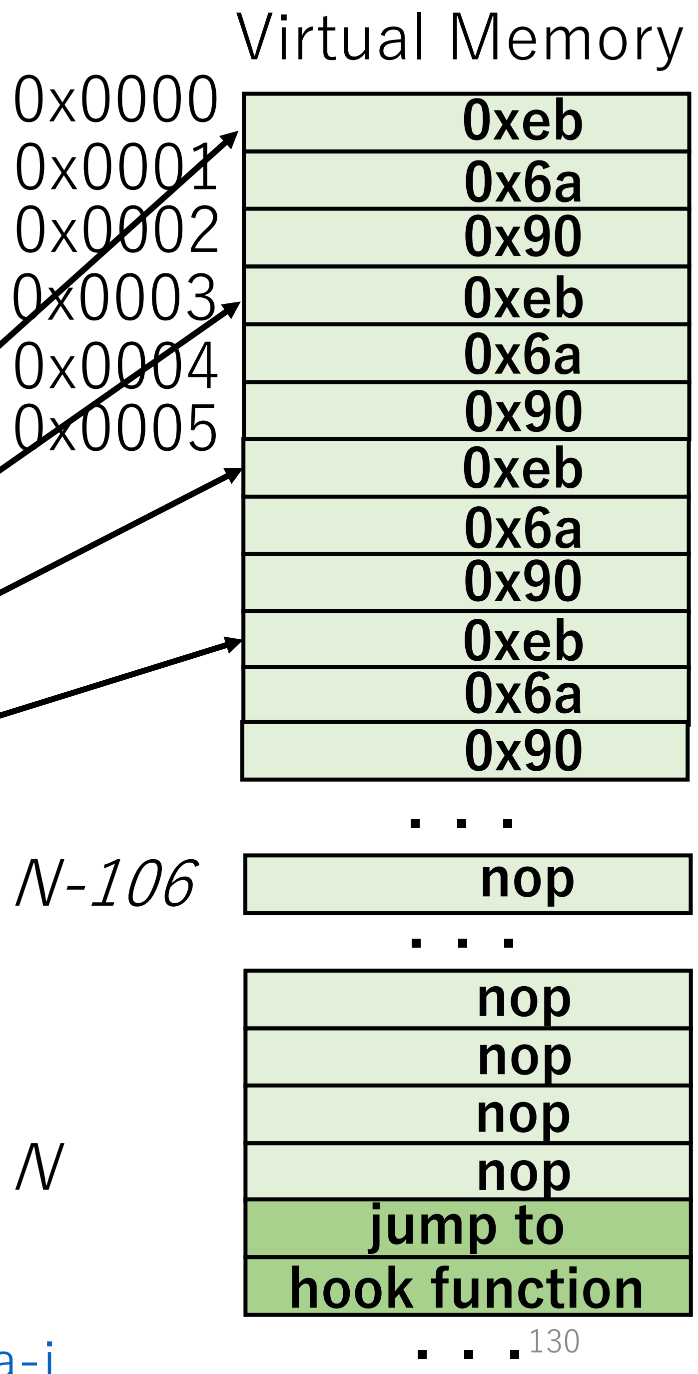
  - n * 3 + 2 : 0x90 0xeb 0x6a



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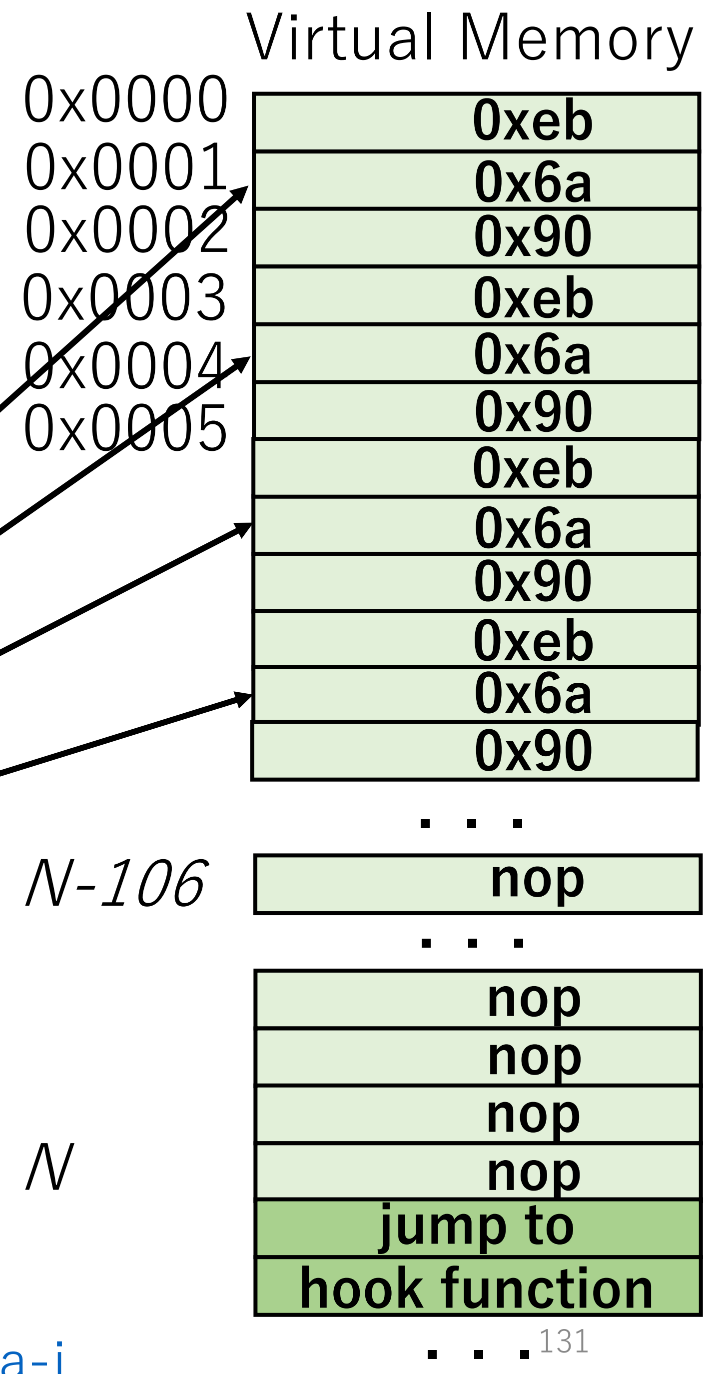

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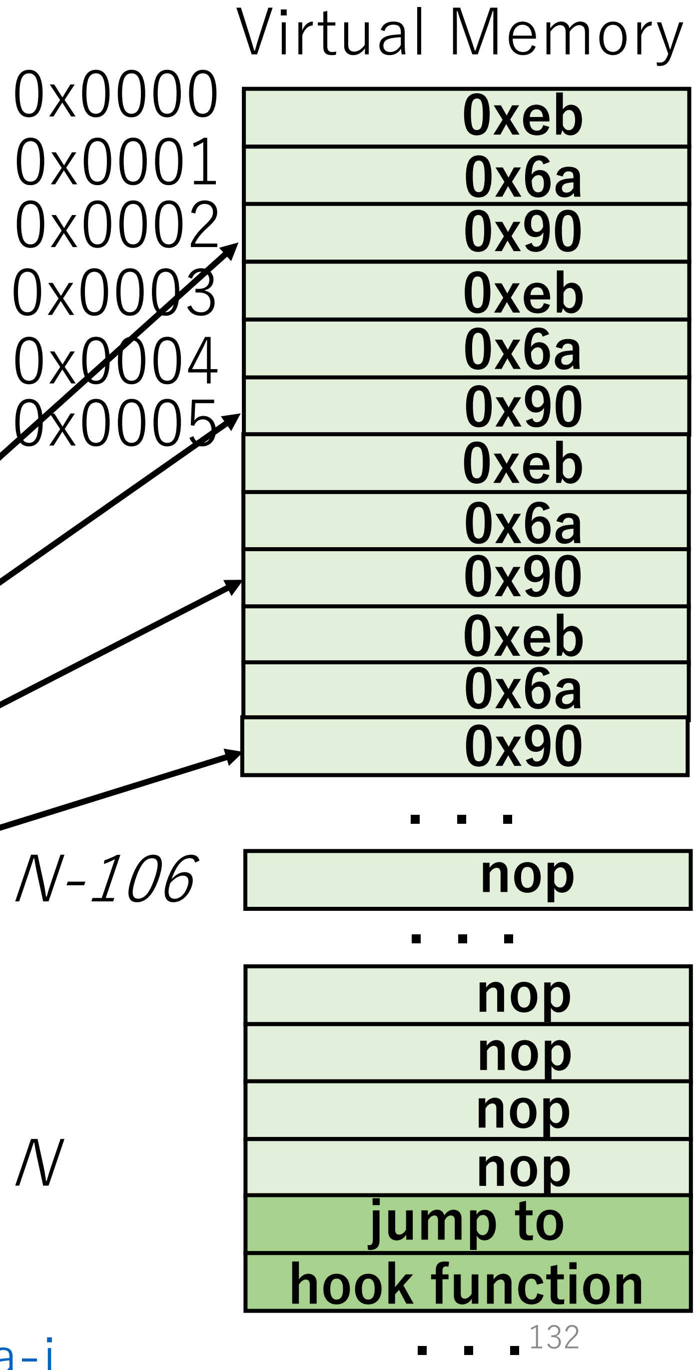

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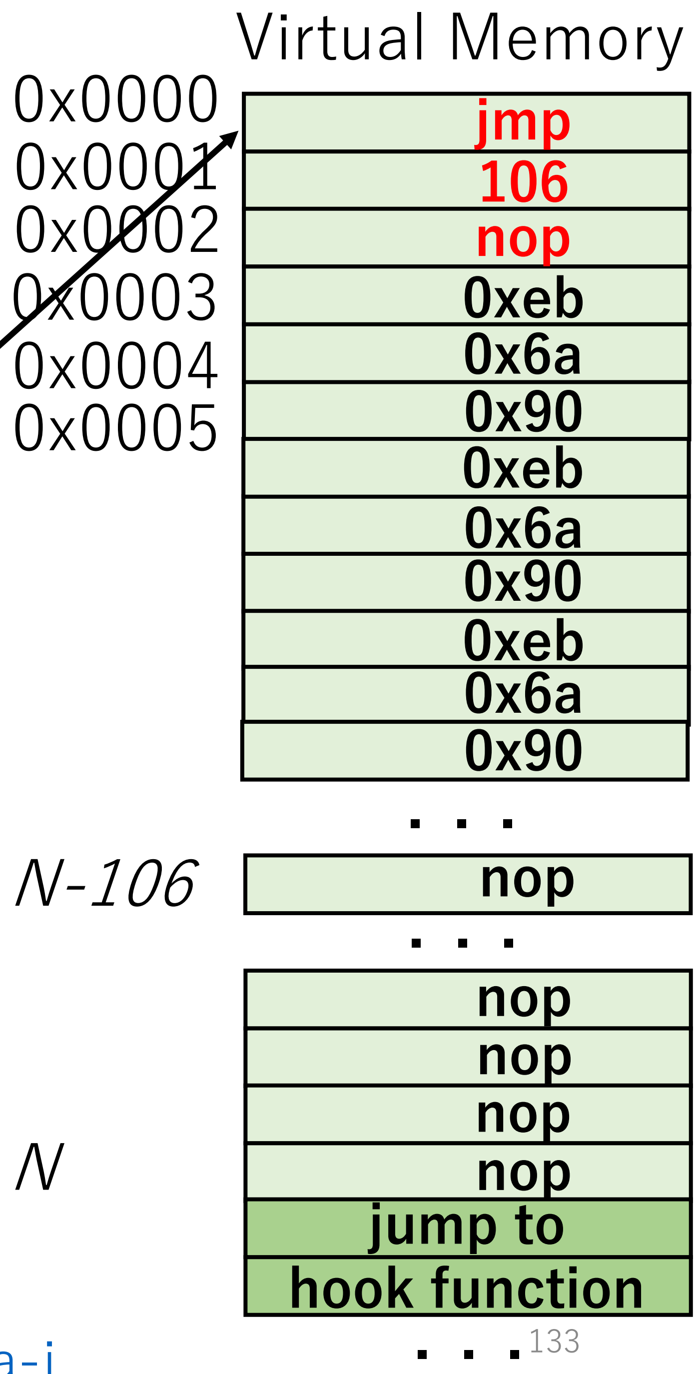

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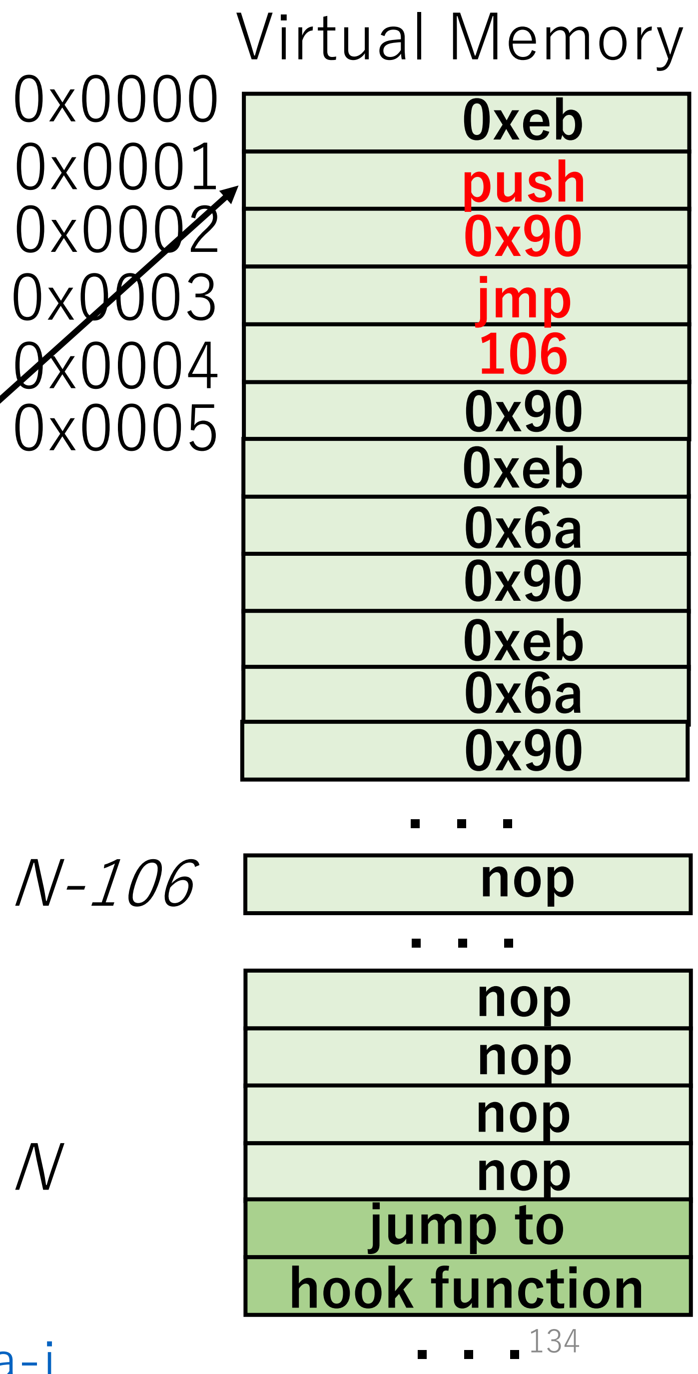

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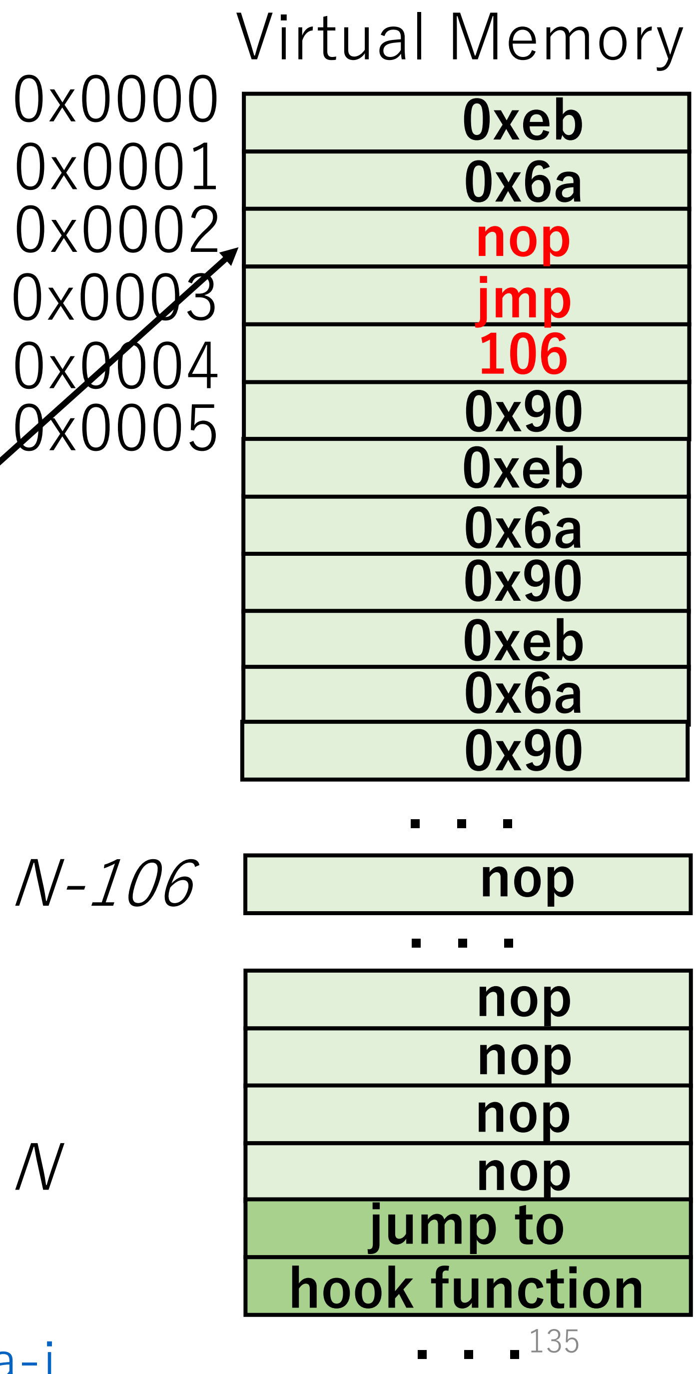

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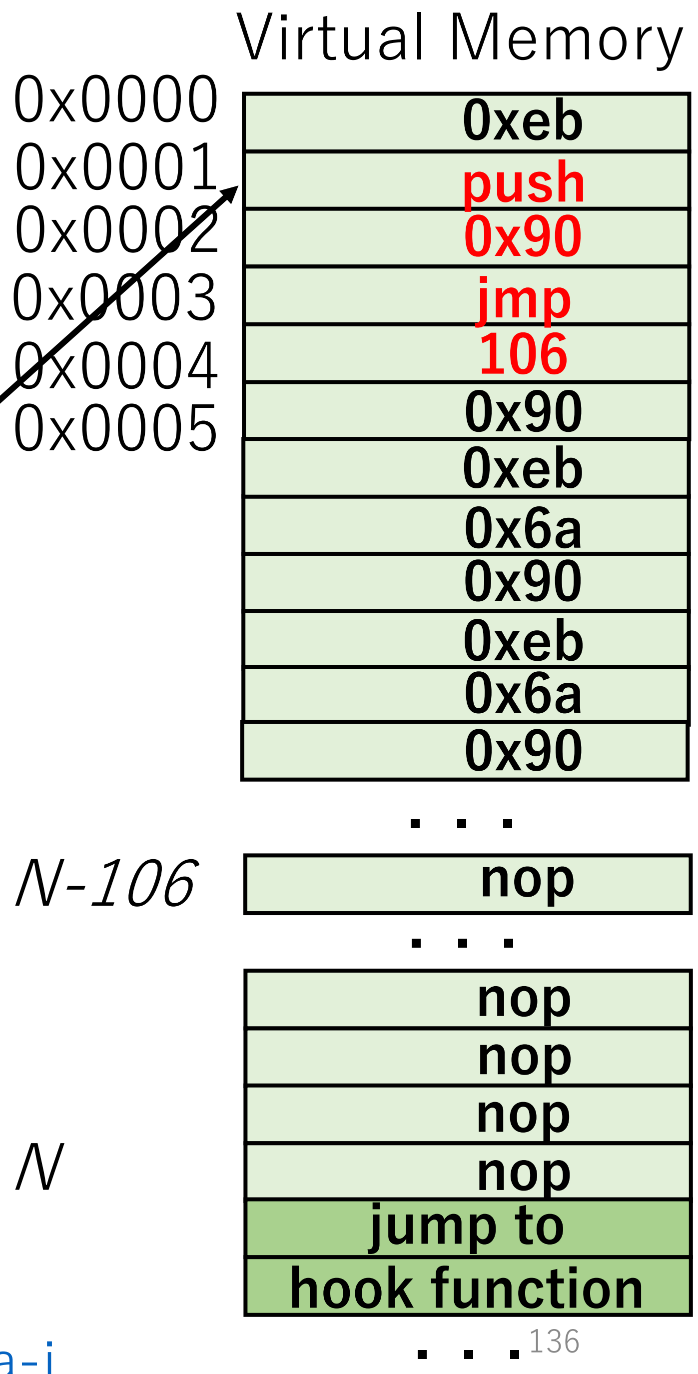
この場合だけ 0x90 がスタックに積まれてしまうので
フック関数の中で捨てるようにする



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最適化 v2

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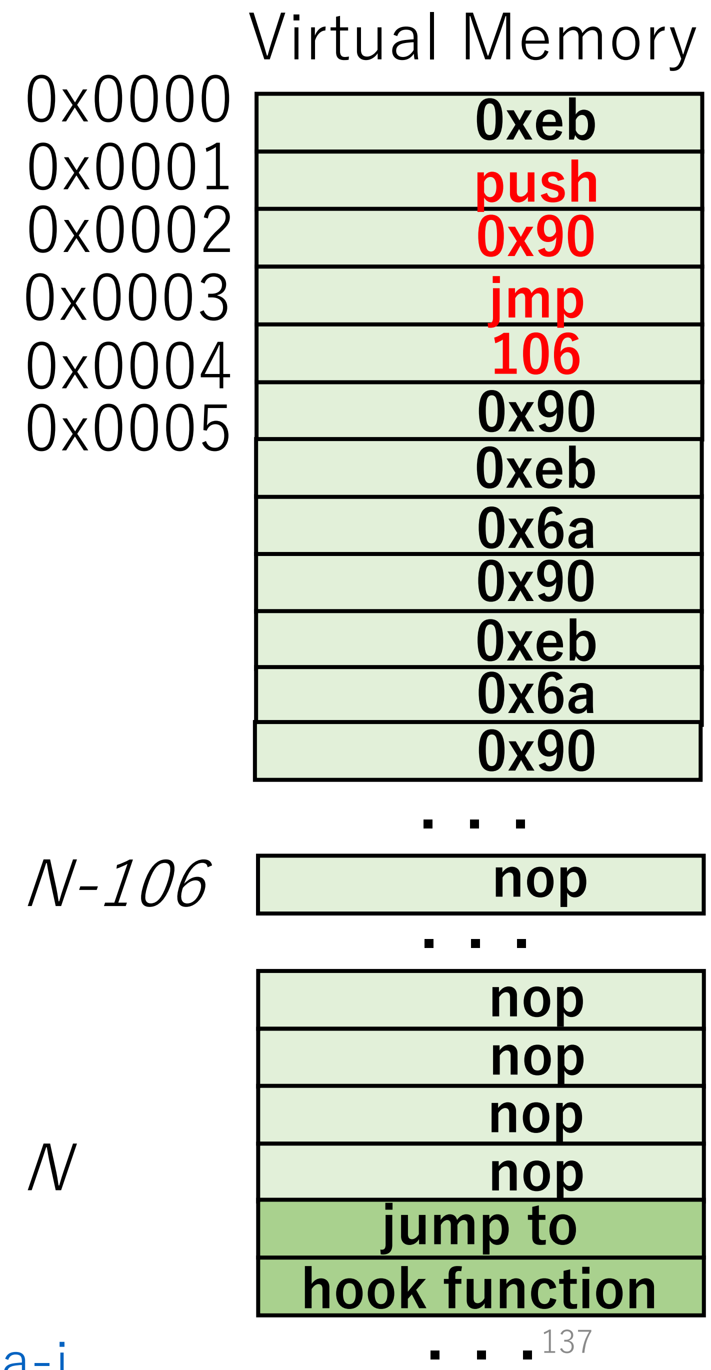
を繰り返す

- この最適化を適用後、フックのコストが 10 ns まで減少（v1 は 31 ns）



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