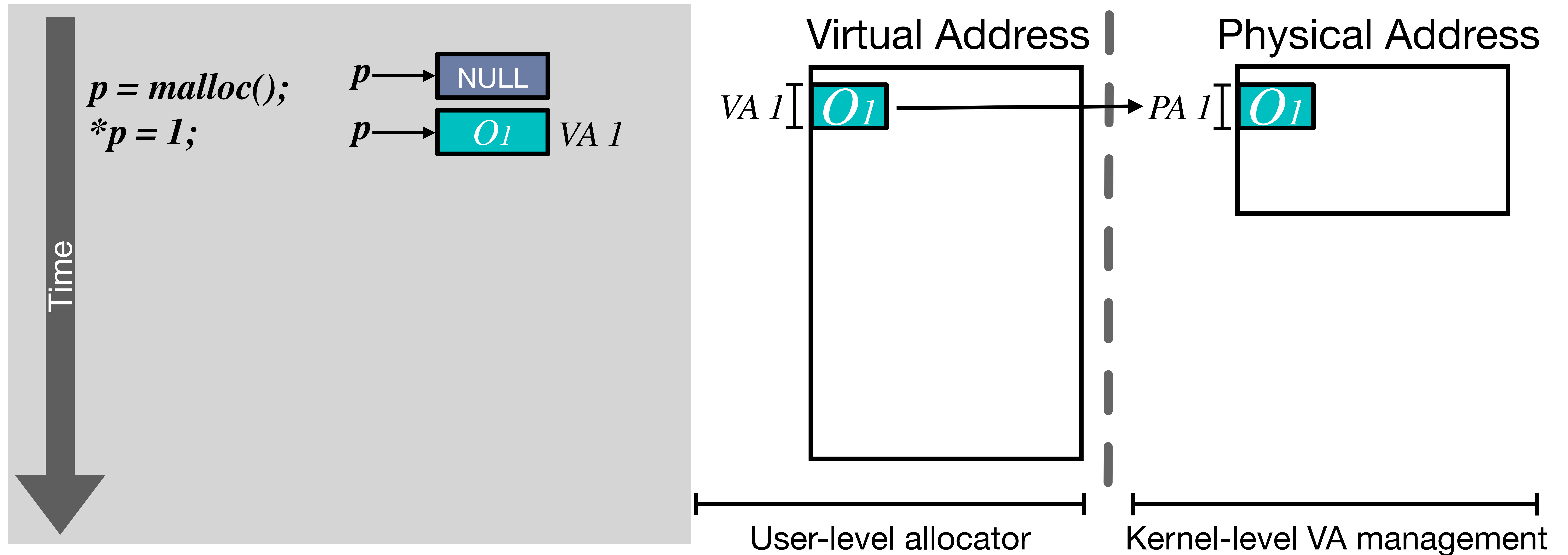
BUDAlloc: Defeating Use-After-Free Bugs by Decoupling Virtual Address Management from Kernel

Junho Ahn, Jaehyeon Lee, Kanghyuk Lee, Wooseok Gwak, Minseong Hwang, Youngjin Kwon

USENIX Security 2024

Use After Free



- Memory allocator assigns a virtual address, mapping virtual address to a physical address

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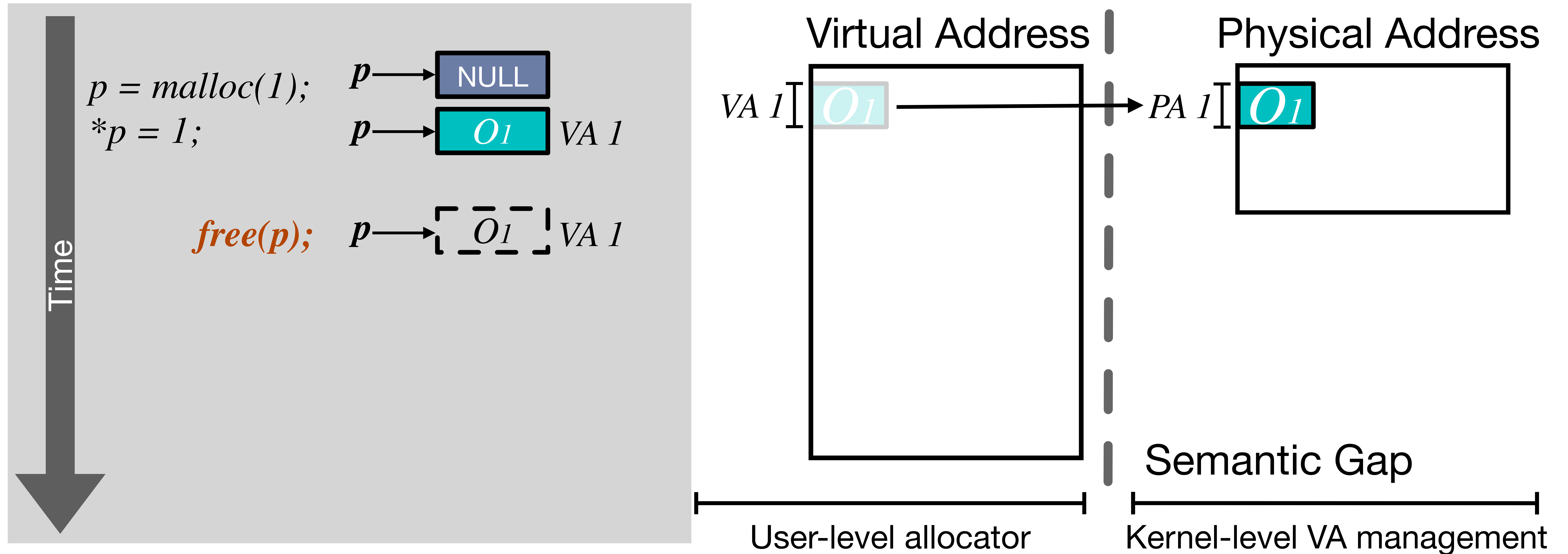
Use After Free



- Memory allocator assigns a virtual address, mapping virtual address to a physical address
- After freeing, the memory allocator retrieves the allocated virtual address

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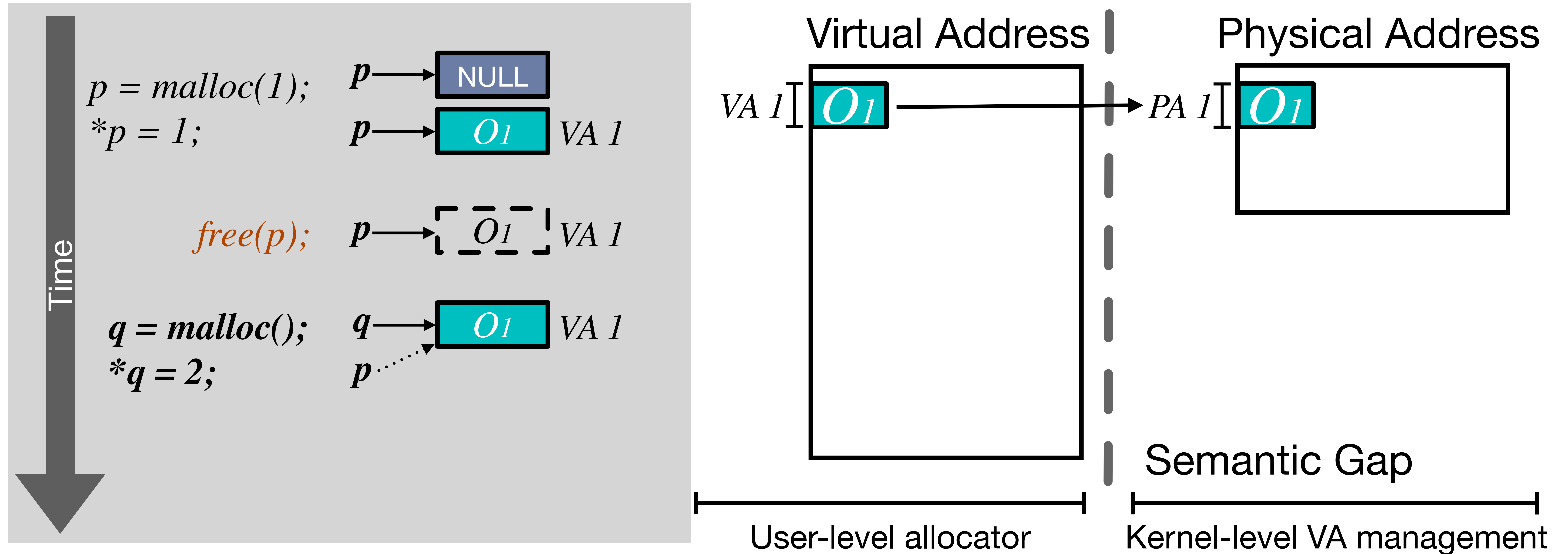

- Use-after-free occurs when program access freed memory
- Attackers can control this freed memory, incurring various malicious behaviors

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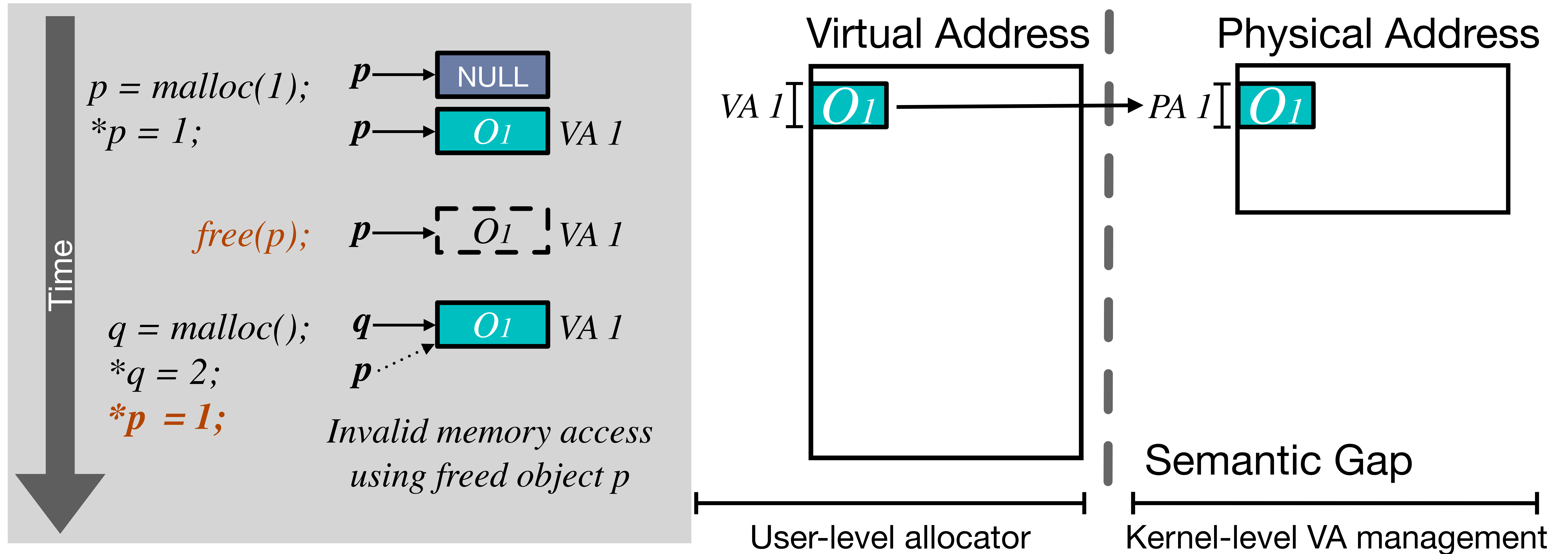

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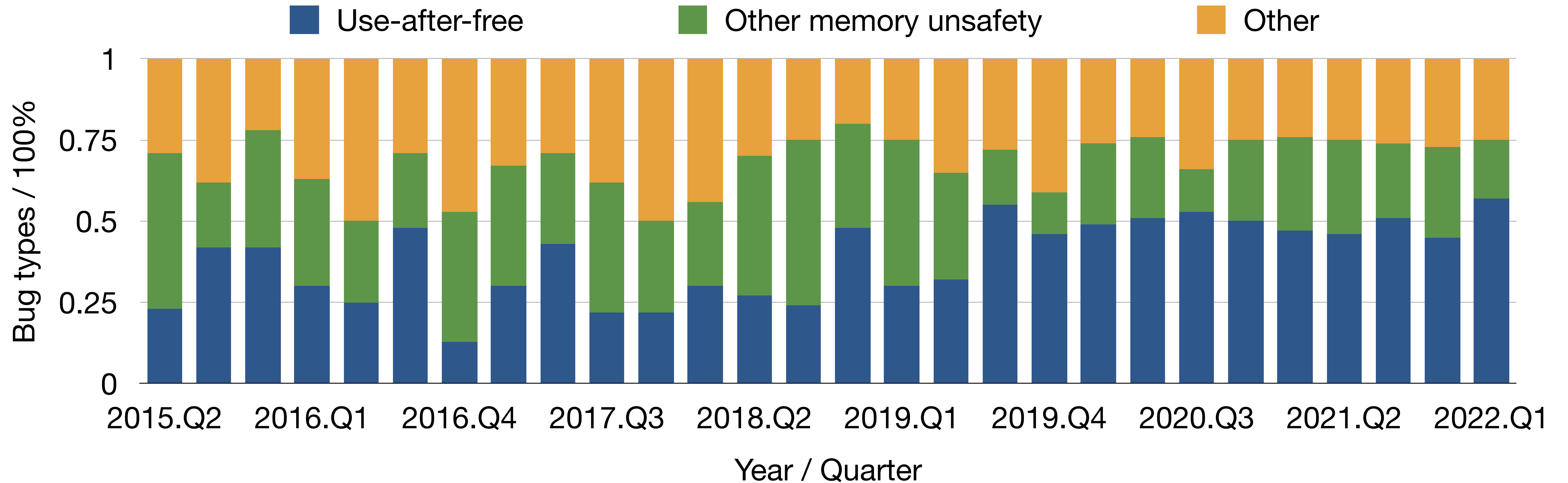

Over 50% of the high-severity bugs discovered in Google Chrome were due to UAF

How to detect and prevent a UAF bug in a C or C++ program?

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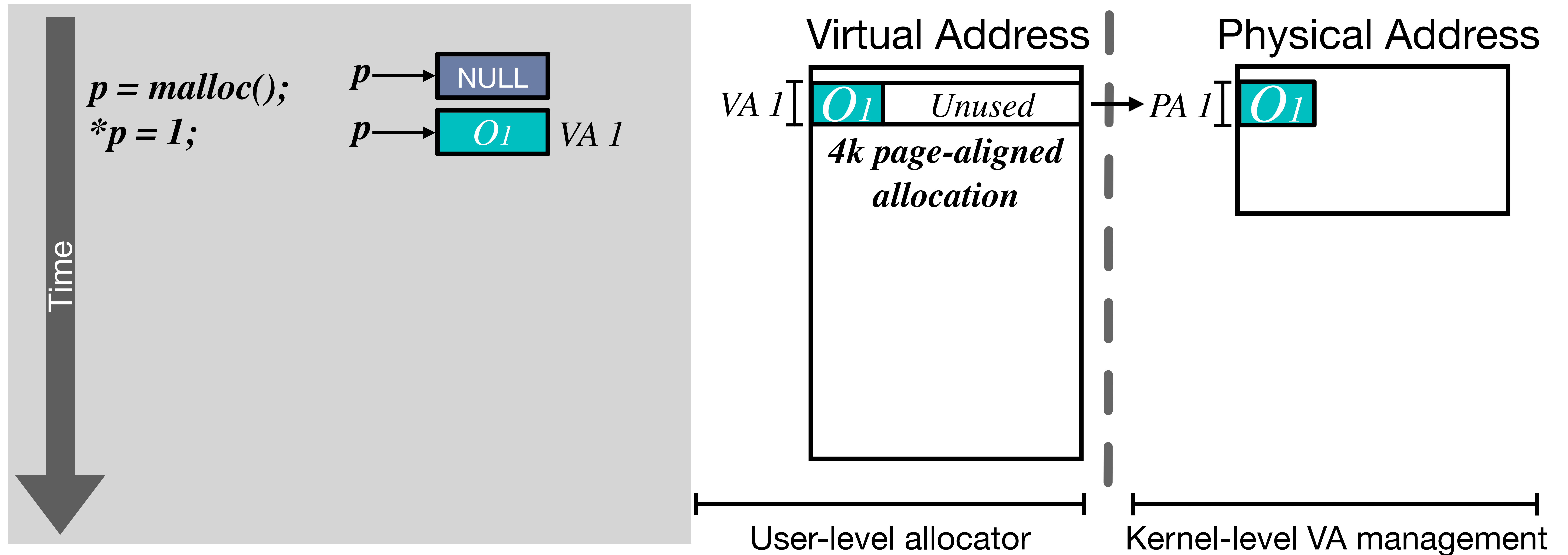
One Time Allocator - Detecting UAF Bugs



- OTA assigns an object on the single **page-aligned memory**

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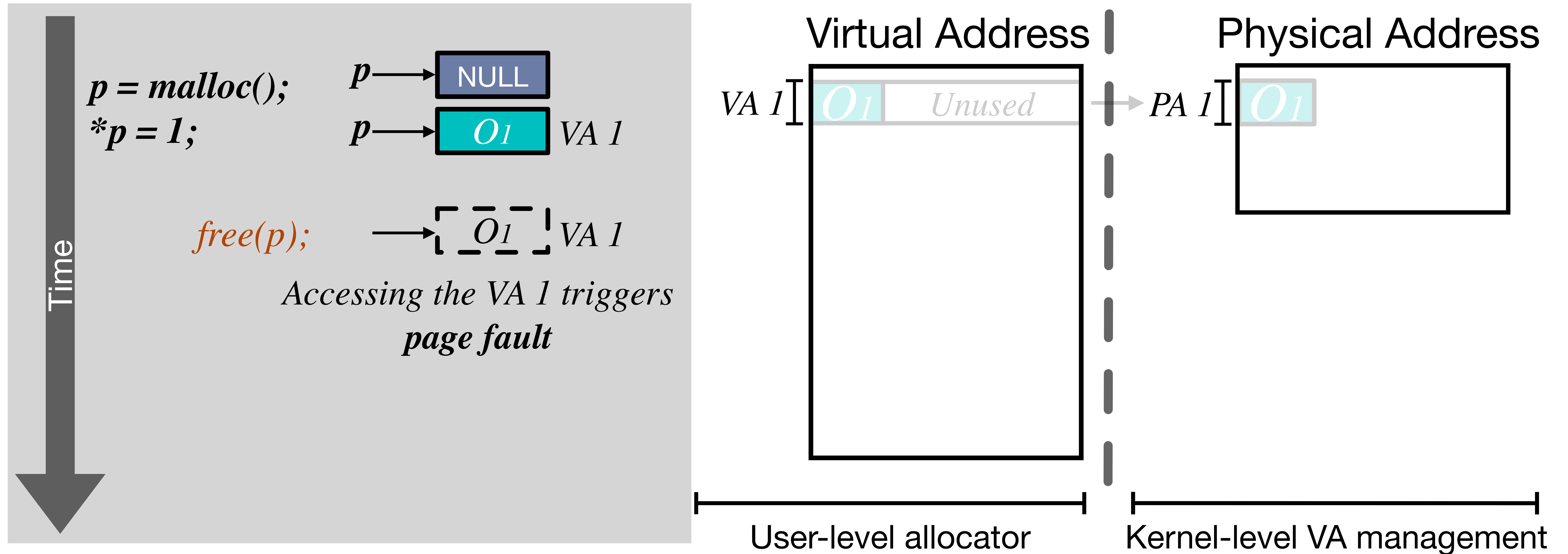
One Time Allocator - Detecting UAF Bugs



- After free the object, OTA removes the mapping **from the page table**
- Accessing the freed object triggers **page-fault**, which **detects** UAF bug

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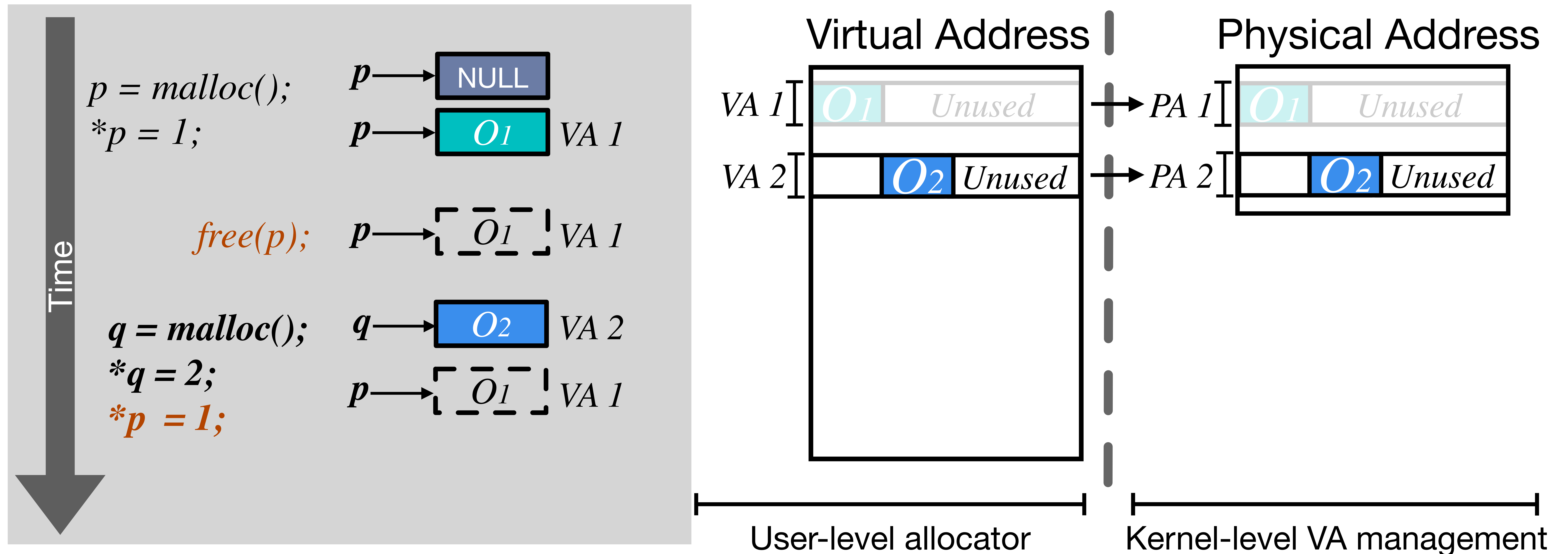
One Time Allocator - Detecting UAF Bugs



- OTA assigns objects on the virtual address **that has not been previously assigned**
- Ensuring that the deallocated object's address is not reused

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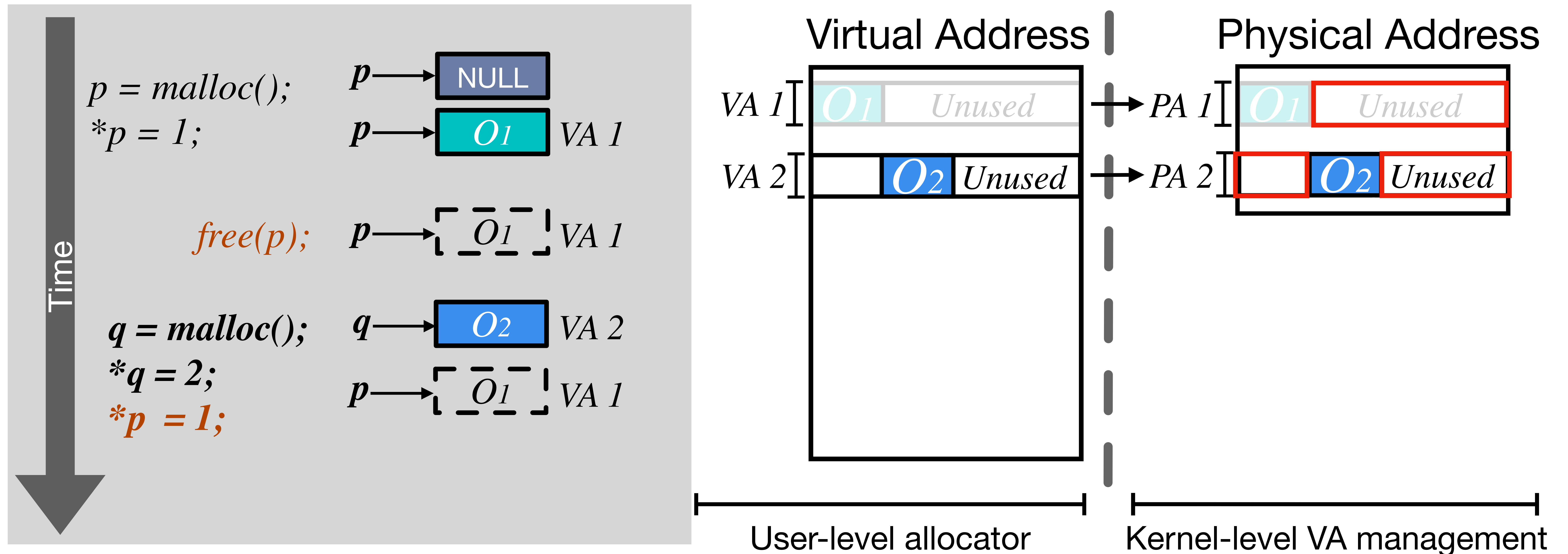
One Time Allocator - Detecting UAF Bugs



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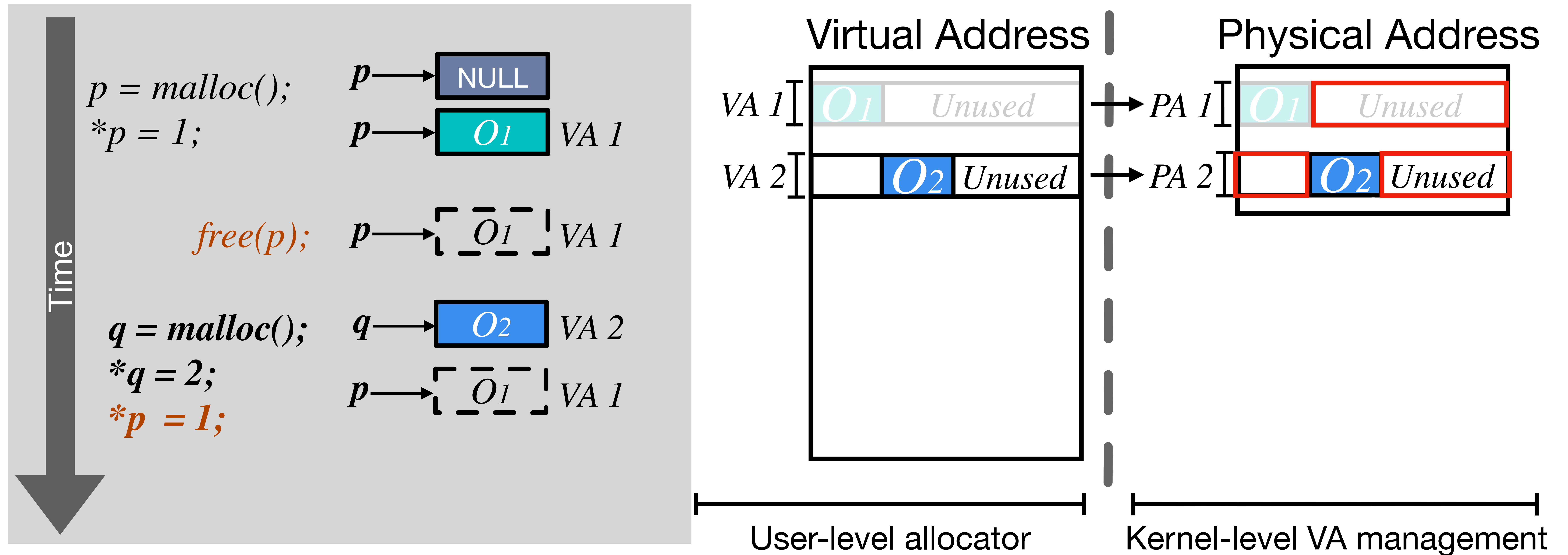

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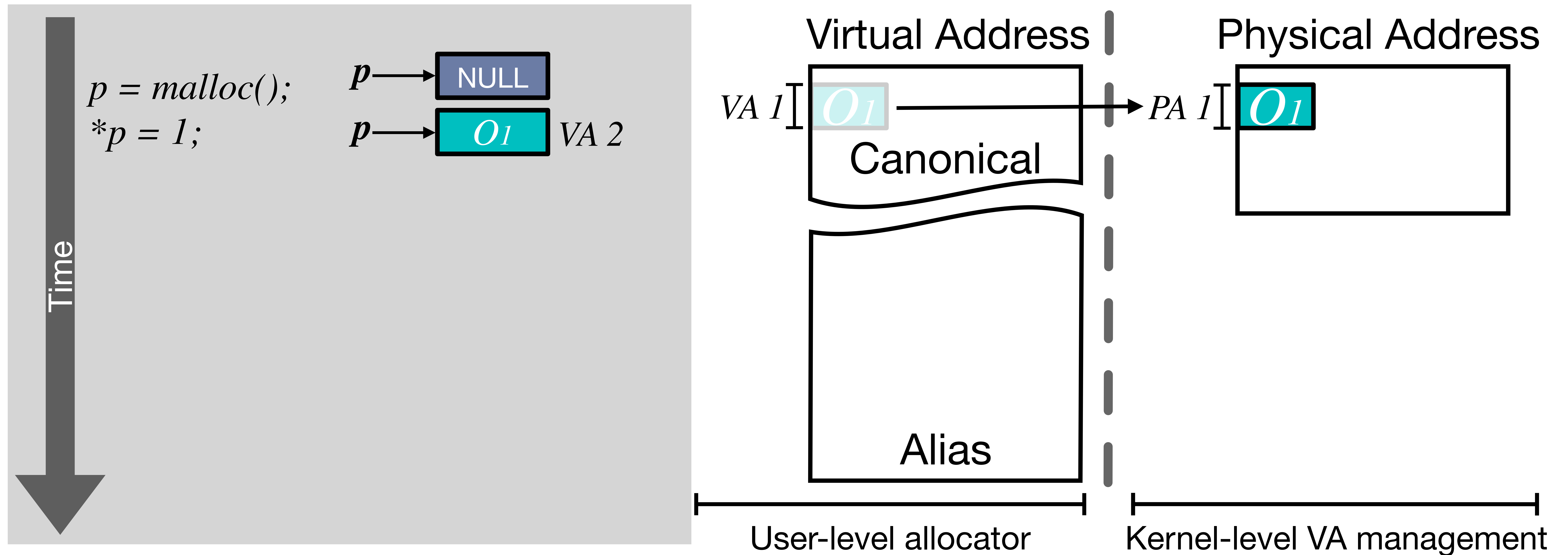
Incurs high memory overheads

One Time Allocator - Alias Mapping



- Alias: **Non-overlapping** VA used by **application**, Canonical: VA used by **allocator**

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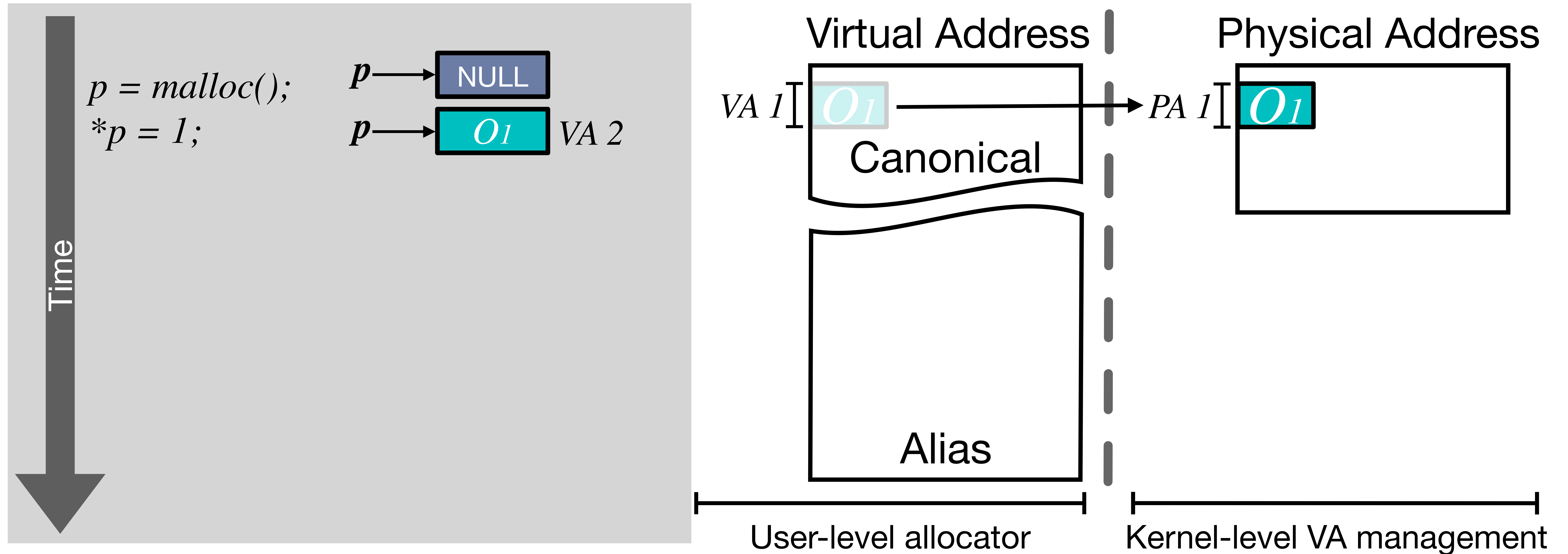

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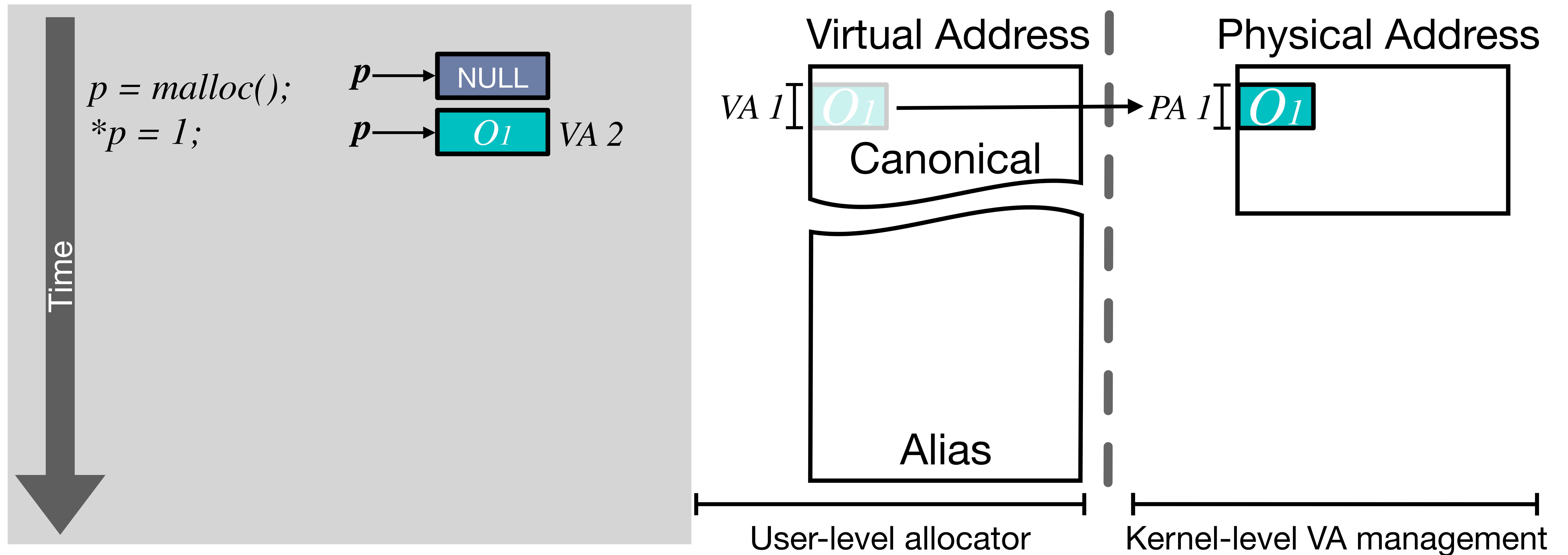

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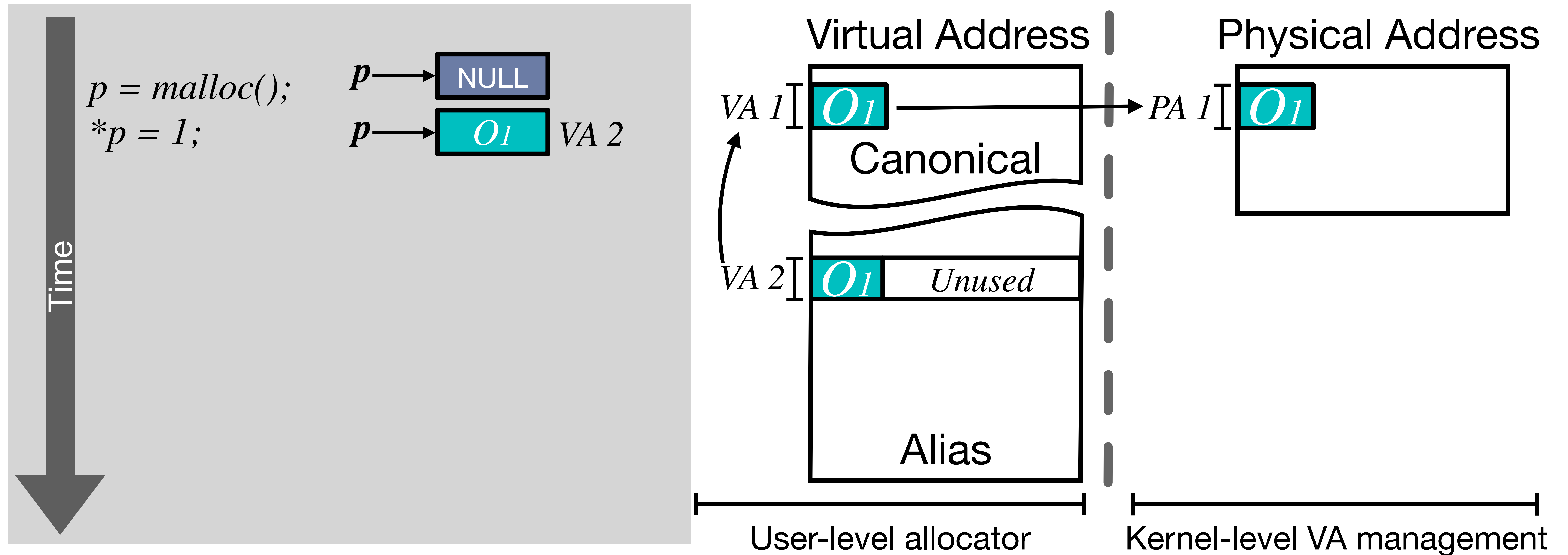

- Alias: **Non-overlapping** VA used by **application**, Canonical: VA used by **allocator**
- OTA maps **multiple page-aligned alias address to canonical address**

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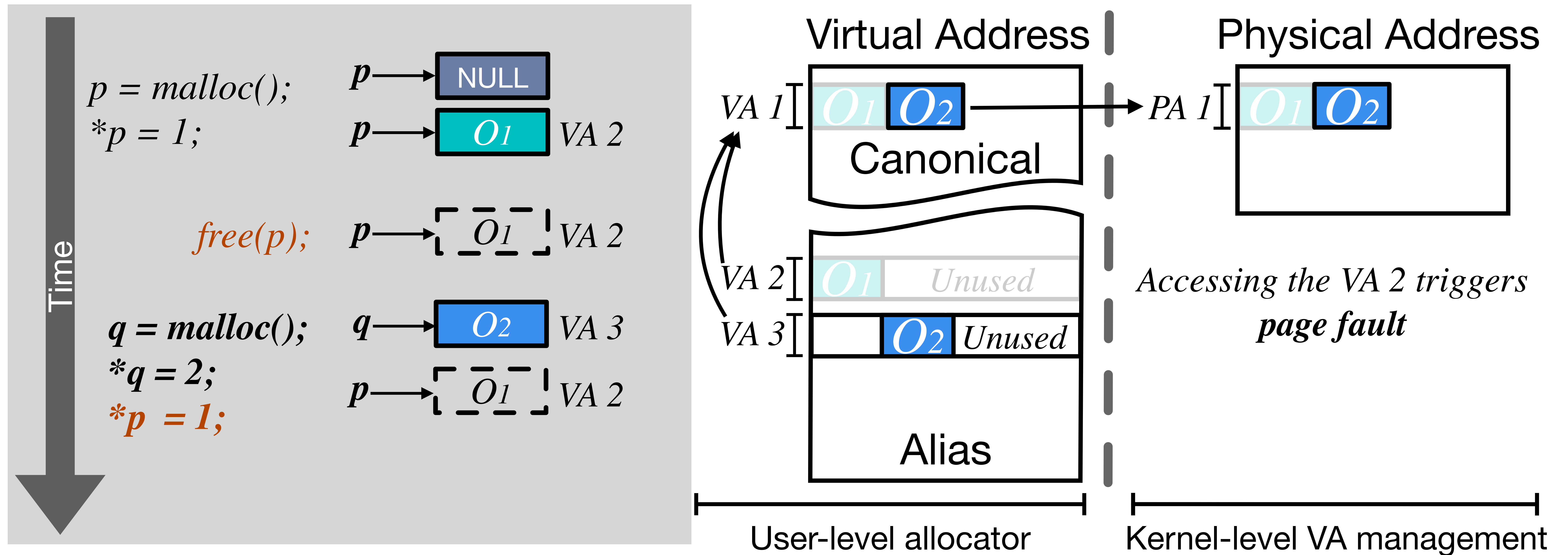

- Alias mapping reuses the freed canonical address, thus **reduce the memory overheads**
- Despite the reuse, alias mapping still can **detect** UAF bugs

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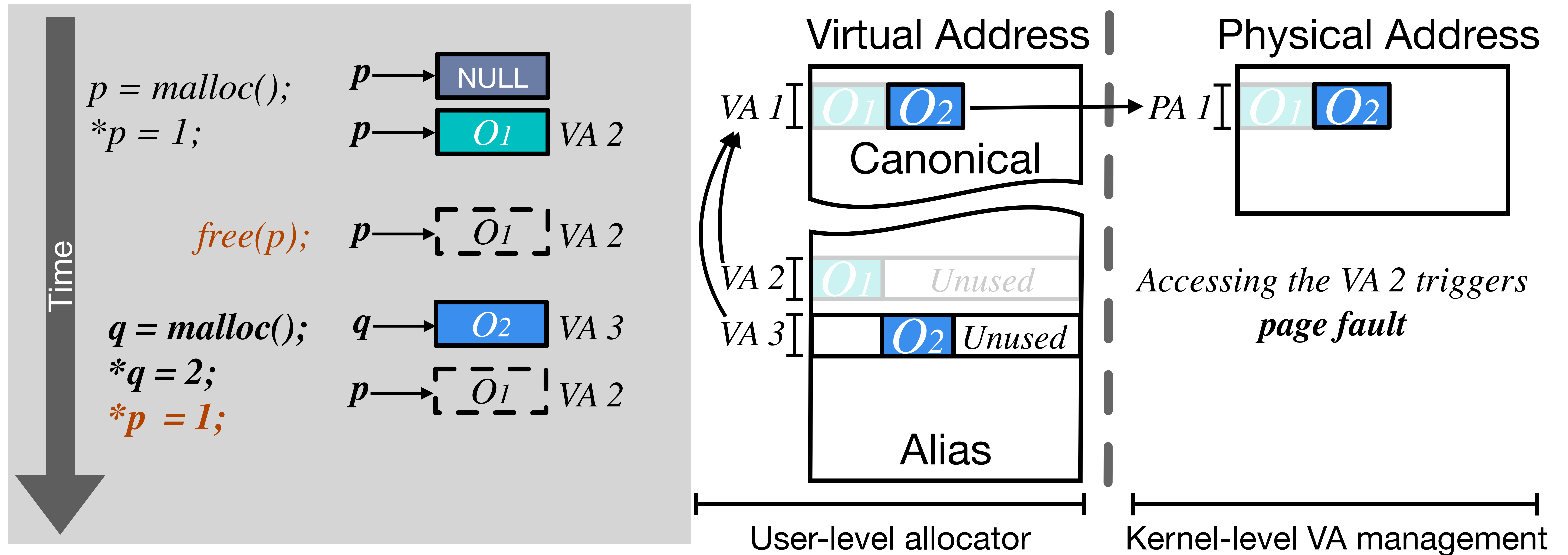

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Incurs high performance overheads

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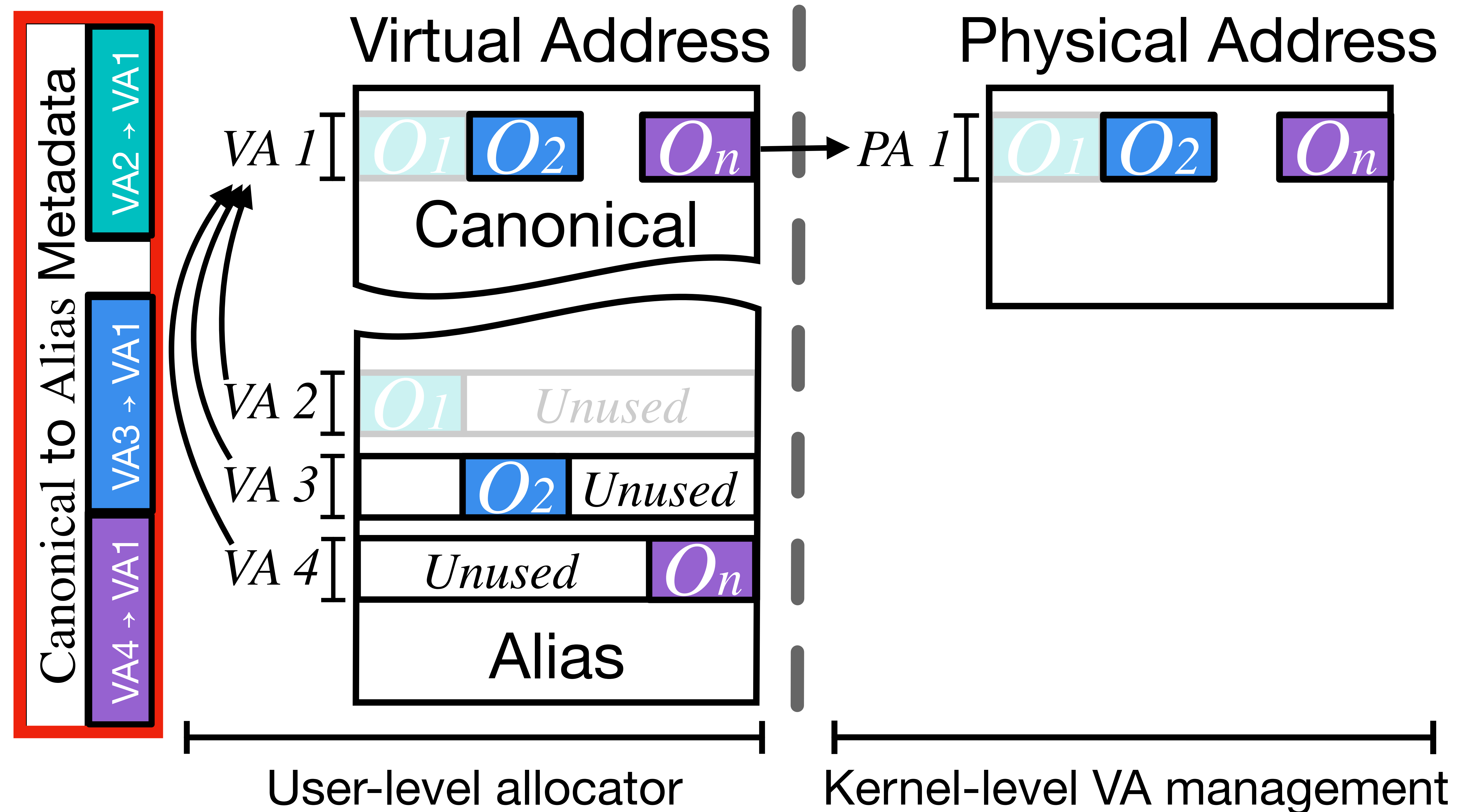
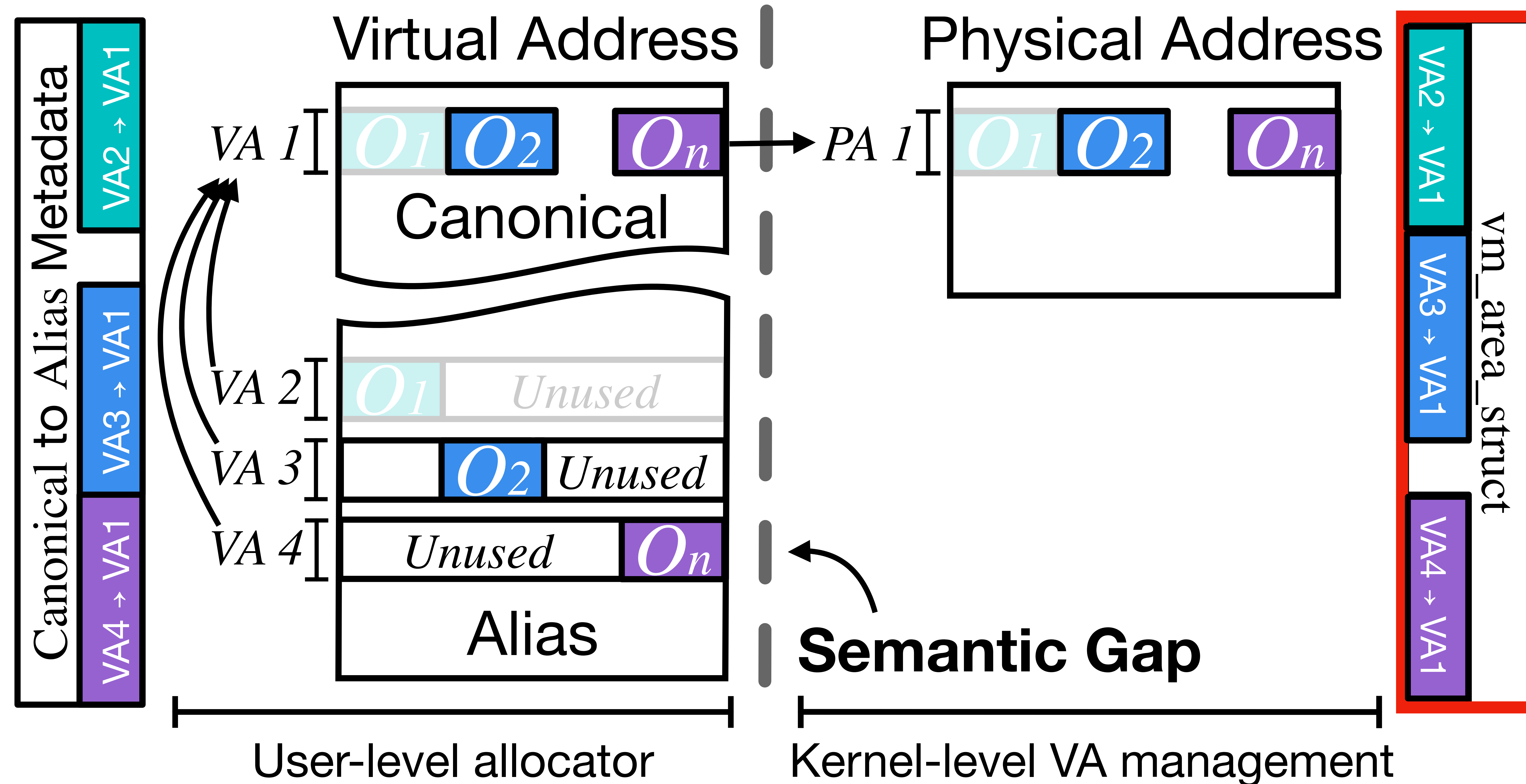
Performance Overhead due to Semantic Gap



- OTA manages the alias to canonical mapping using the **user-level metadata**

Performance Overhead due to Semantic Gap



- Kernel manages the virtual address to the physical address mappings
- User and kernel doesn't know each other's states: **Semantic Gap**

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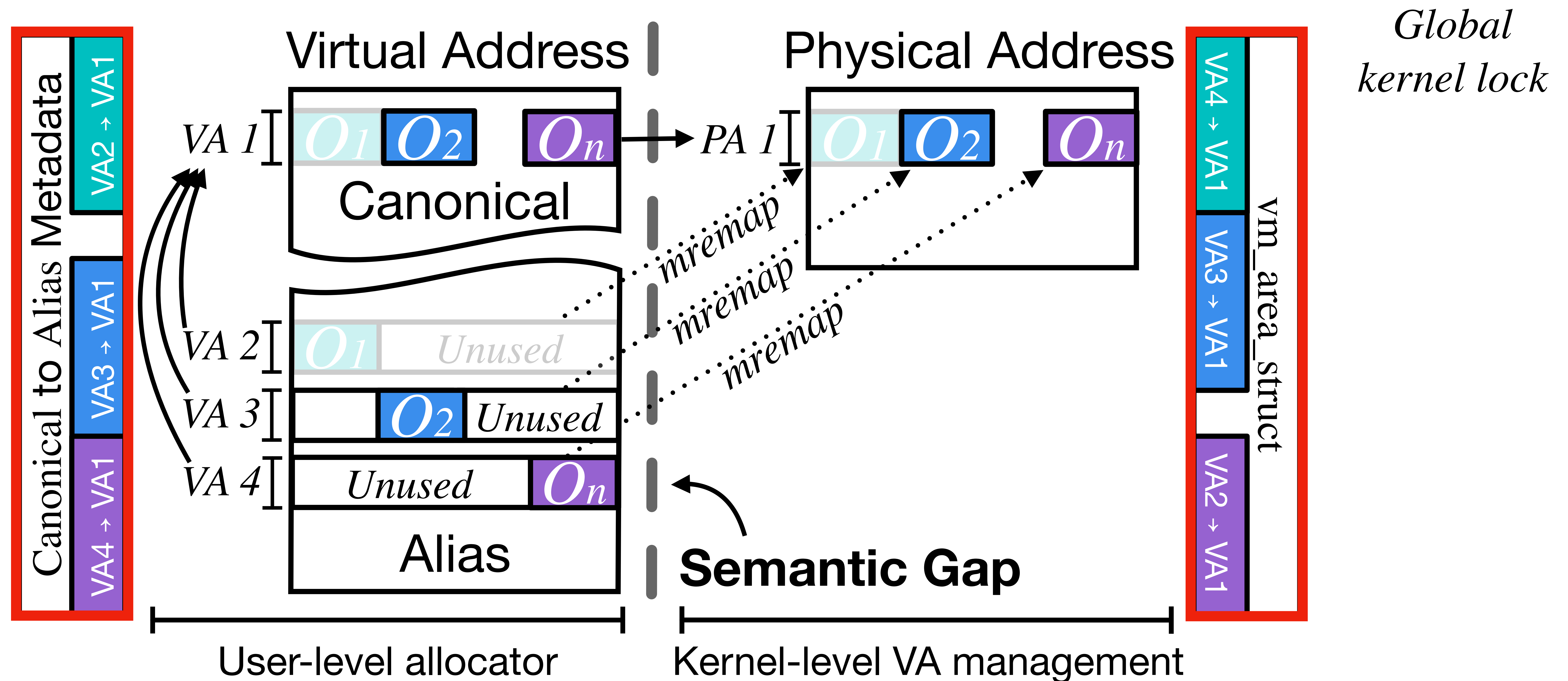
Performance Overhead due to Semantic Gap



- OTA must issue a costly system call for each allocation to update the kernel
- *Frequent execution of system calls leads to these global locks becoming a major bottleneck*

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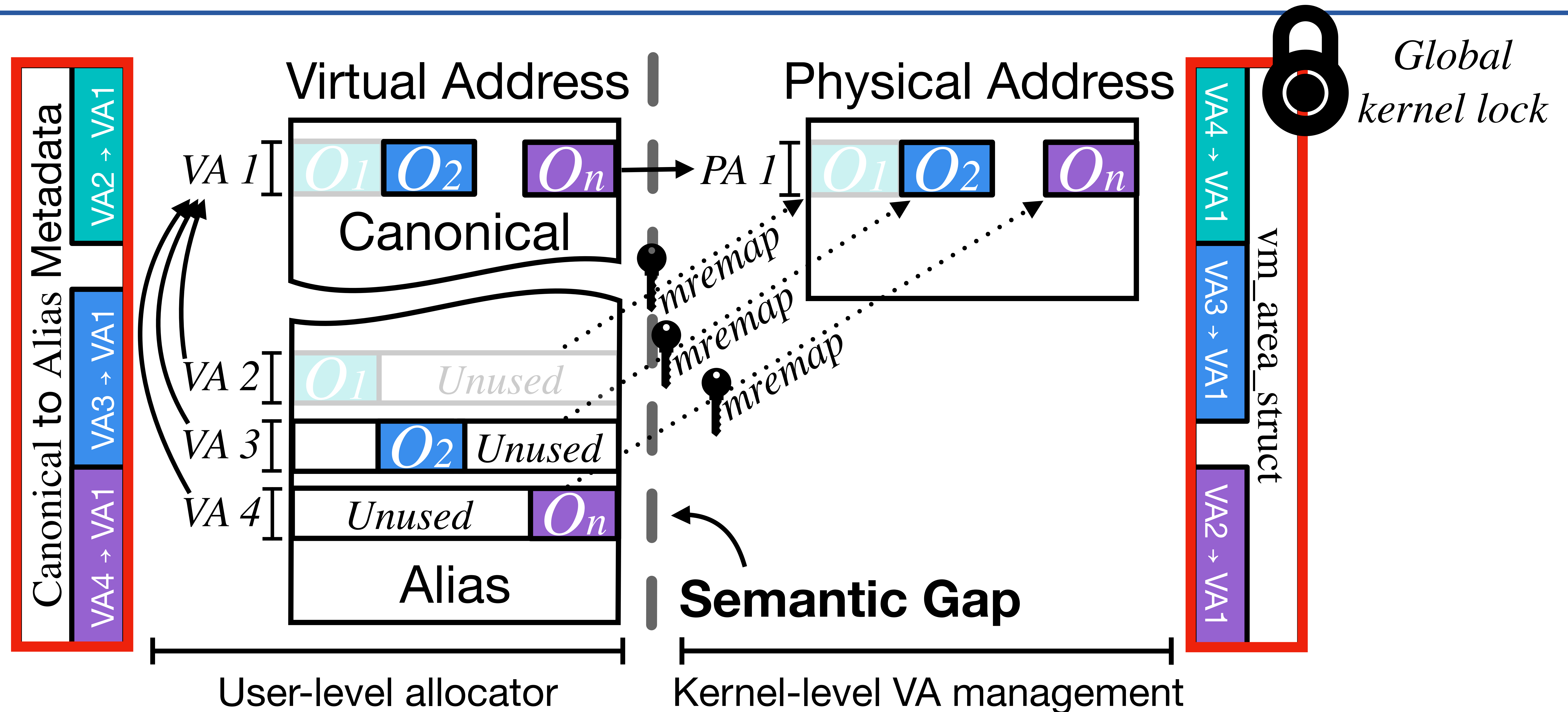

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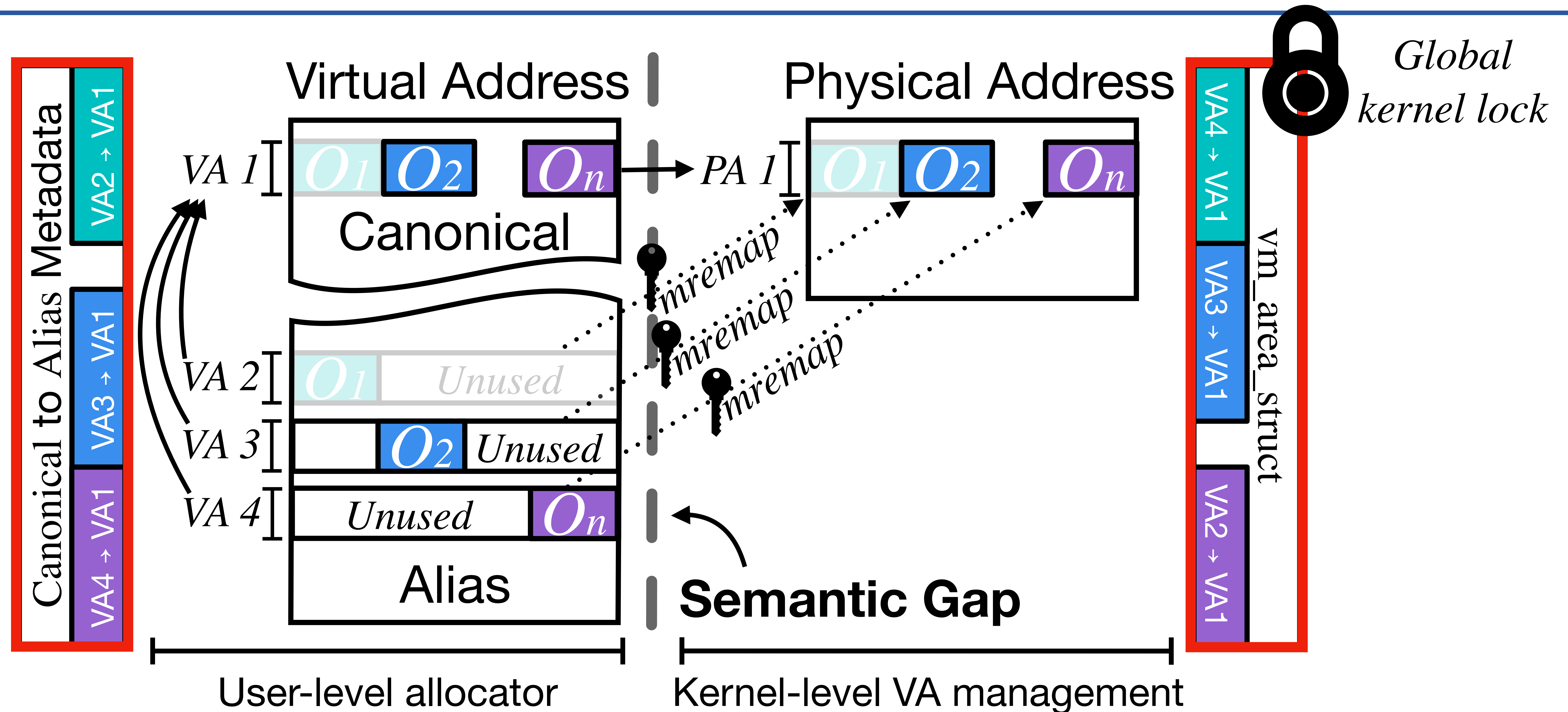

- OTA must issue a costly system call for each allocation to update the kernel

Semantic Gap is the major constraints of OTA

Previous Approaches: How to Address the Semantic Gap

	Oscar	FFMalloc	DangZero
Method	*USENIX Security 2017* Batching system calls	*USENIX Security 2021* Remove alias mapping	*ACM CCS 2022* Library operating system
Pros	+ Moderate memory overhead	+ Fast performance	+ Moderate memory overhead + High bug-detect precision
Cons	- Low performance - Low scalability - Cannot support copy-on-write	- High memory overhead - Low bug-detect precision	- Virtualization overhead - Low scalability - Cannot support copy-on-write - Lack of compatibilities

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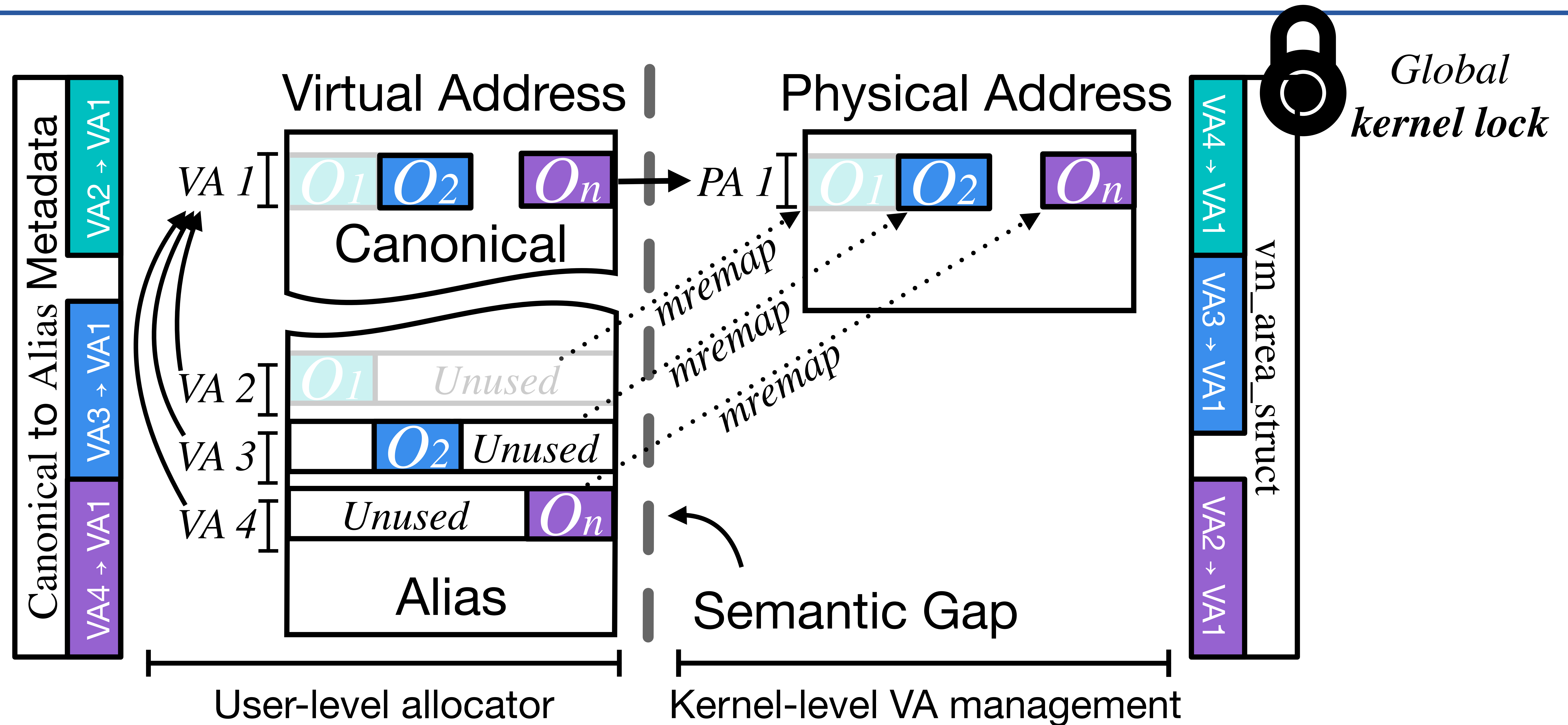
None of the previous work fully balance performance, memory, bug detection, and compatibility

Previous OTA Design Using Alias Mapping



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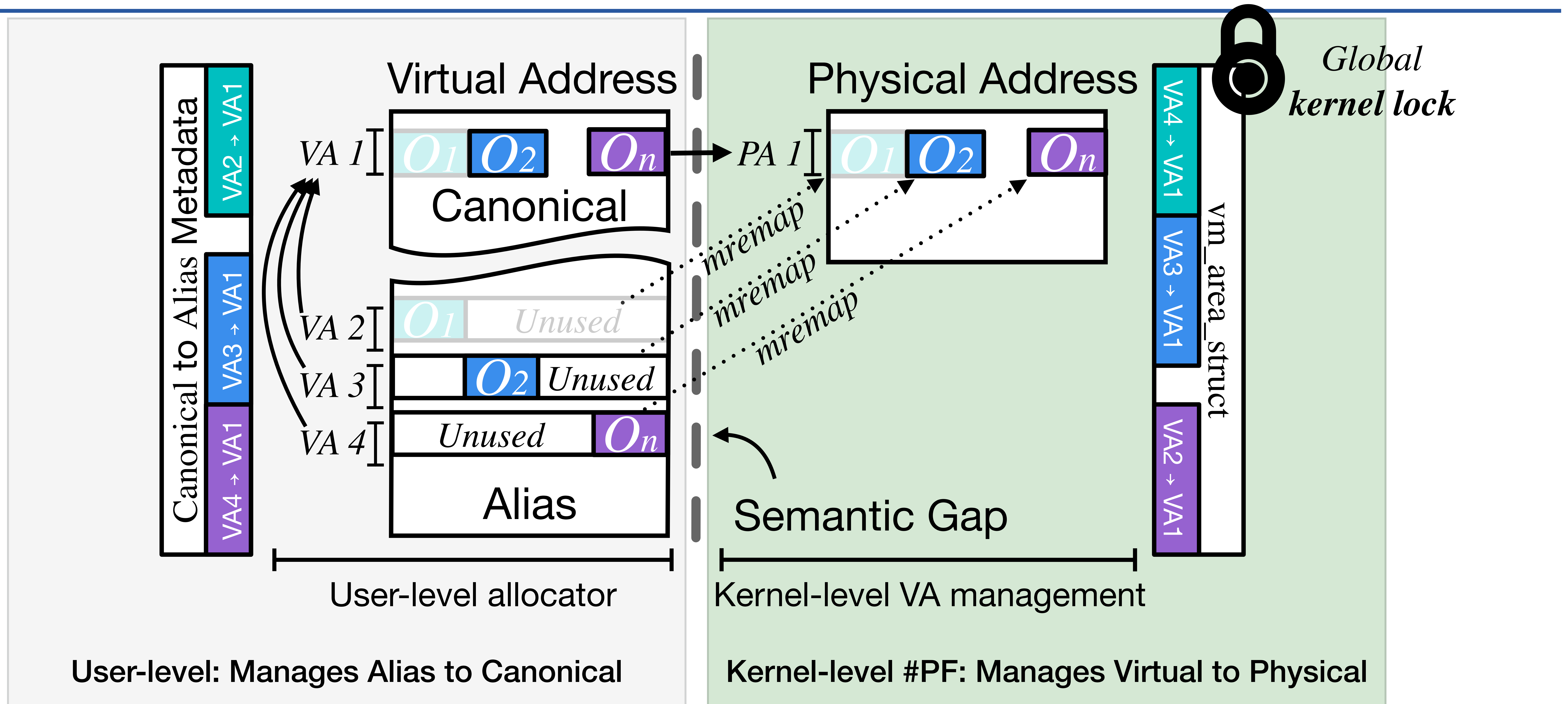

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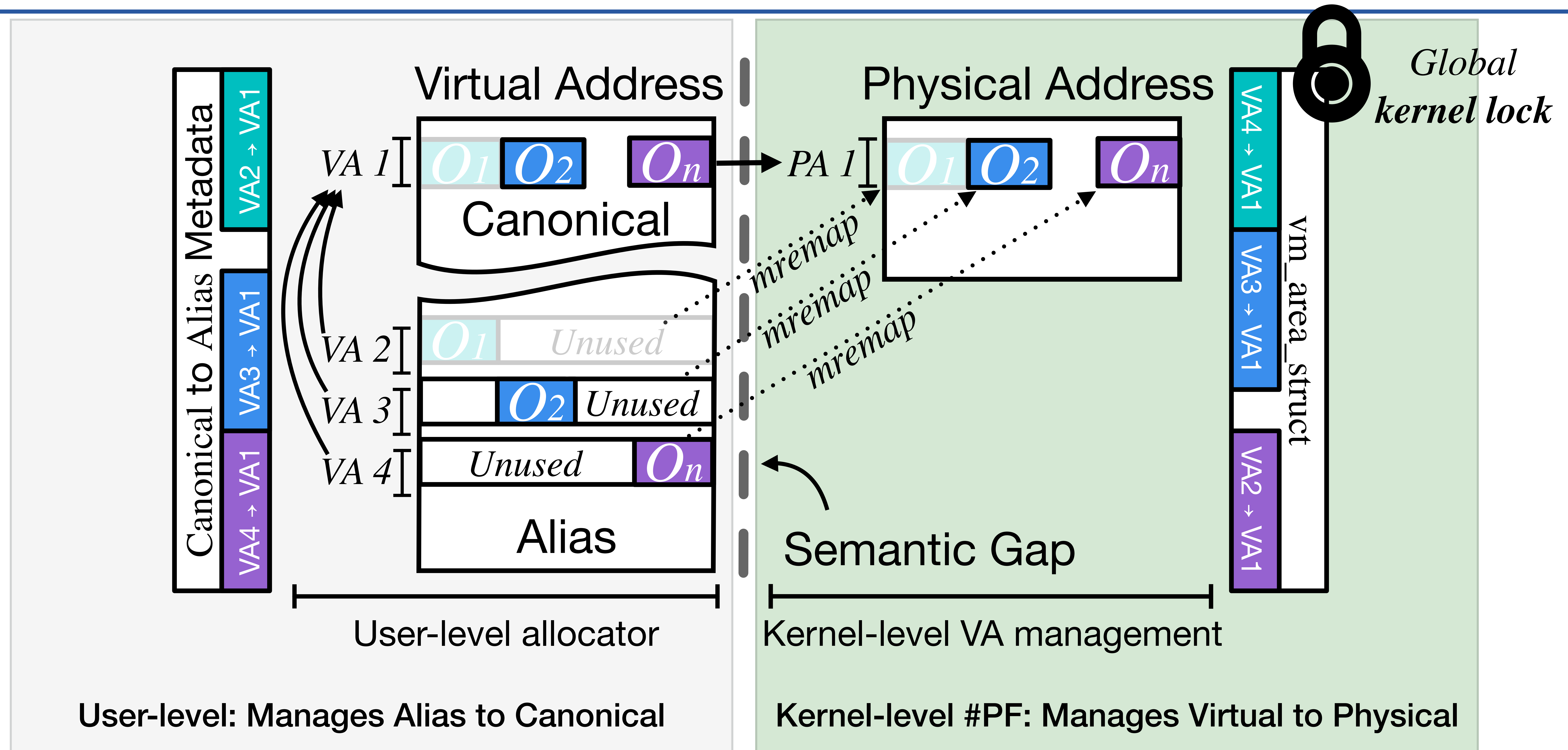
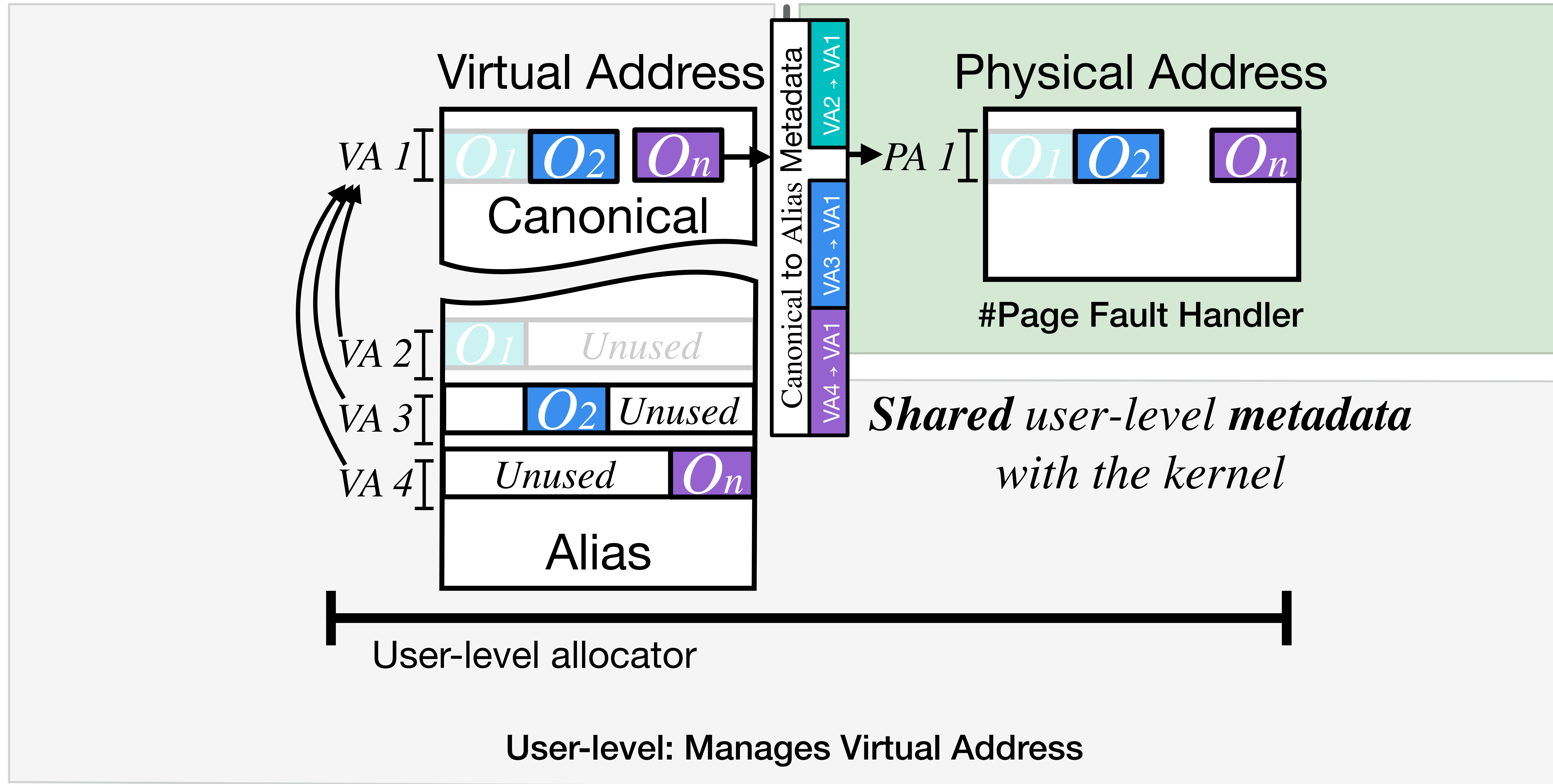


Decoupling virtual address management from kernel

BUDAlloc: Decoupling Virtual Address Management from Kernel



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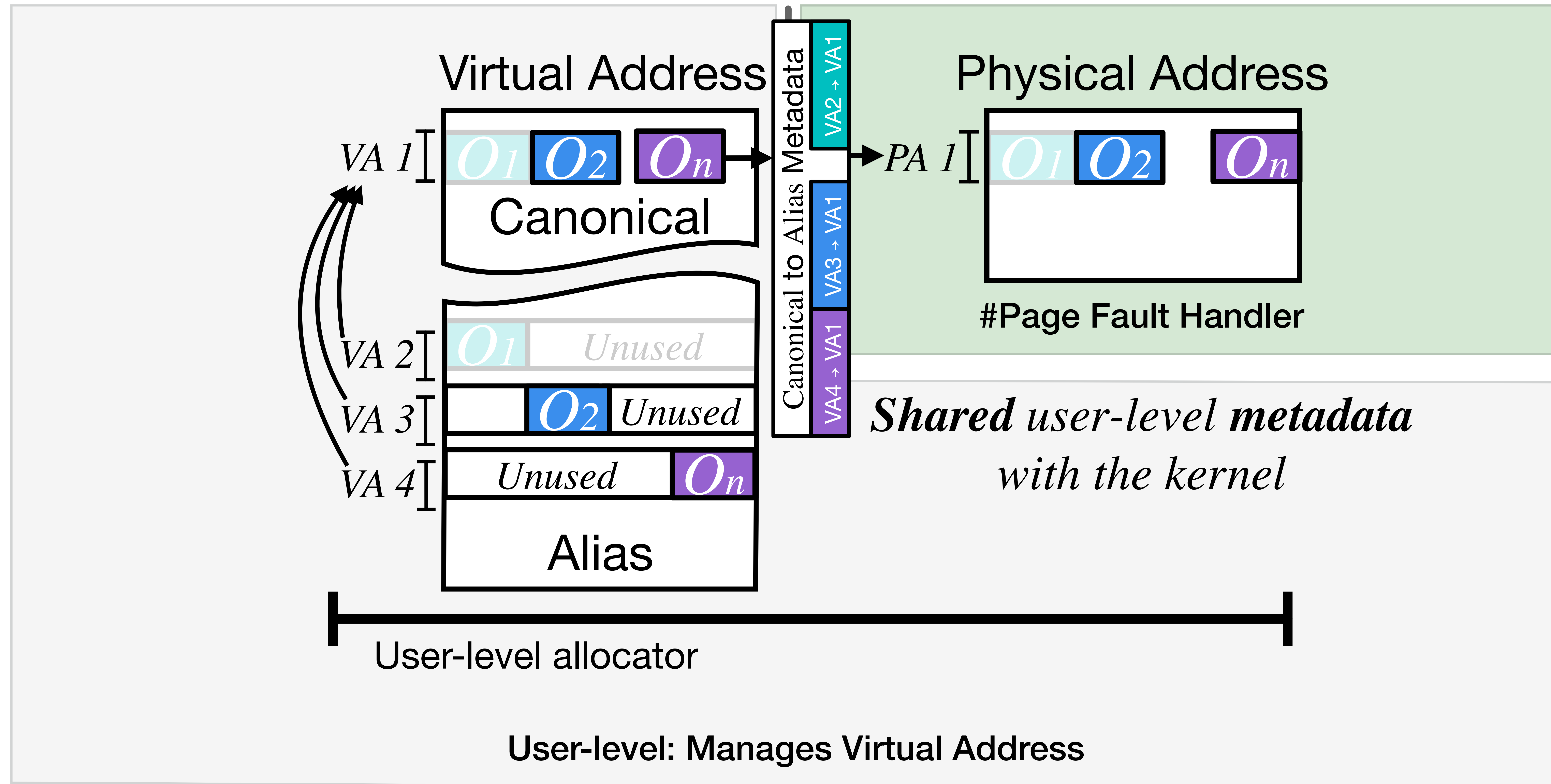
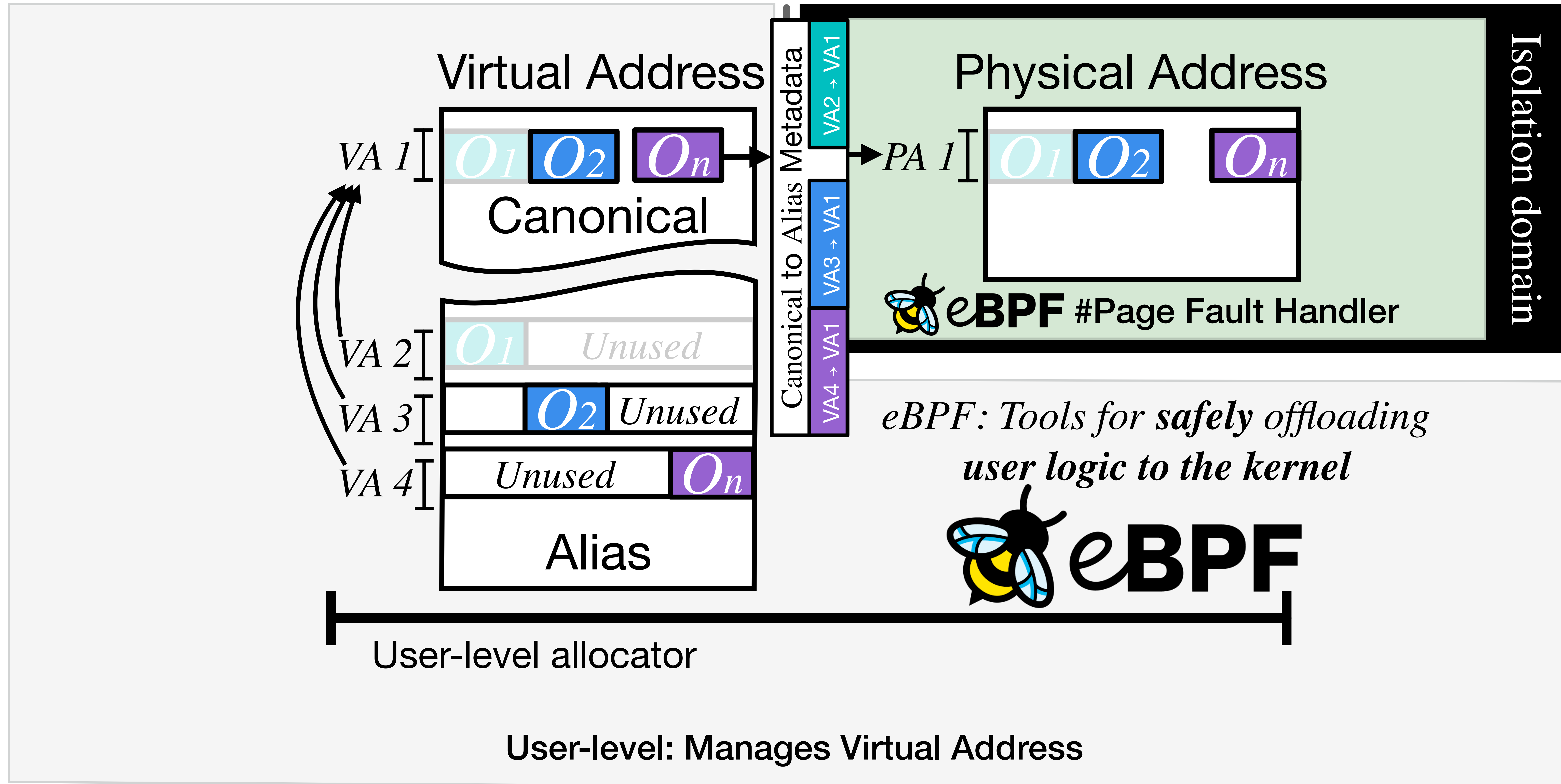


Manages the virtual address directly using a shared metadata

BUDAlloc: Decoupling Virtual Address Management from Kernel



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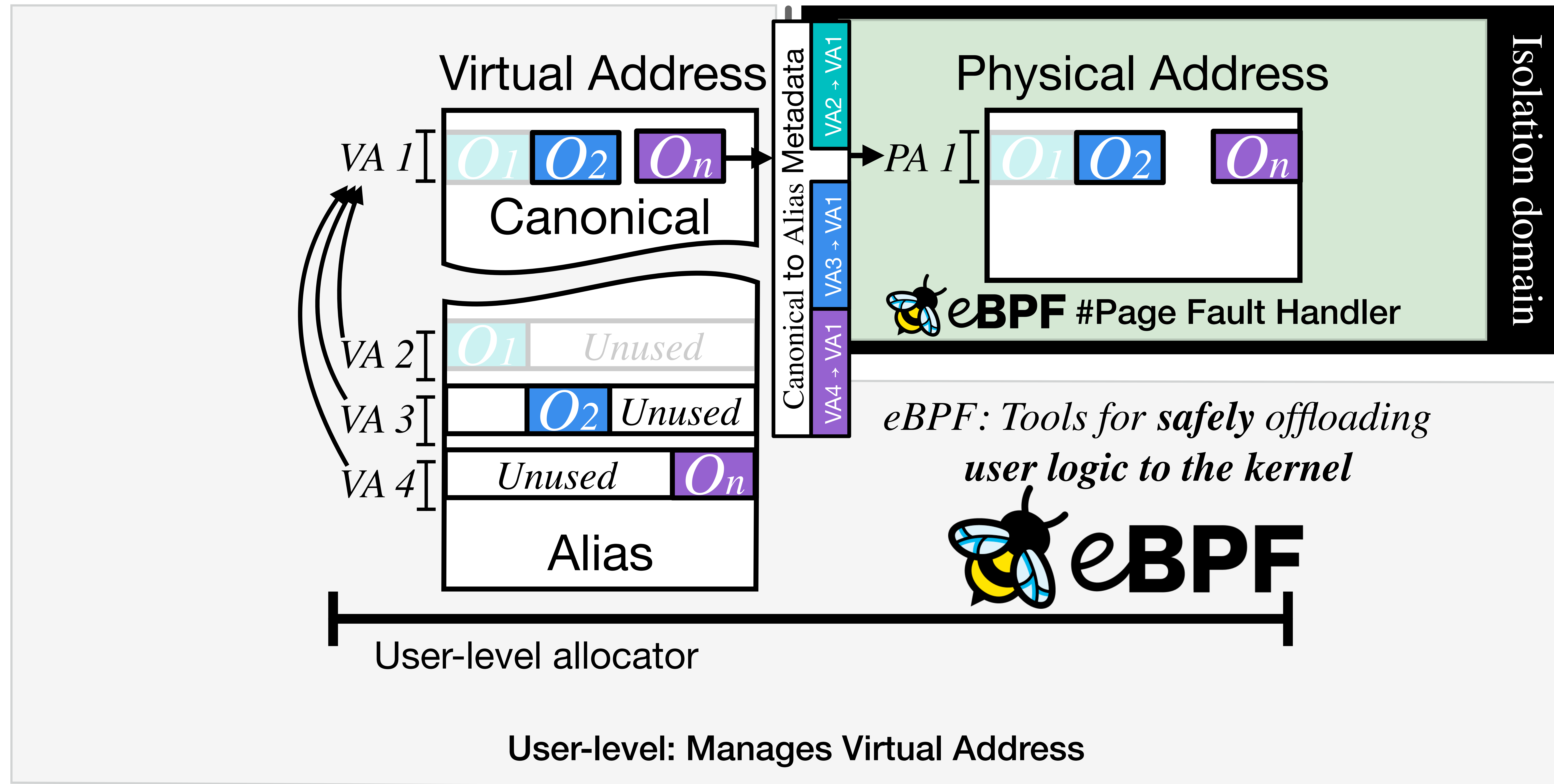
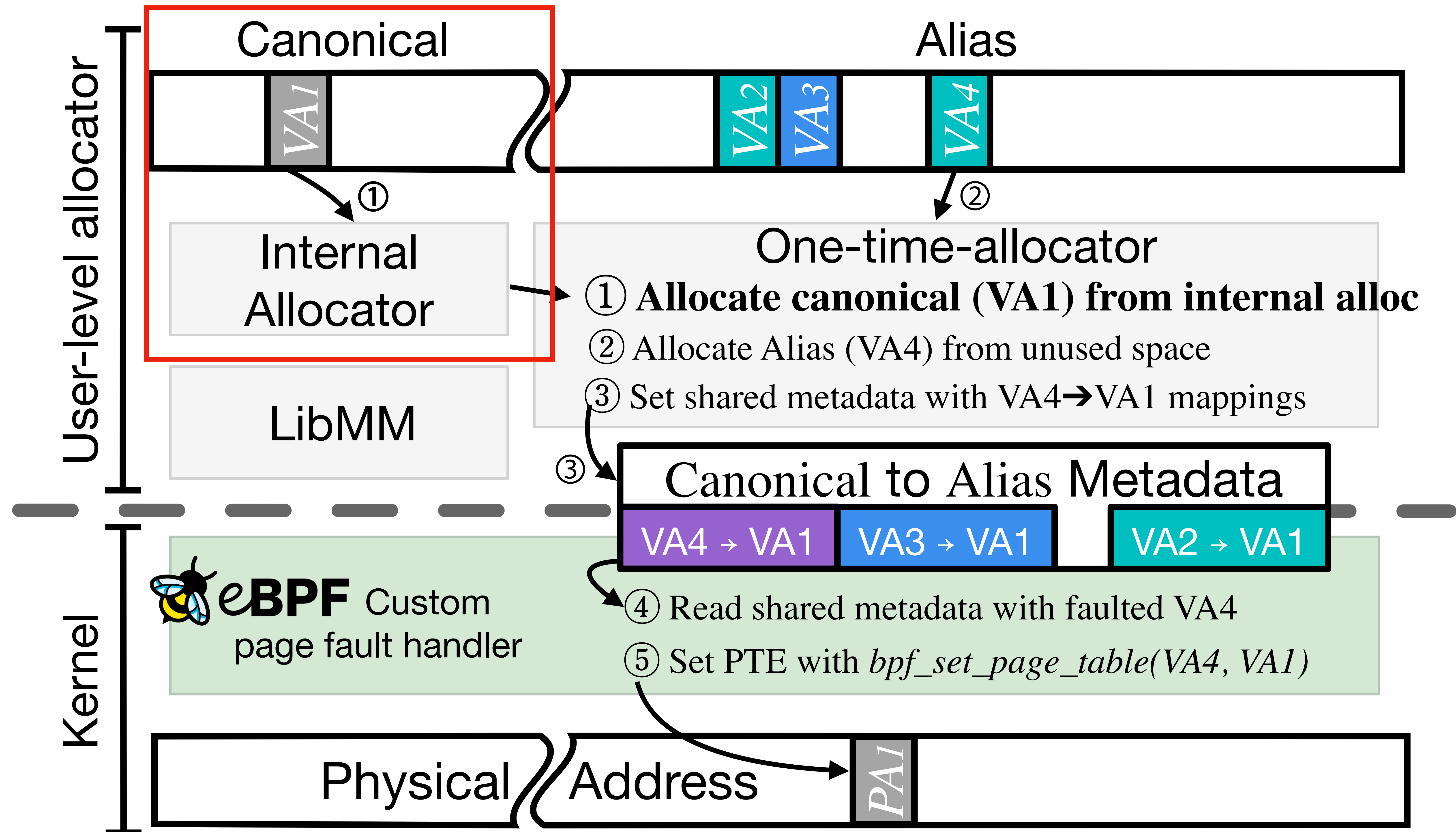


Secure and efficient page table modification using eBPF

Co-design: User-level Allocator and Kernel #PF Handler



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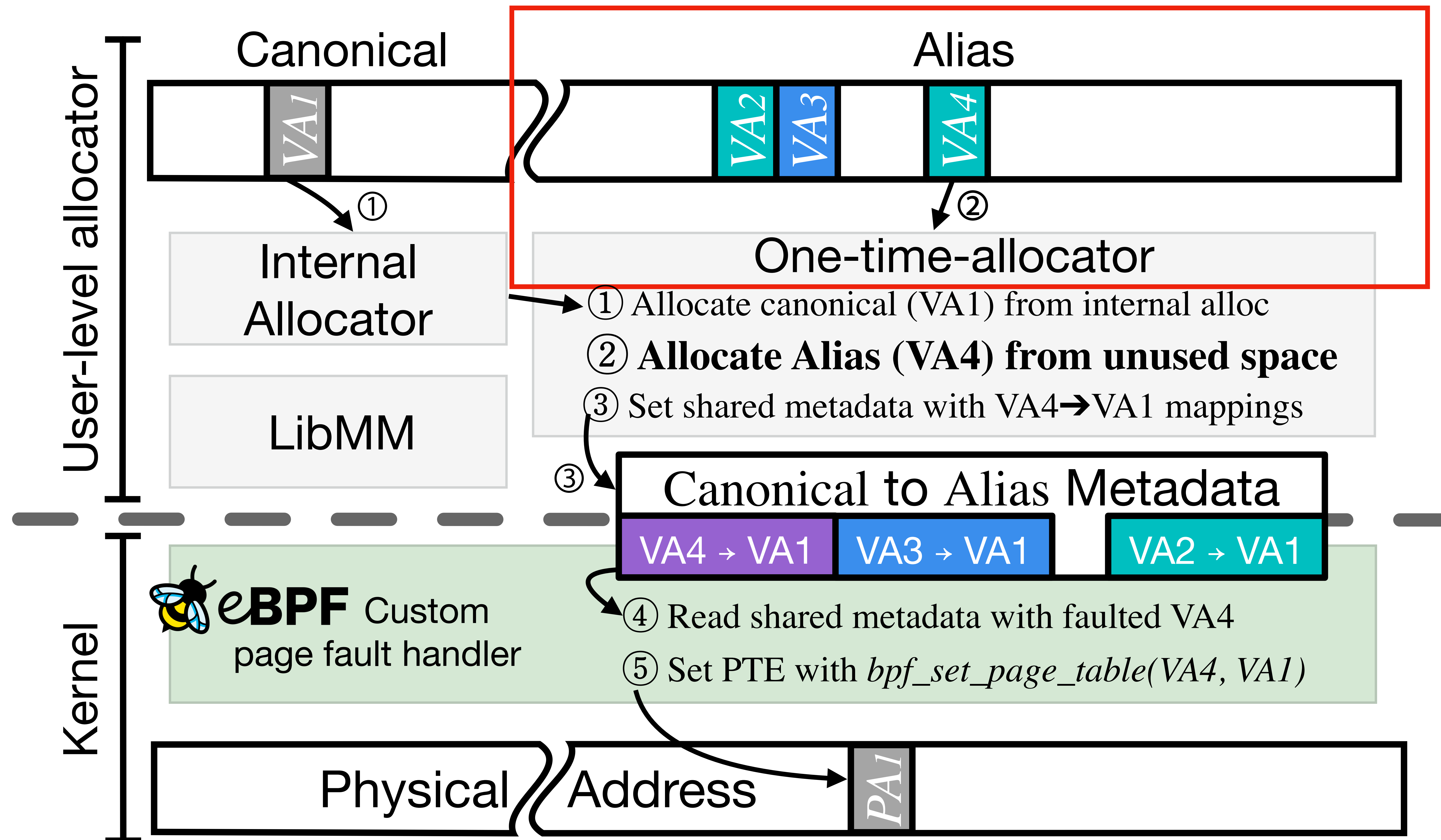

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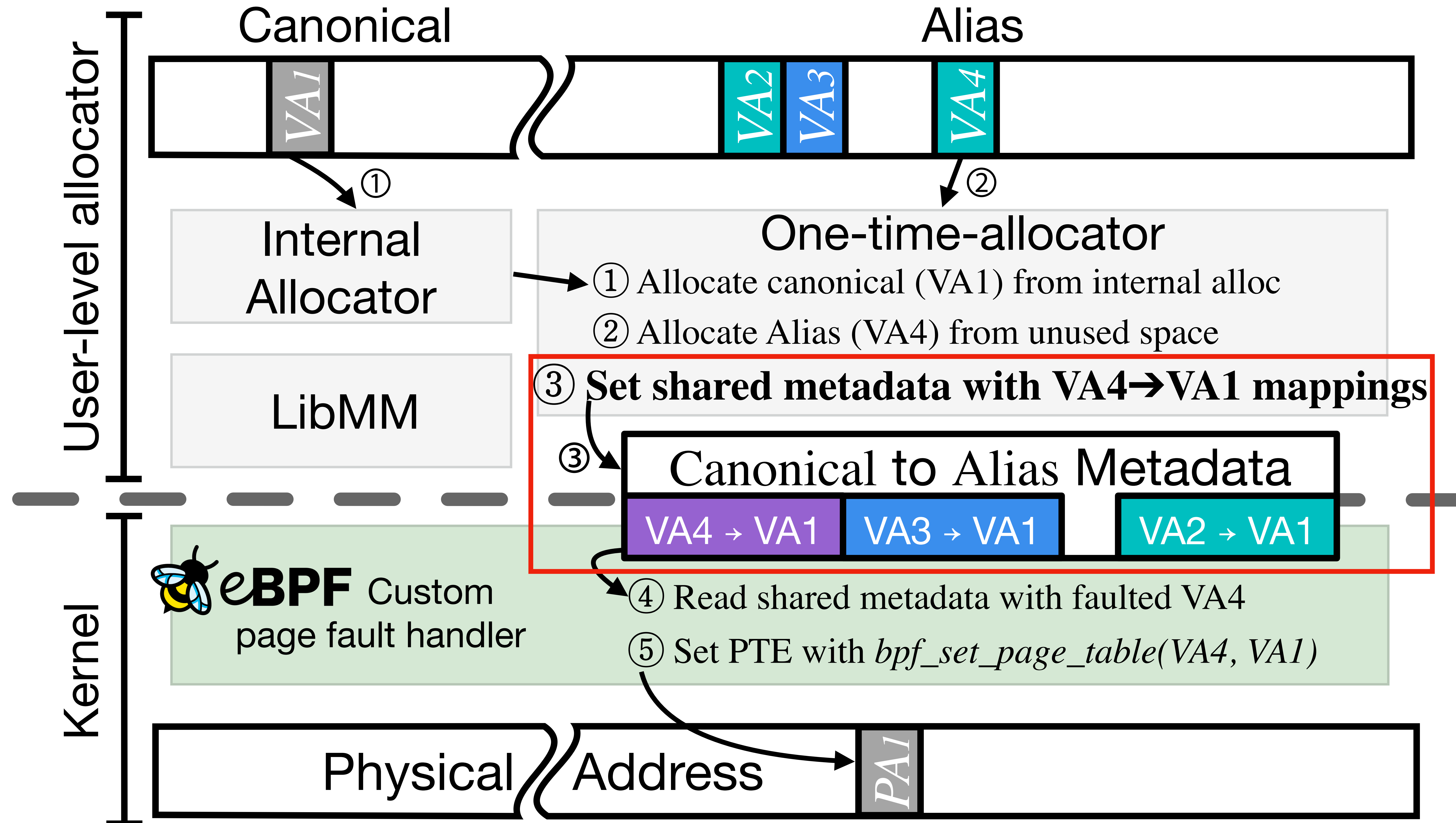

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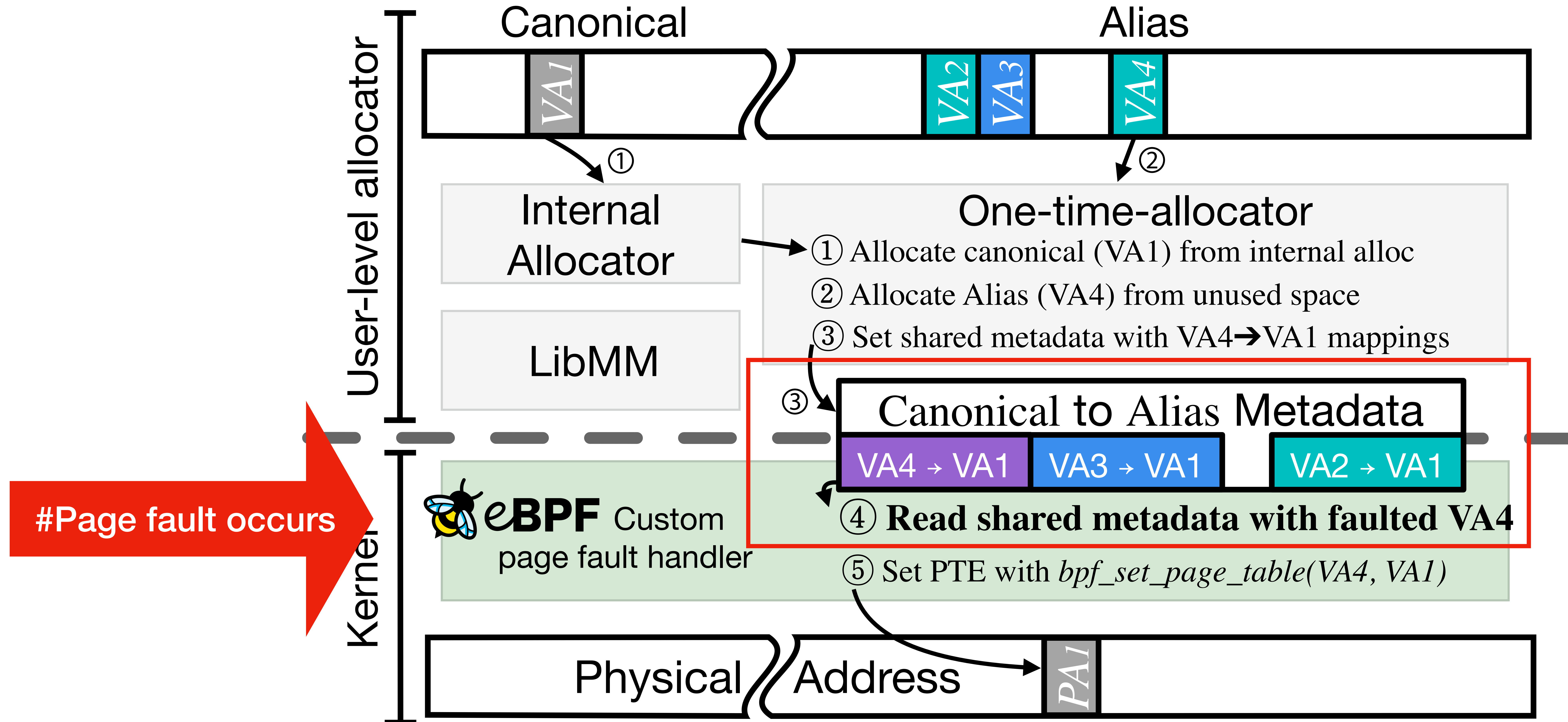

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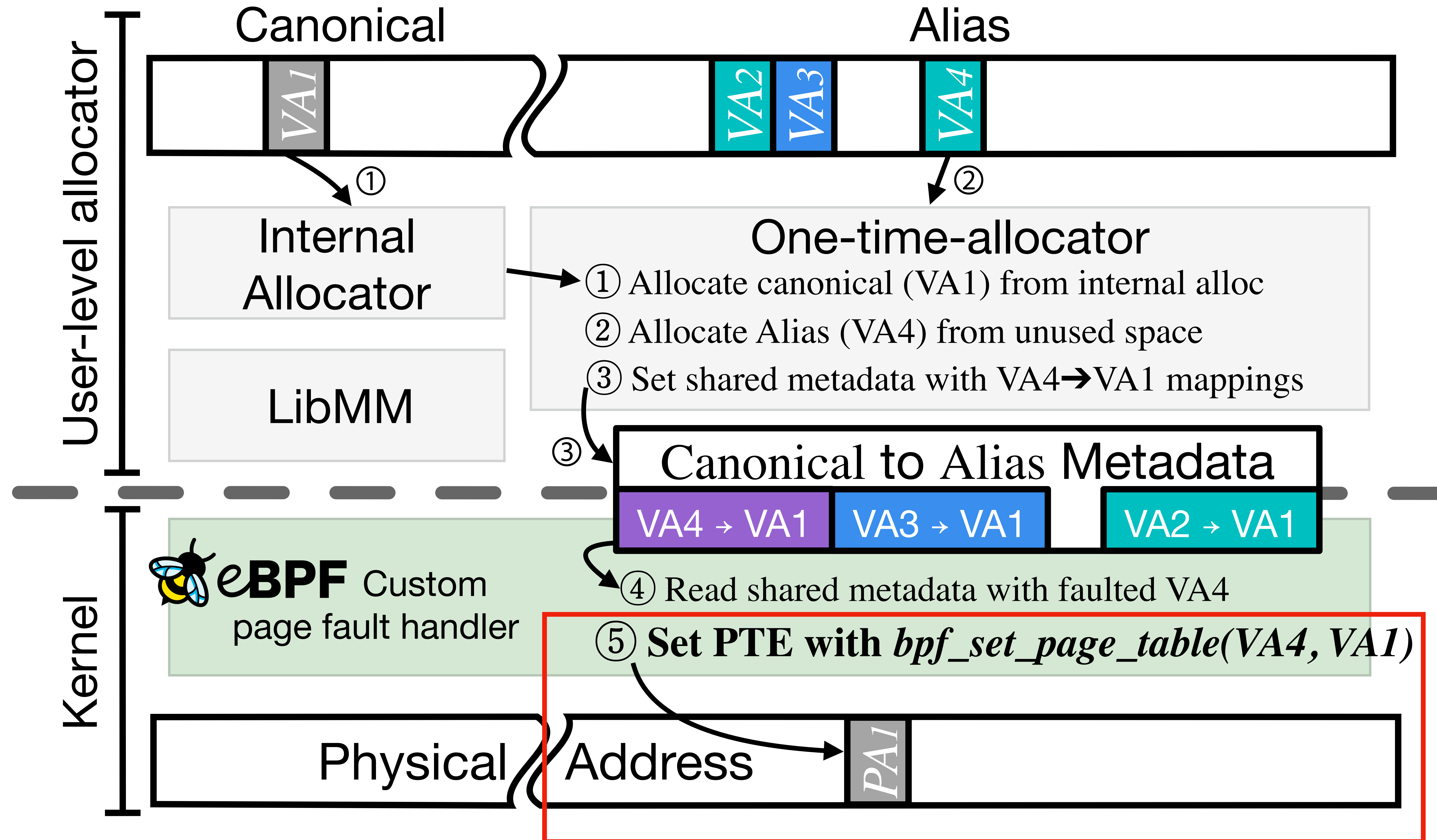

Benefits from the Co-design

- **Performance**
  - BUDAlloc offers an **optional mode** deferring alias address free until the **next page fault,** called **BUDAlloc-prevent**
- **Scalability**
  - BUDAlloc eliminates the global kernel lock
  - BUDAlloc supports **fine-grained locking** using **user-level** semantics
- **Compatibility**
  - BUDAlloc seamlessly **reuses all kernel** physical memory management features

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UAF Bug Detection: BUDAlloc-p Detects Most of Bugs

- BUDAlloc-detection (without deferring)
  - ✓Show **100% precision** of detection
- BUDAlloc-prevention (deferring)
  - ✓Show **97% precision** of detection
- BUDAlloc's detection window is at **least next page fault**

Vulnerability	Program	BUDAlloc-p	BUDAlloc-d	FFmalloc	DangZero
UAFBench					
CVE-2016-3189	bzip2	●	●	◑	●
*CVE-2016-4487	cxxfilt	●	●	●	●
CVE-2017-10686	nasm	●	●	◑	●
CVE-2018-10685	lrzip	●	●	◑	●
CVE-2018-11496	lrzip	●	●	◑	●
*CVE-2018-11416	jpegoptim	●	●	●	●
CVE-2018-20623	readelf	●	●	◑	●
*CVE-2019-20633	patch	●	●	●	●
*CVE-2019-6455	rec2csv	●	●	●	●
Issue 74	giflib	●	●	◑	●
*Issue 122	gifsicle	●	●	●	●
Issue 73	mjs	●	●	◑	●
Issue 78	mjs	●	●	◑	●
Issue 91	yasm	●	●	◑	●
ffmalloc & DangZero					
CVE-2015-2787	PHP	●	●	◑	●
*CVE-2015-3205	libmimedir	●	●	●	●
CVE-2015-6835	PHP	●	●	◑	●
CVE-2016-5773	PHP	●	●	◑	●
Issue 3515	mruby	●	●	◑	●
Issue 24613	Python	●	●	◑	●
Exploit Database					
CVE-2019-6076	Lua	●	●	◑	●
CVE-2019-7703	Binaryen	●	●	◑	●
CVE-2019-8343	nasm	●	●	◑	●
CVE-2019-17582	libzip	●	●	◑	●
CVE-2020-24346	nginx	●	●	◑	●
CVE-2022-1934	mruby	●	●	◑	●
CVE-2022-1106	mruby	◑	●	◑	●
CVE-2022-35164	LibreDWG	●	●	◑	●
*BUG-66783	PHP	●	●	●	●
BUG-80927	PHP	●	●	◑	●

●: Detect UAF bug ◑: Prevent UAF bug

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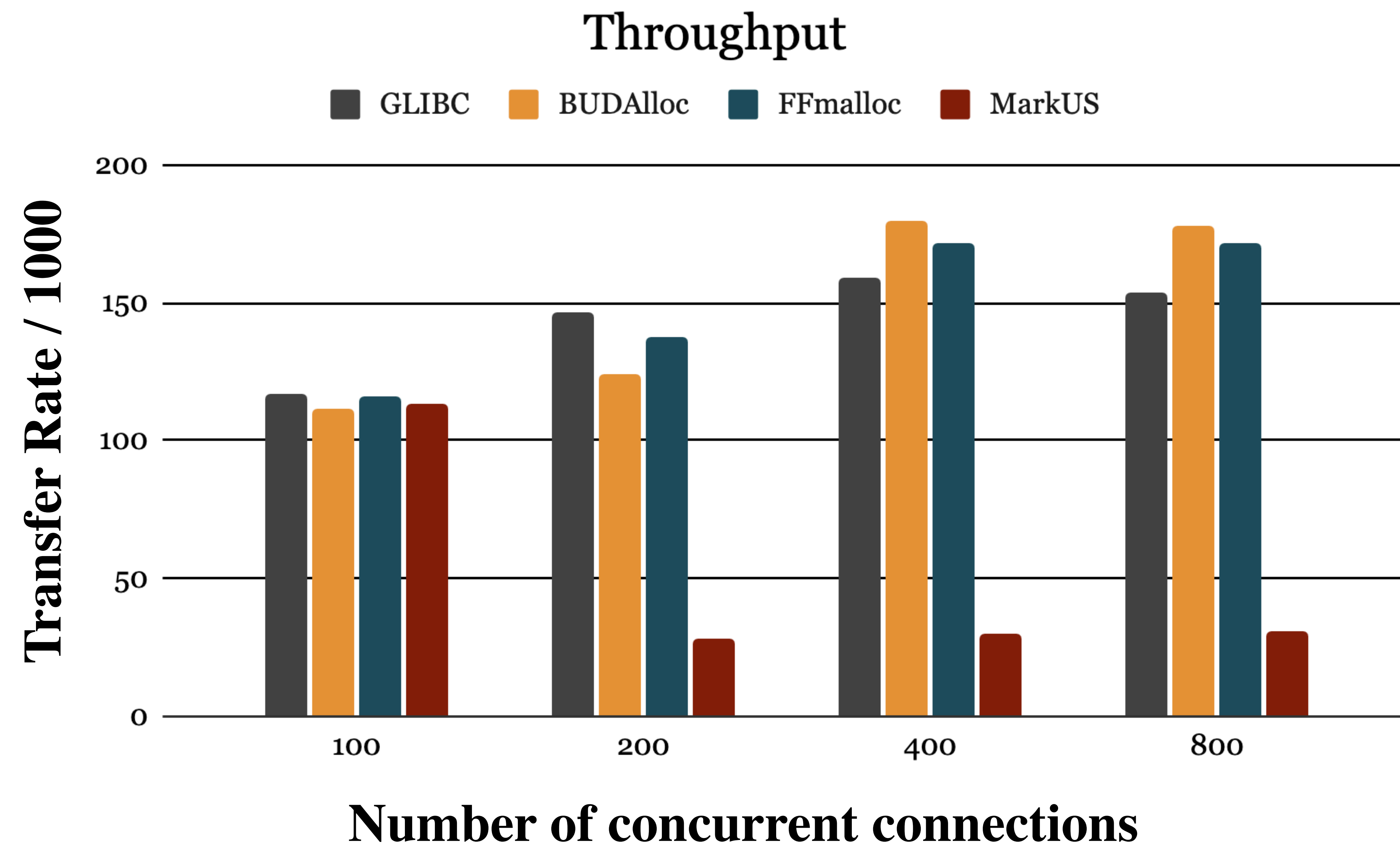
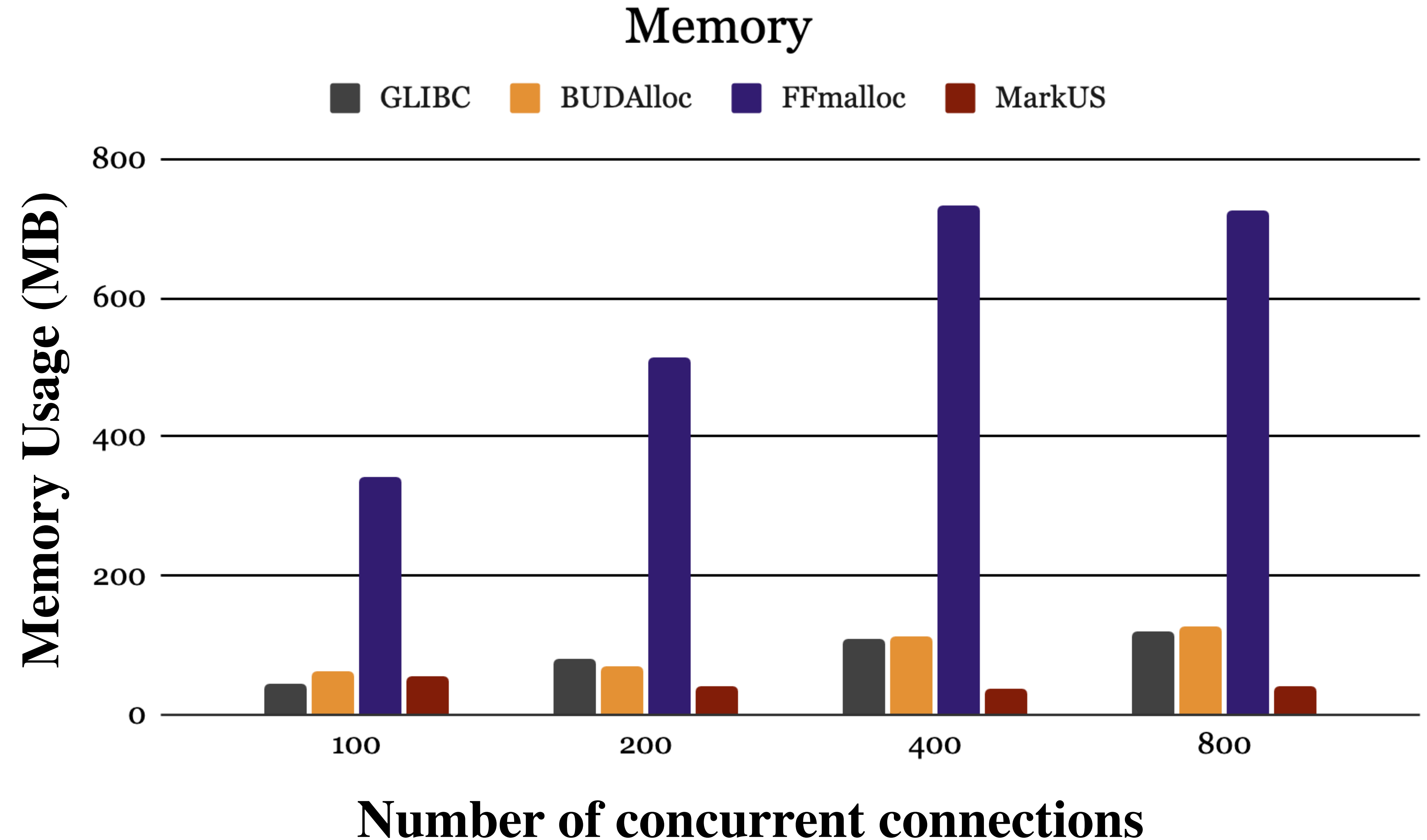
Apache Web Server: BUDAlloc is Fast and Efficient





- BUDAlloc shows the **highest scalability** despite the **superior precision of detection**
- BUDAlloc shows the **similar results** with the GLIBC in performance and memory overhead

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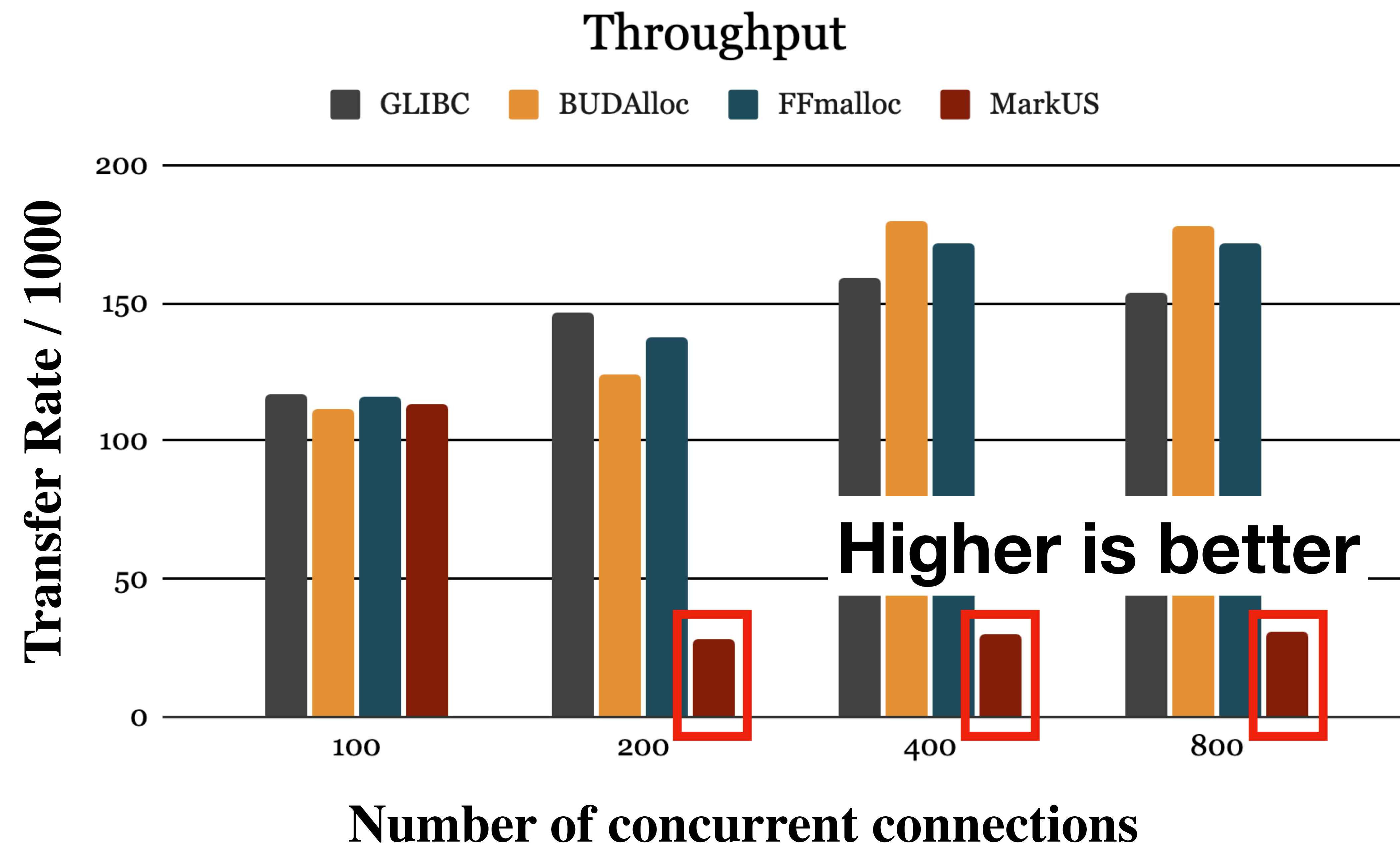

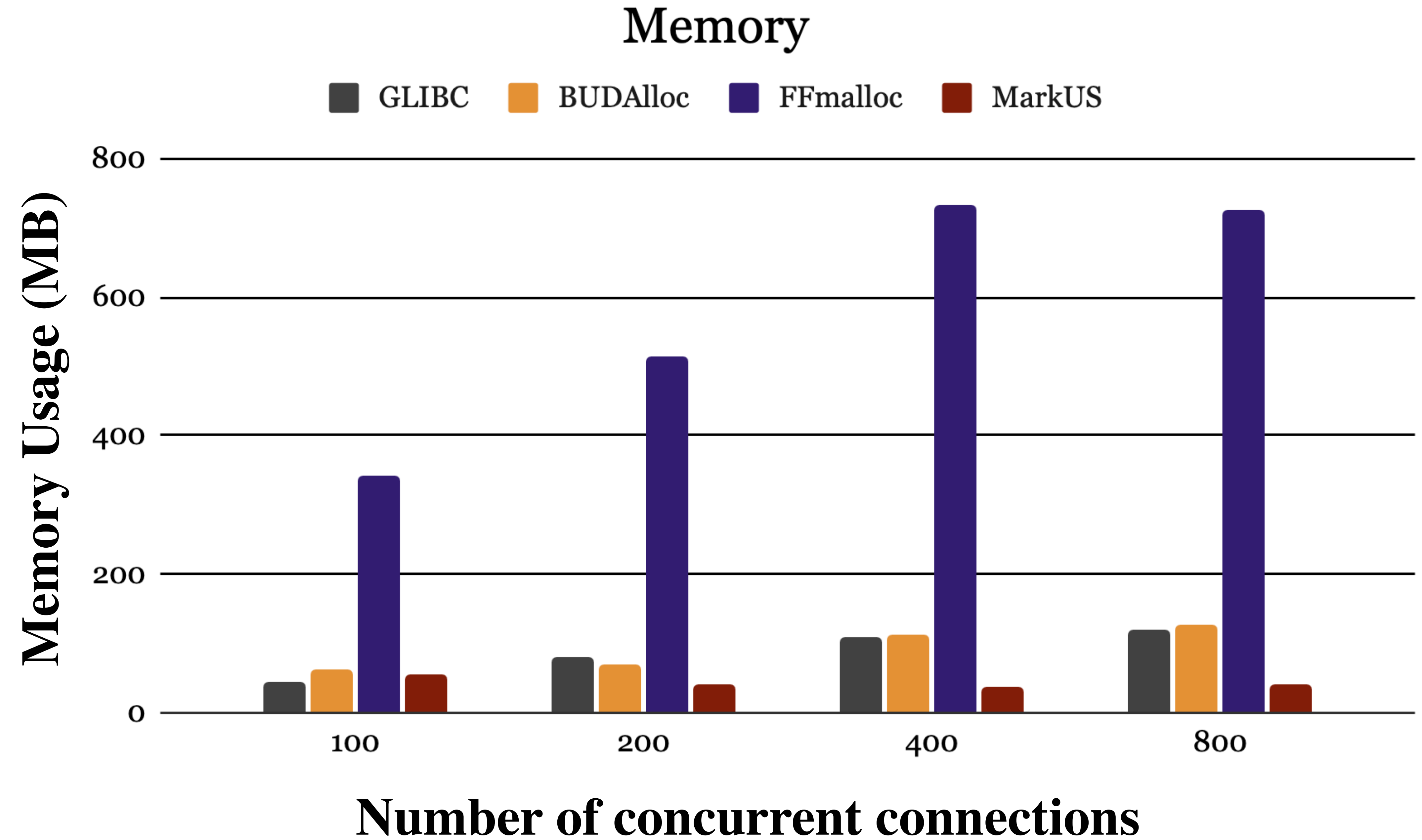

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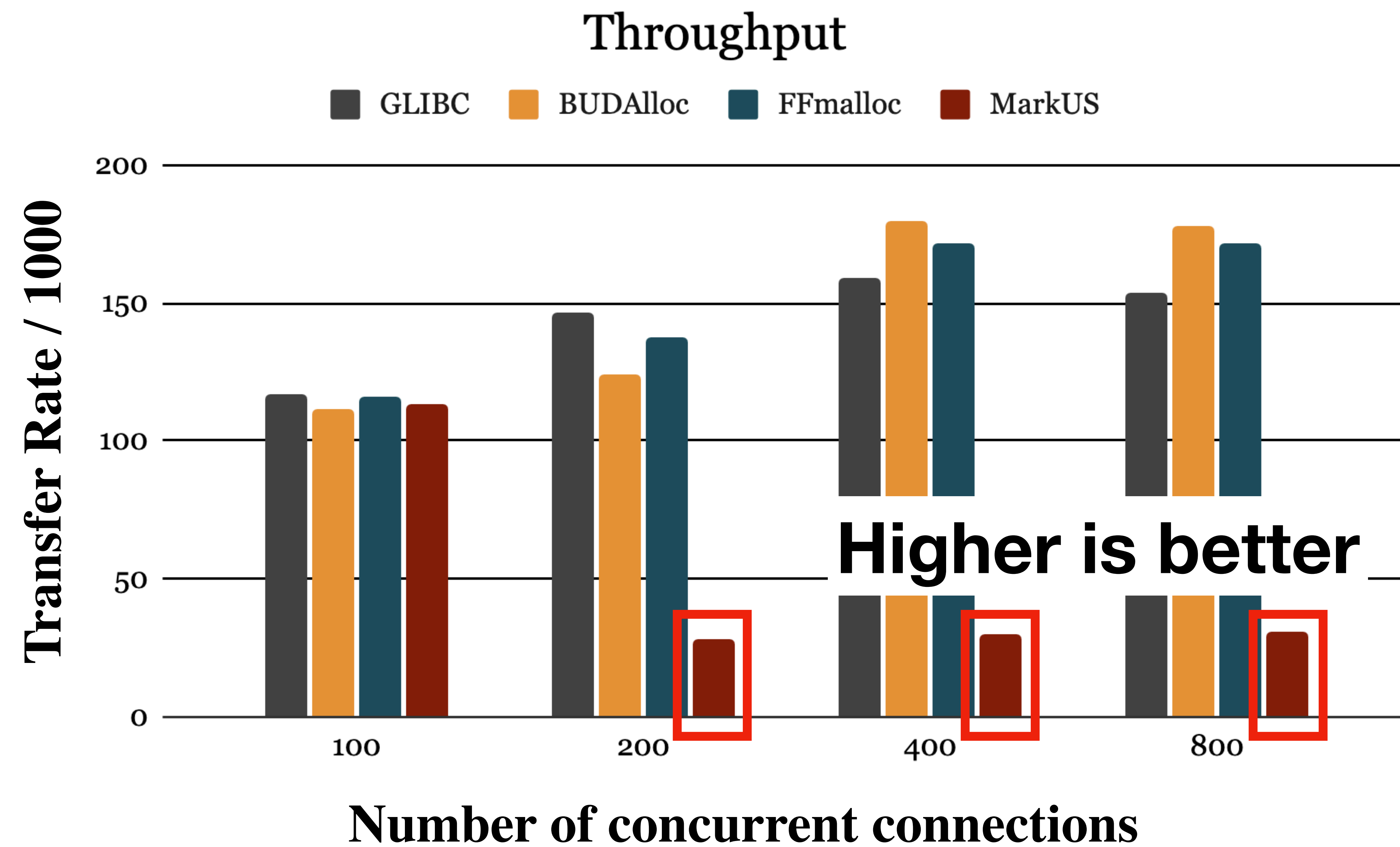

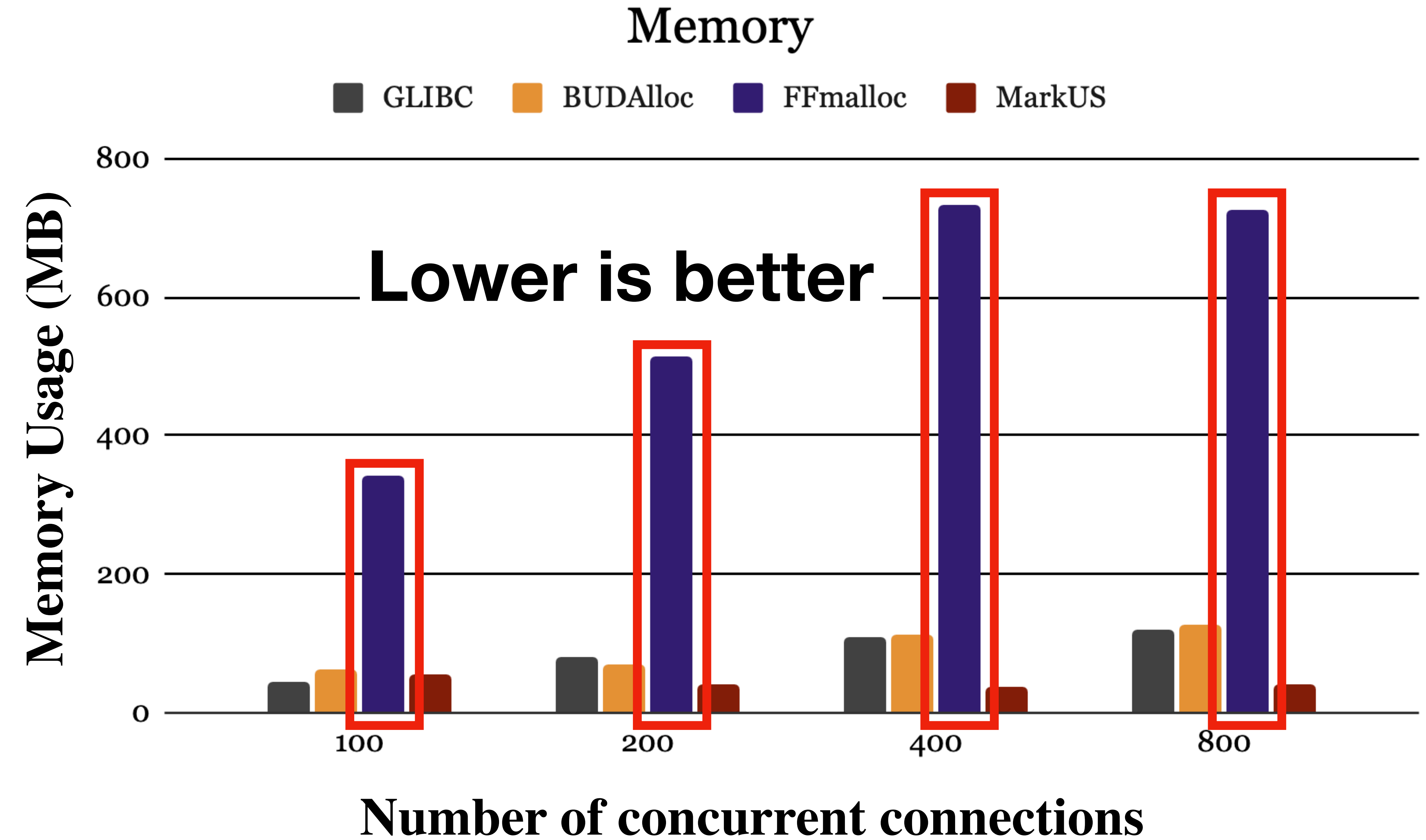

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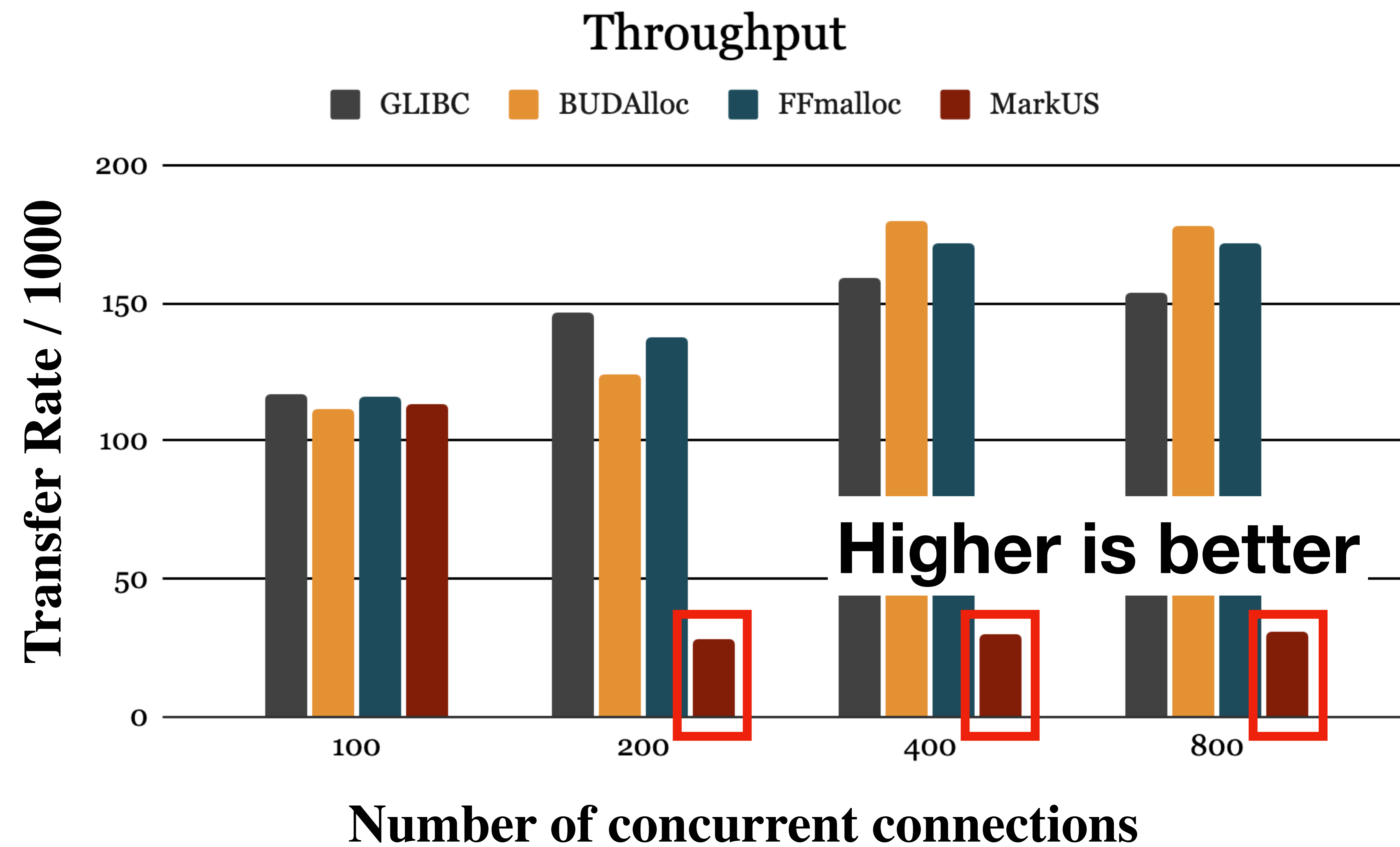

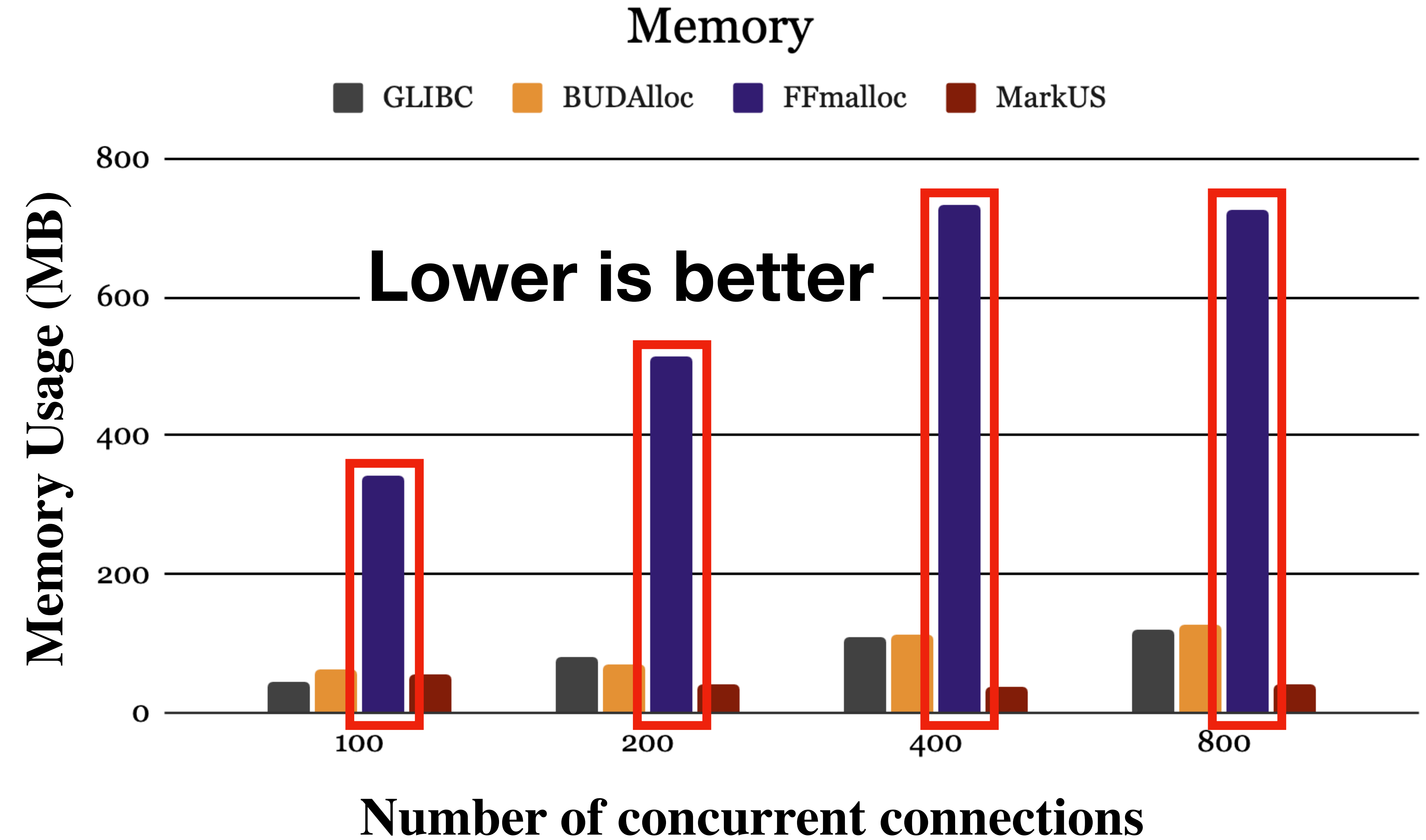

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High performance, Low memory overhead, Good scalability, and Superior precision of bug detection

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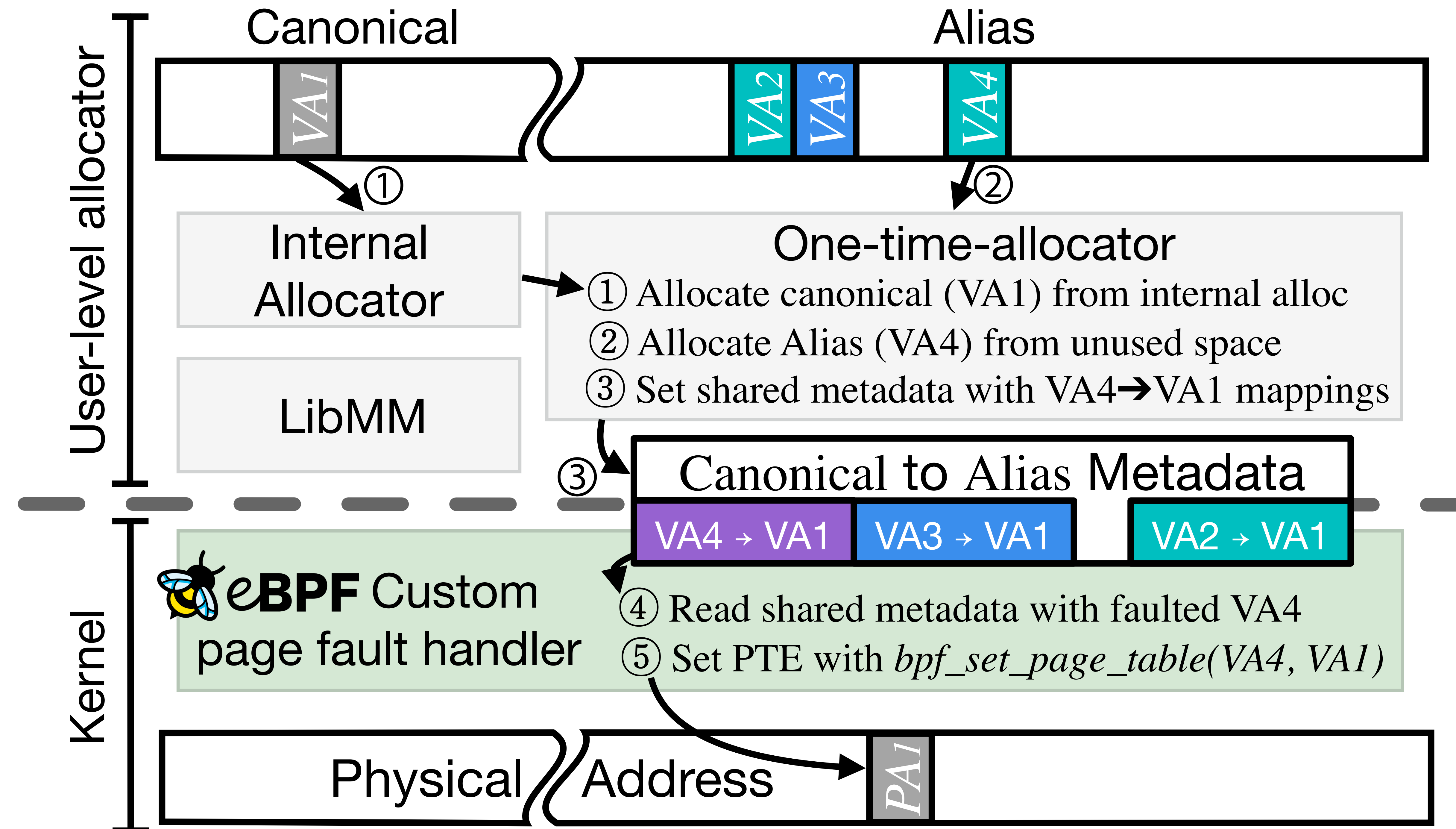
Summary



- We **decouple** virtual address from the kernel using **eBPF**
- By decoupling, we remove **semantic gap**, and introduce several **optimizations**
- BUDAlloc shows the **superior** detectability and performance

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Questions

- GITHUB: https://github.com/casys-kaist/BUDAlloc
- EMAIL: junhoahn@kaist.ac.kr
- CV: https://sites.google.com/view/junhoahn/

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