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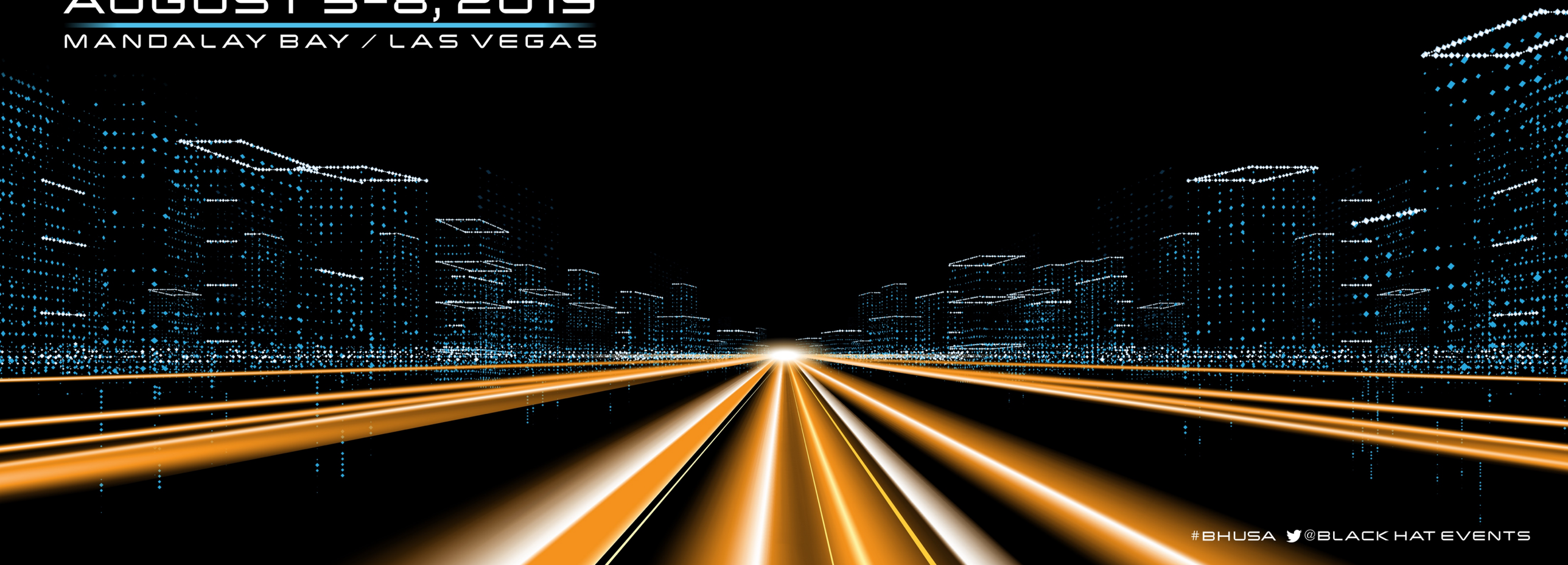

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PeriScope: An Effective Probing and Fuzzing Framework for the Hardware-OS Boundary

Dokyung Song, Felicitas Hetzelt, Dipanjan Das, Chad Spensky, Yeoul Na, Stijn Volckaert, Giovanni Vigna, Christopher Kruegel, Jean-Pierre Seifert, Michael Franz

UCI
Technische Universität Berlin
UCSB
KU LEUVEN

Remote Compromise of Peripheral Chips

ars TECHNICA

BIZ & IT —

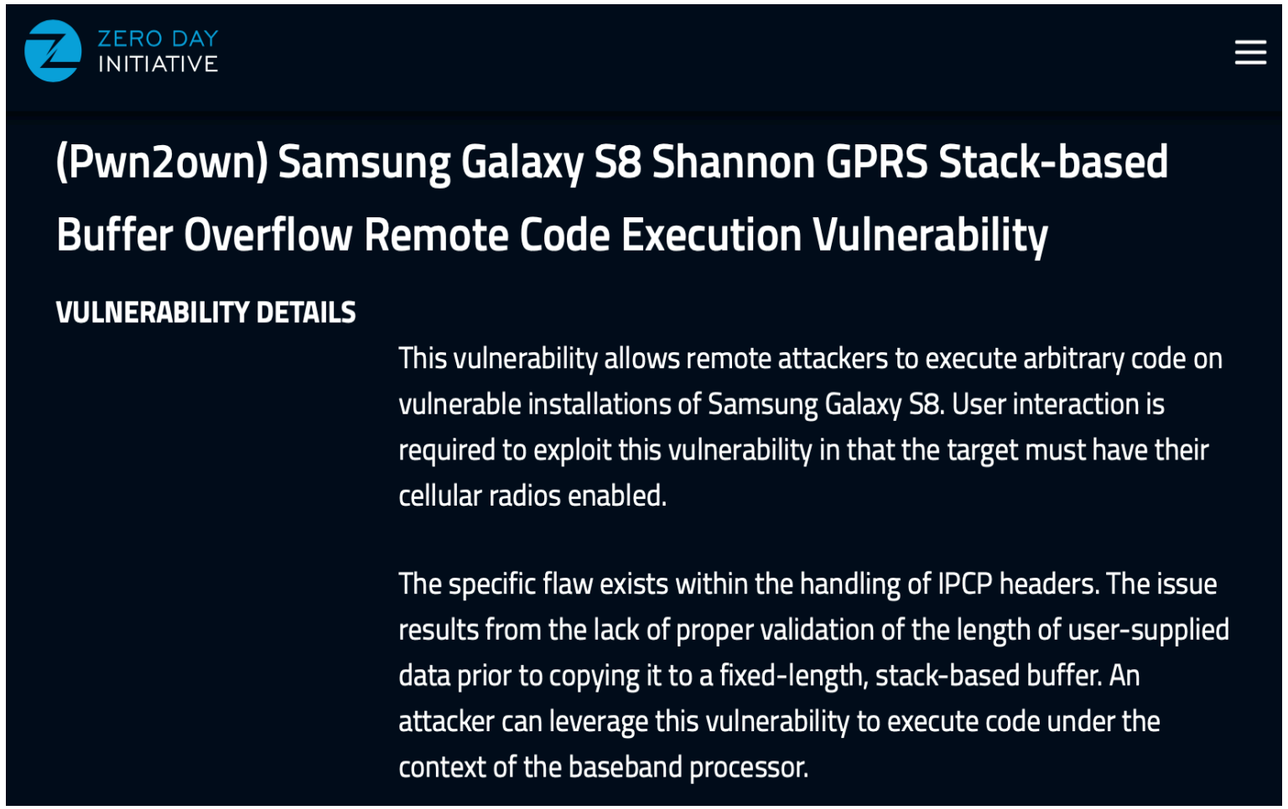
Broadcom chip bug opened 1 billion phones to a Wi-Fi-hopping worm attack

Wi-Fi chips used in iPhones and Android may revive worm attacks of old.

DAN GOODIN - 7/28/2017, 12:35 PM

Worm Attack via Arbitrary Code Execution on Broadcom Wi-Fi chip (aka BroadPwn)
– Nitay Artenstein at Black Hat USA 2017

Remote Compromise of Peripheral Chips



Vulnerability used to achieve Arbitrary Code Execution on Shannon Baseband Chip – Amat Cama at Mobile Pwn2Own

Remote Compromise of Peripheral Chips

ZDNet | CLOUD | AI | INNOVATION | SECURITY | MORE | NEWSLETTERS | ALL WRITERS

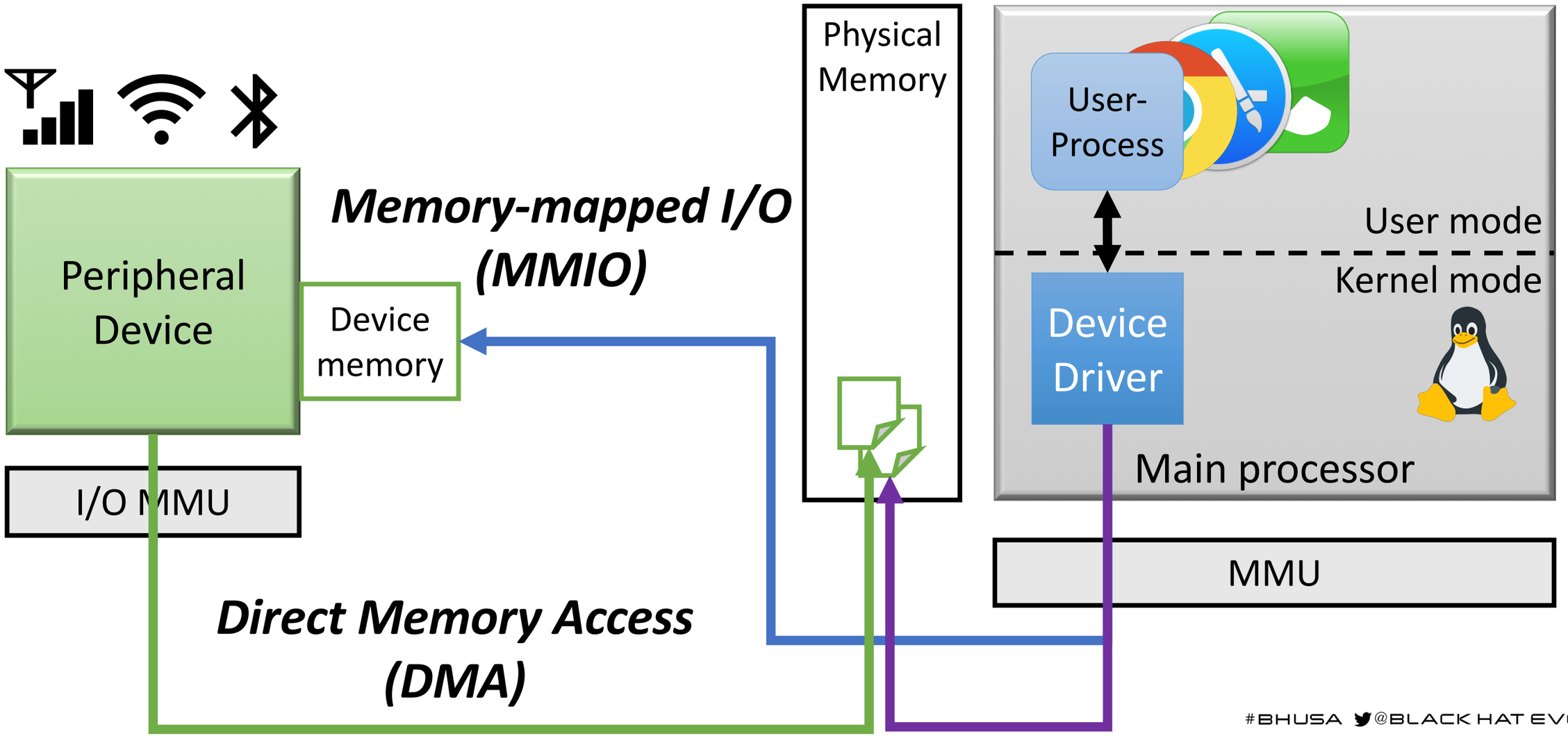
iPhone, Android hit by Broadcom Wi-Fi chip bugs: Now Apple, Google plug flaws

Google's Project Zero shows how attackers could target increasingly powerful Wi-Fi chips on phones as low-hanging fruit.

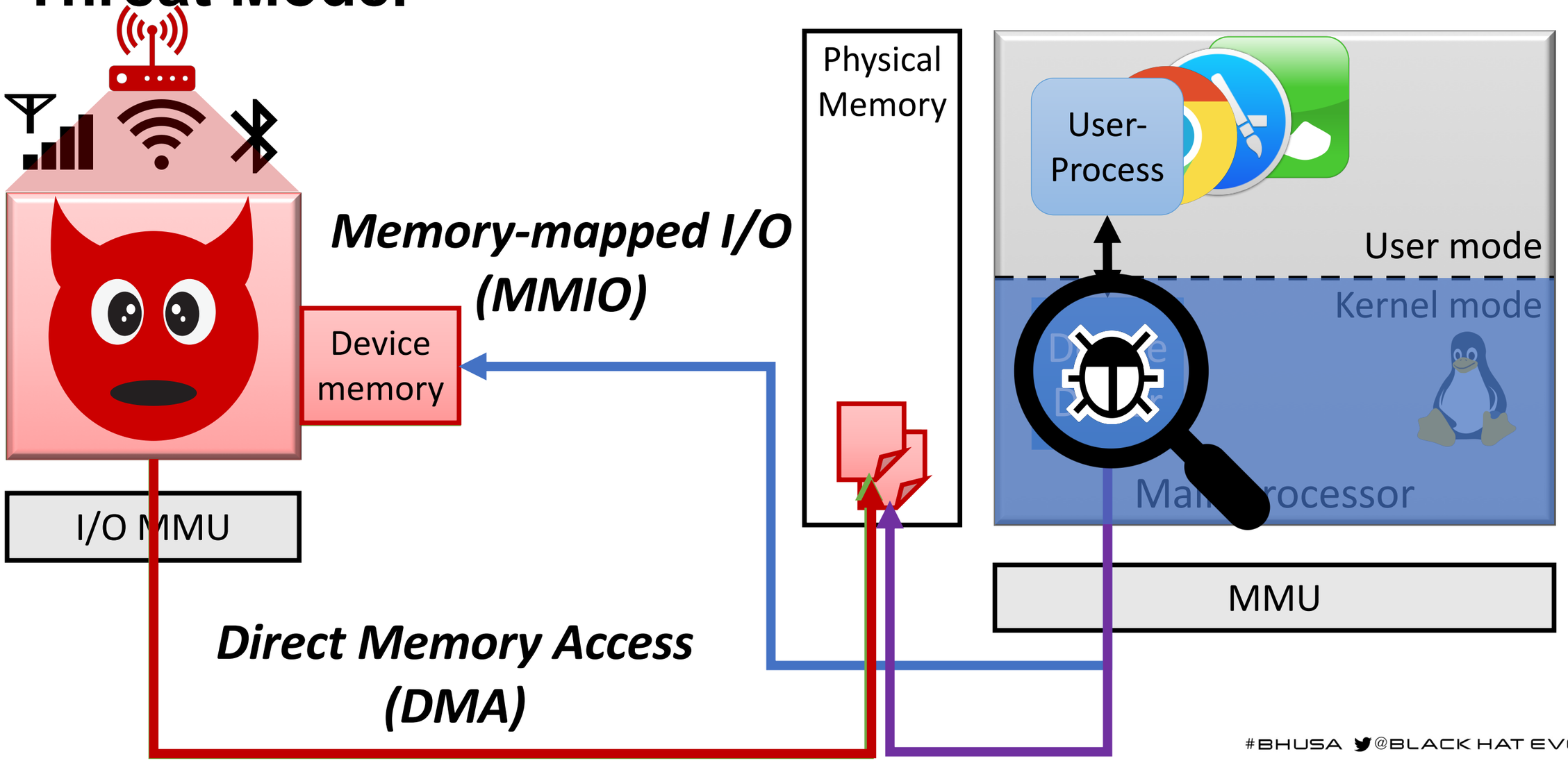
By Liam Tung | April 5, 2017 -- 10:48 GMT (03:48 PDT) | Topic: Security

Arbitrary Code Execution on Broadcom Wi-Fi chips *and* Main Processor
– Gal Beniamini at Google Project Zero

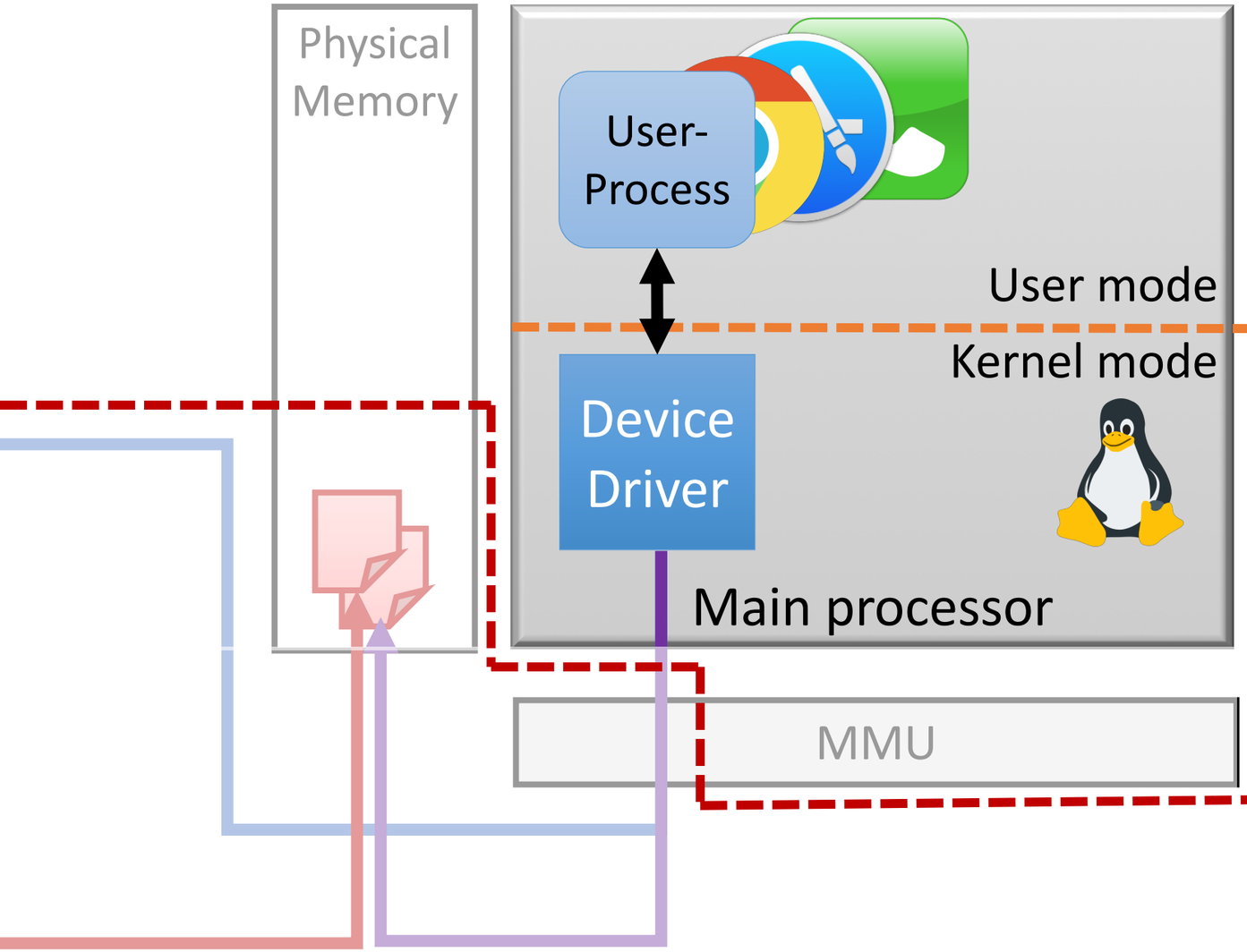
Hardware-OS Interface: MMIO and DMA



Threat Model



Hardware-OS Boundary vs. System Call Boundary



System Call Boundary

(A diverse set of) Sandboxes

- App sandbox, e.g., per-app UID
- Mandatory access control, i.e., SELinux
- Browser sandbox, e.g., seccomp
- I/O daemons

Hardware-OS Boundary

Sandbox: Page-granularity IOMMU

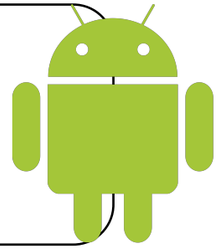
Memory Exploit Mitigations: Peripheral Firmware vs. User-mode Process

ARMv7, Xtensa, MIPS, …
(aka microcontrollers)

ARMv8

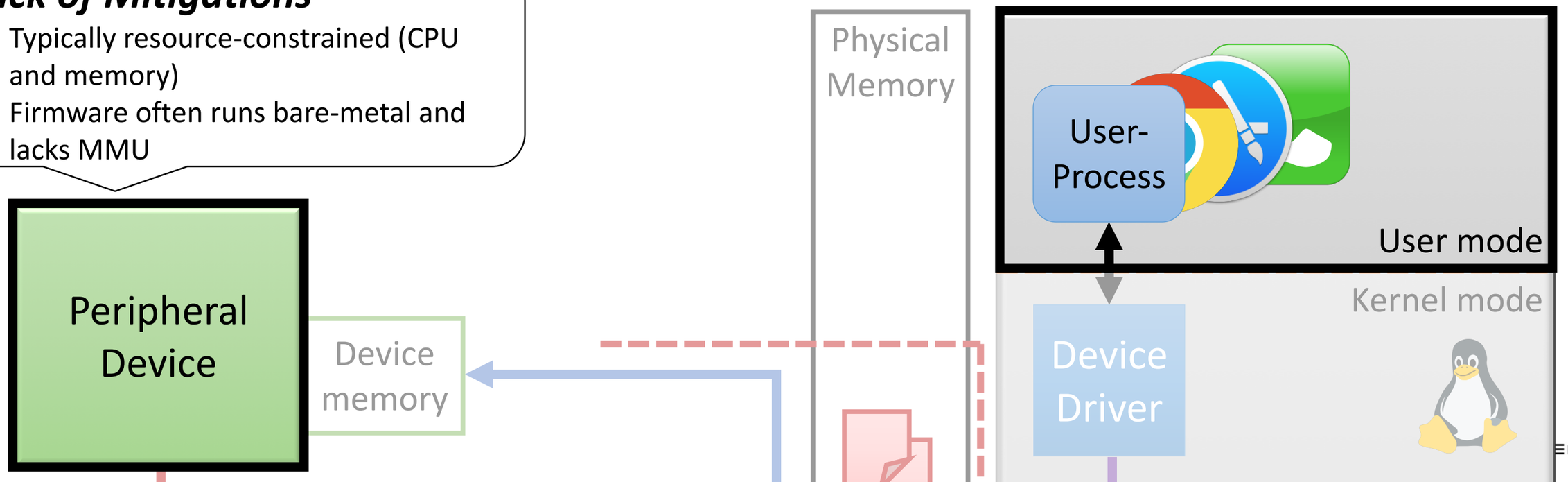
(A diverse set of) Mitigations

- ASLR and DEP
- Control-Flow Integrity
- Secure Heap Allocator

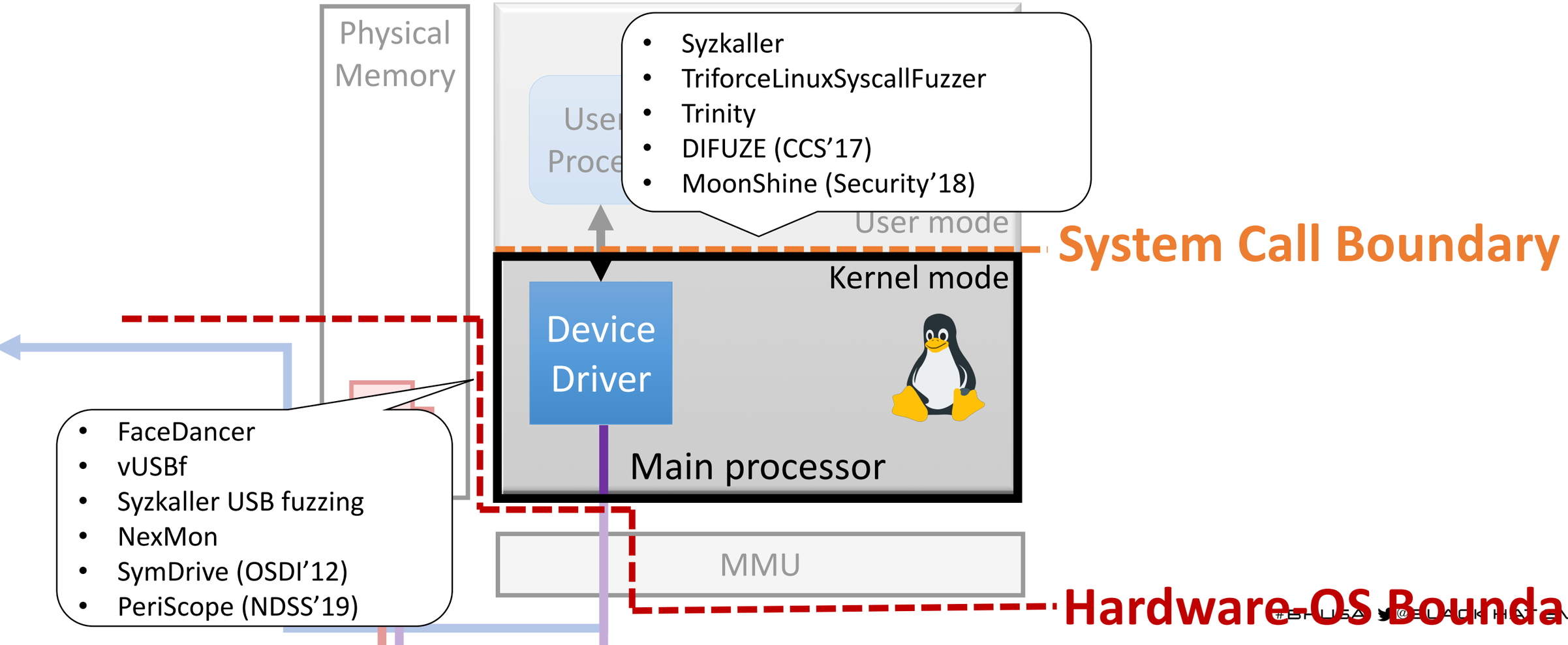


Lack of Mitigations

- Typically resource-constrained (CPU and memory)
- Firmware often runs bare-metal and lacks MMU

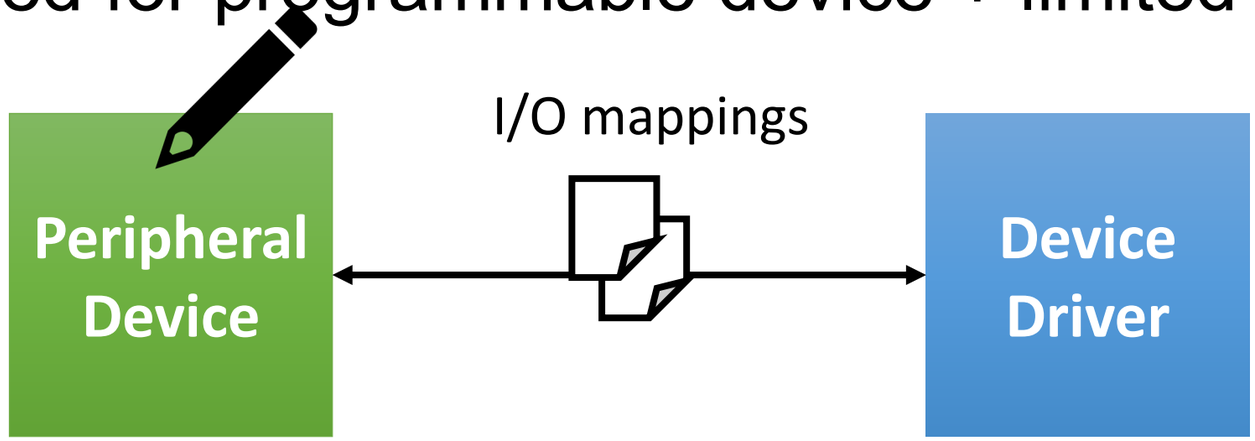


Analysis Tools: Hardware-OS Boundary vs. System Call Boundary



State-of-the-art: Analyzing HW-OS Interface (1/3)

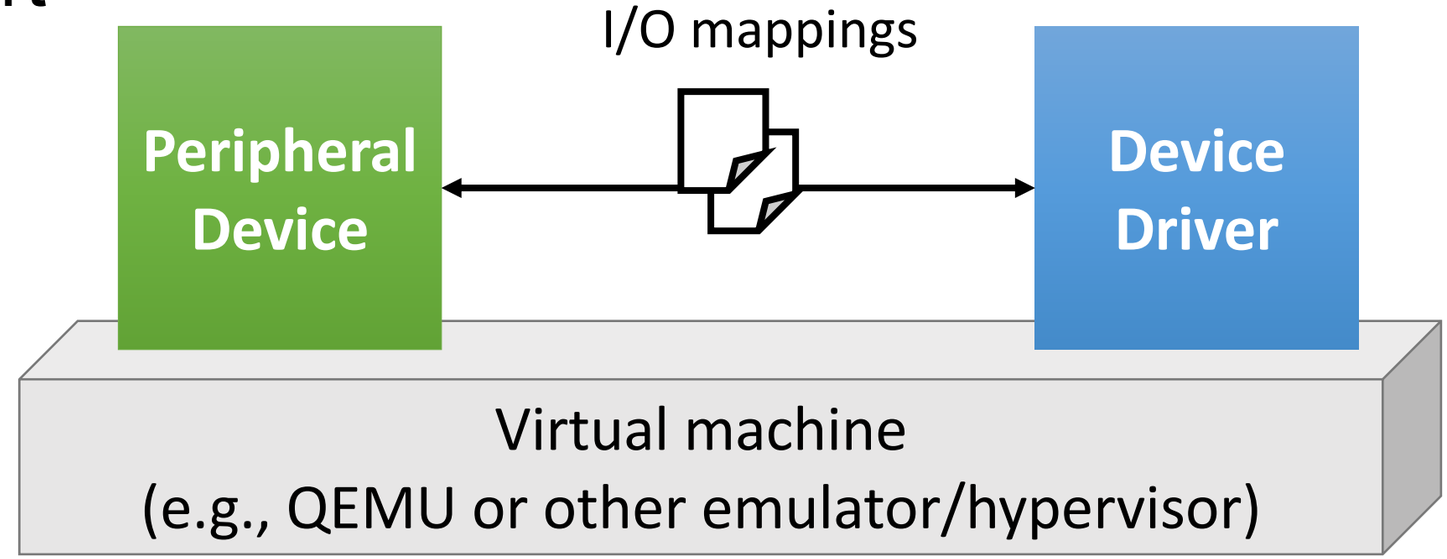
- ***Device Adaptation***
  - Pros: Non-intrusive (OS-independent)
  - Cons: Need for programmable device + limited visibility into driver



Reprogram the device
(e.g., FaceDancer21 custom USB)

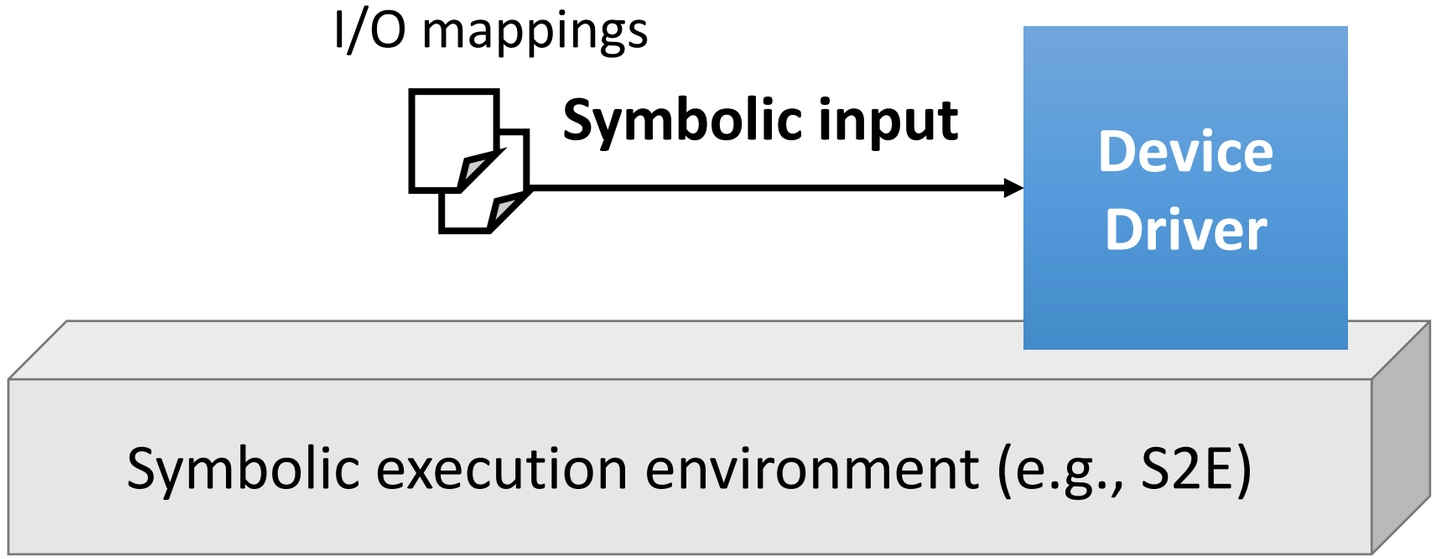
State-of-the-art: Analyzing HW-OS Interface (2/3)

- ***Virtual Machine Introspection***
  - Pros: High visibility yet non-intrusive
  - Cons: Need for virtual device and/or virtualization HW support



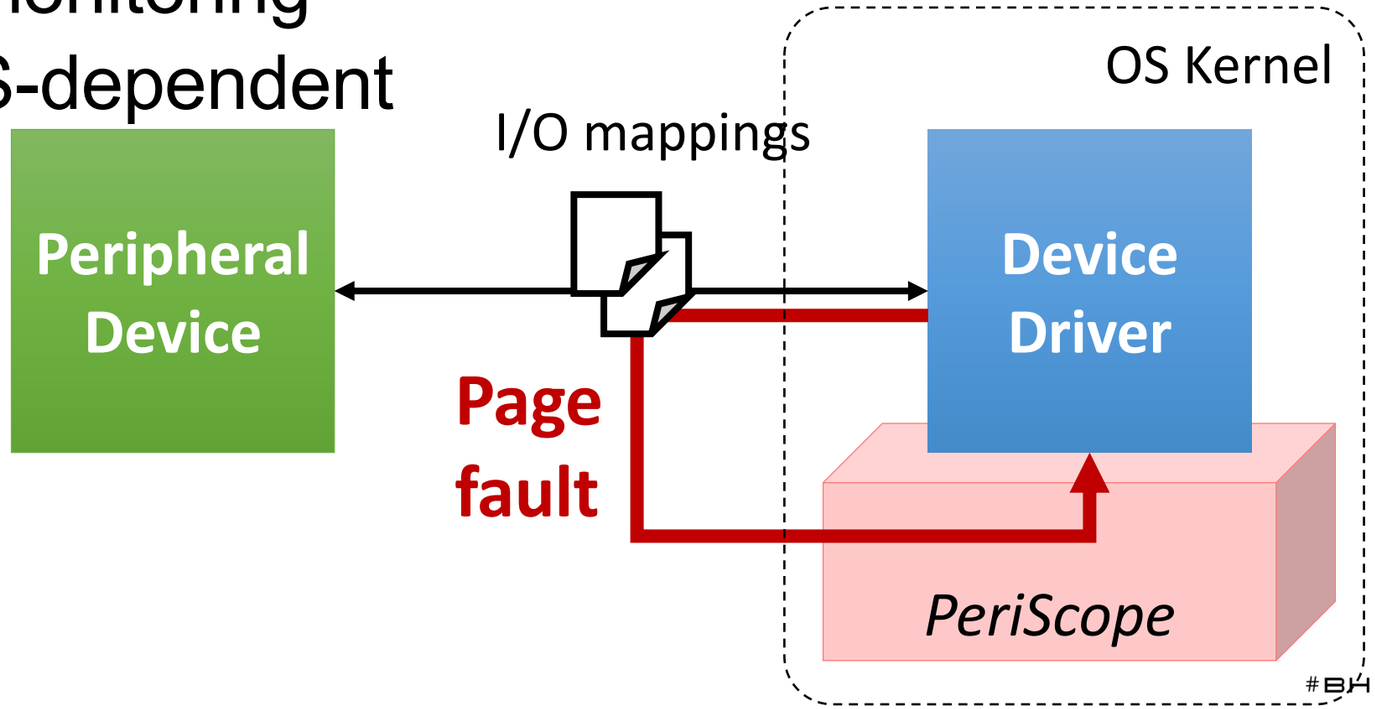
State-of-the-art: Analyzing HW-OS Interface (3/3)

- ***Symbolic Devices***
  - Pros: No need for physical/virtual device
  - Cons: Inherits cons of symbolic execution

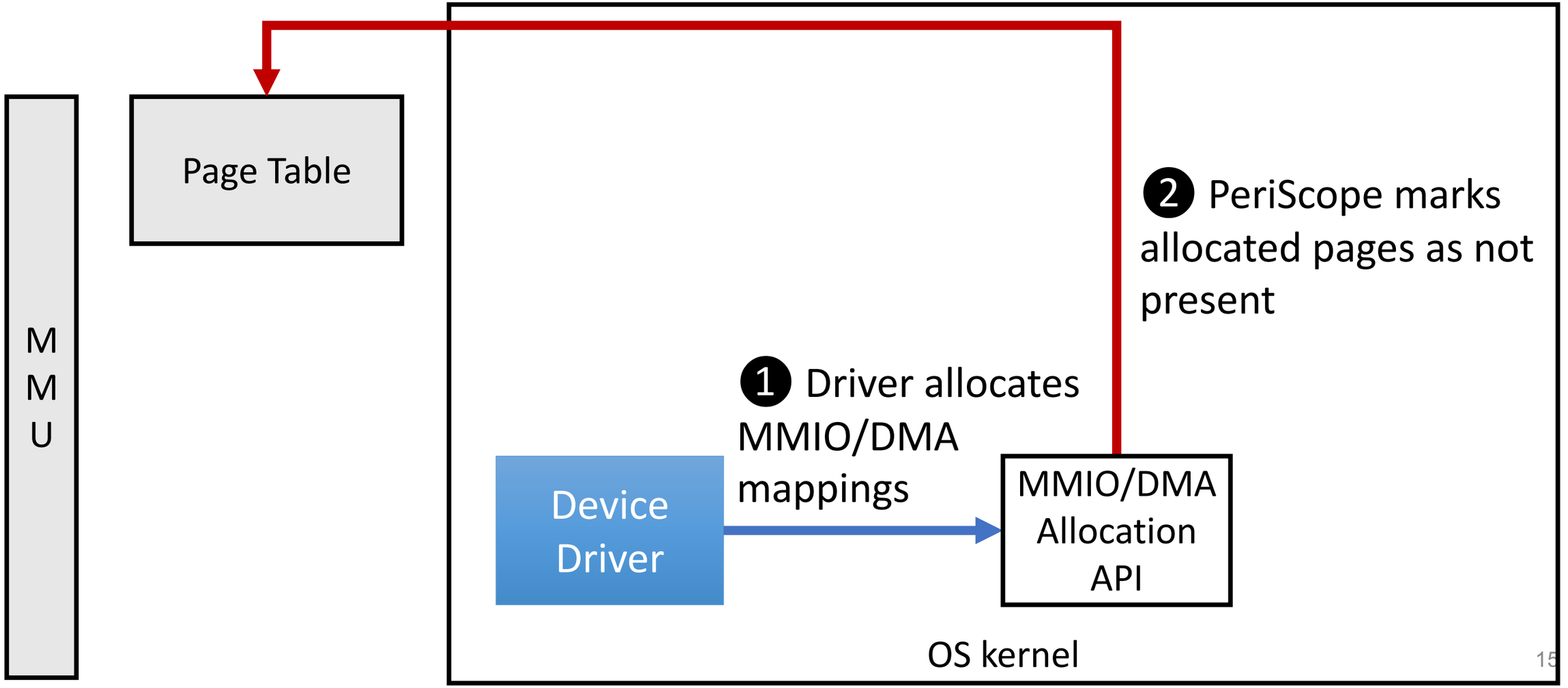


PeriScope – Our Approach

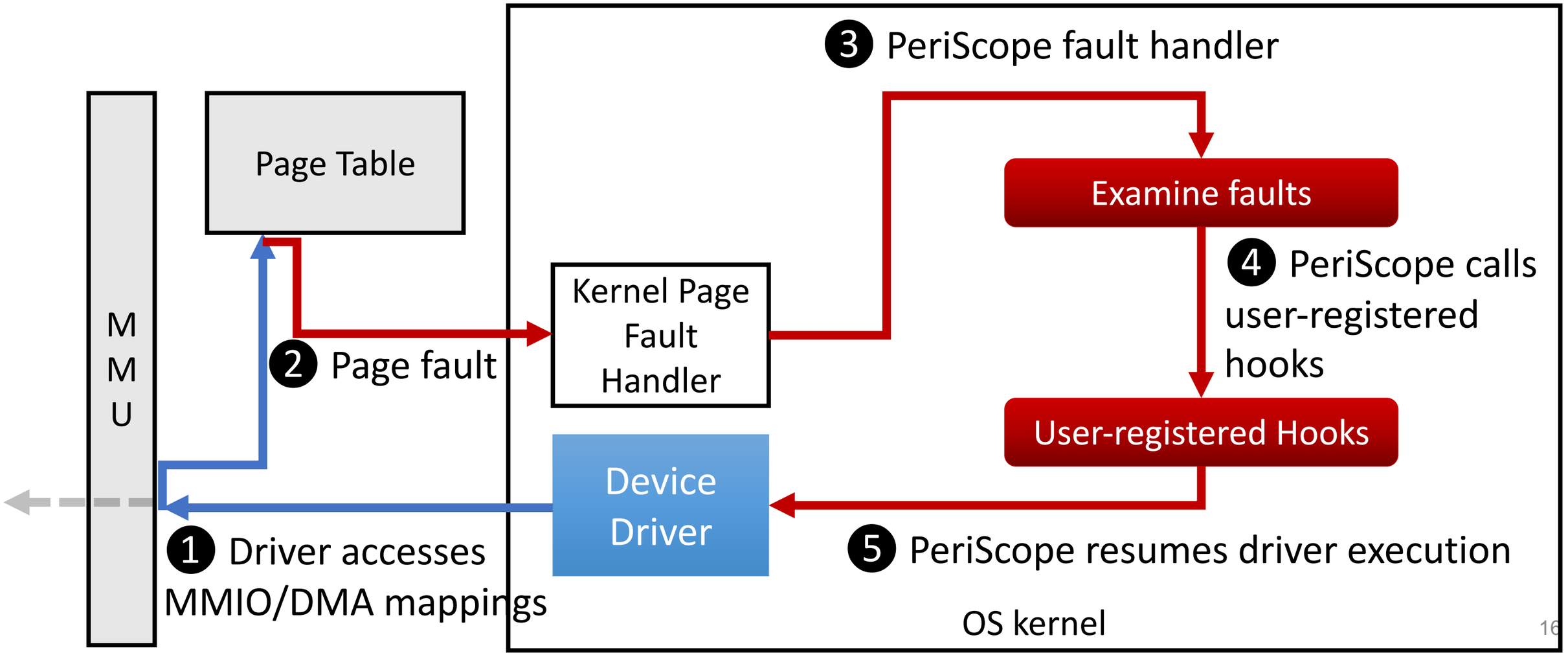
- ***In-kernel, page-fault-based monitoring***
  - Pros: No device-specific/virtual device requirement yet fine-grained monitoring
  - Cons: OS-dependent



PeriScope Overview



PeriScope Overview

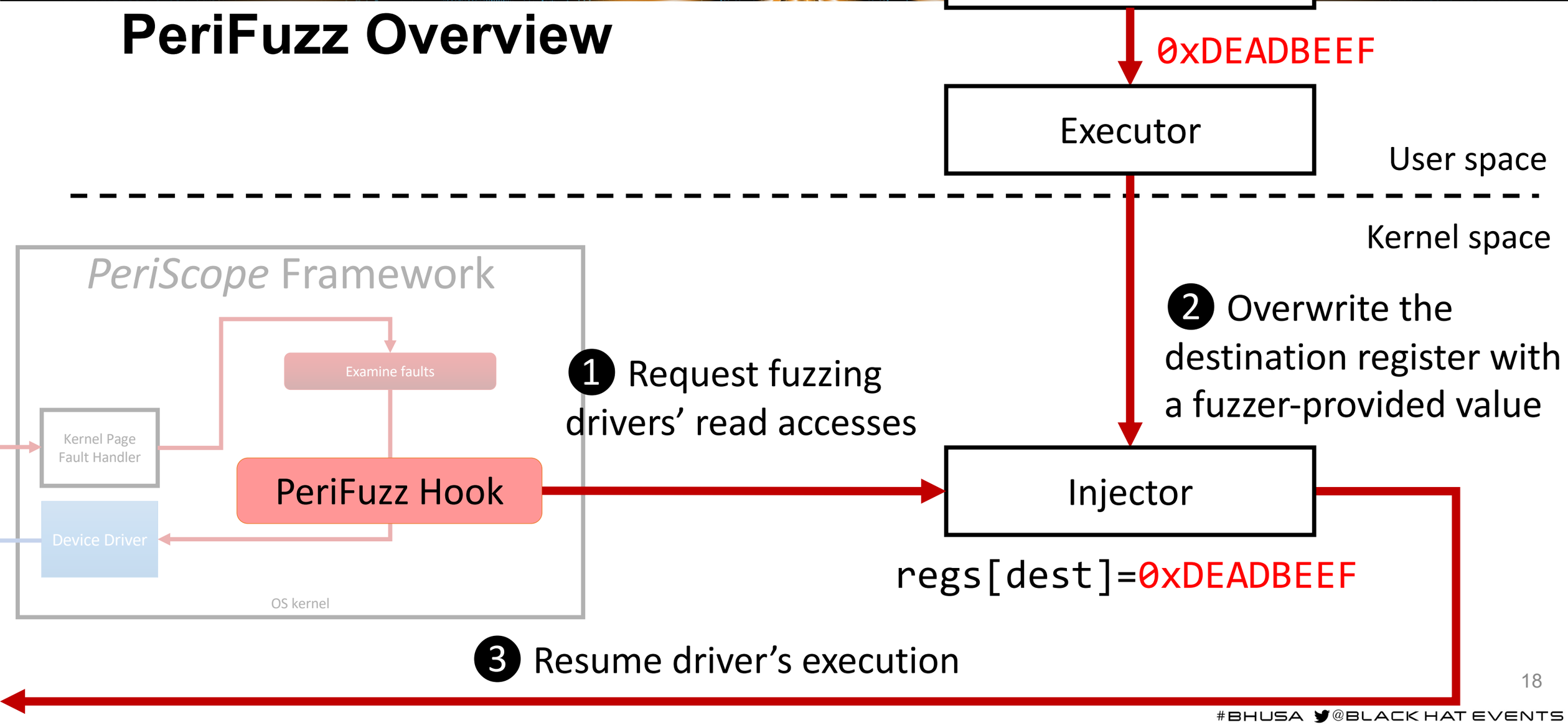


PeriFuzz – Fuzzer for the HW-OS boundary

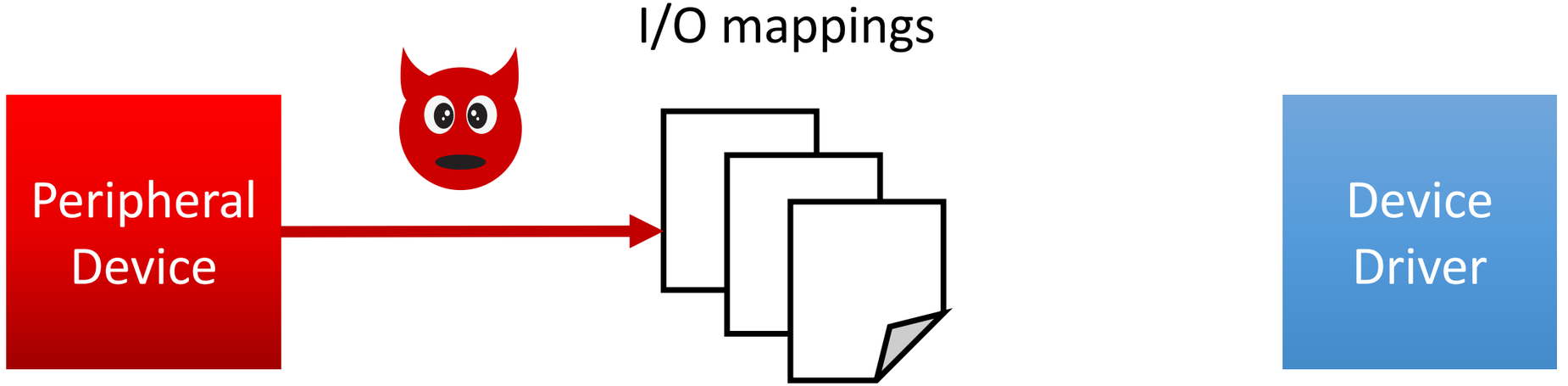
- **Goal**: To find vulnerabilities in kernel drivers reachable from a compromised device

- Therefore, *PeriFuzz* fuzzes **Driver's Read Accesses** to MMIO and DMA mappings

PeriFuzz Overview



Threat Model Review



Attacker can write any value to the I/O mappings even multiple times at any time

Potential Double-fetch Bugs in I/O Mappings

An I/O mapping

Peripheral Device

```
00 00 00 00
00 00 11 00
   ...
```

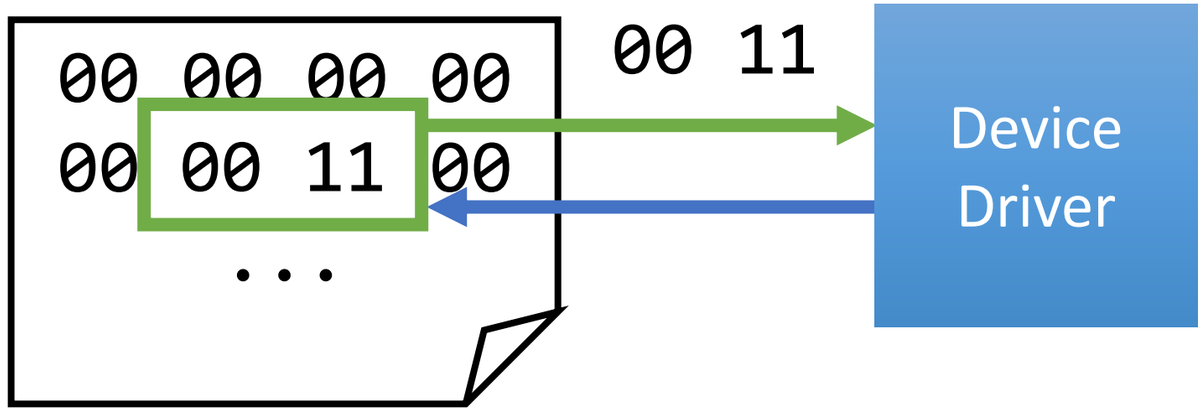
Device Driver

```
if (*map_ptr <= 0x00FF) {
   ...

  array[*map_ptr] = ...;
```

Potential Double-fetch Bugs in I/O Mappings

An I/O mapping

Peripheral Device

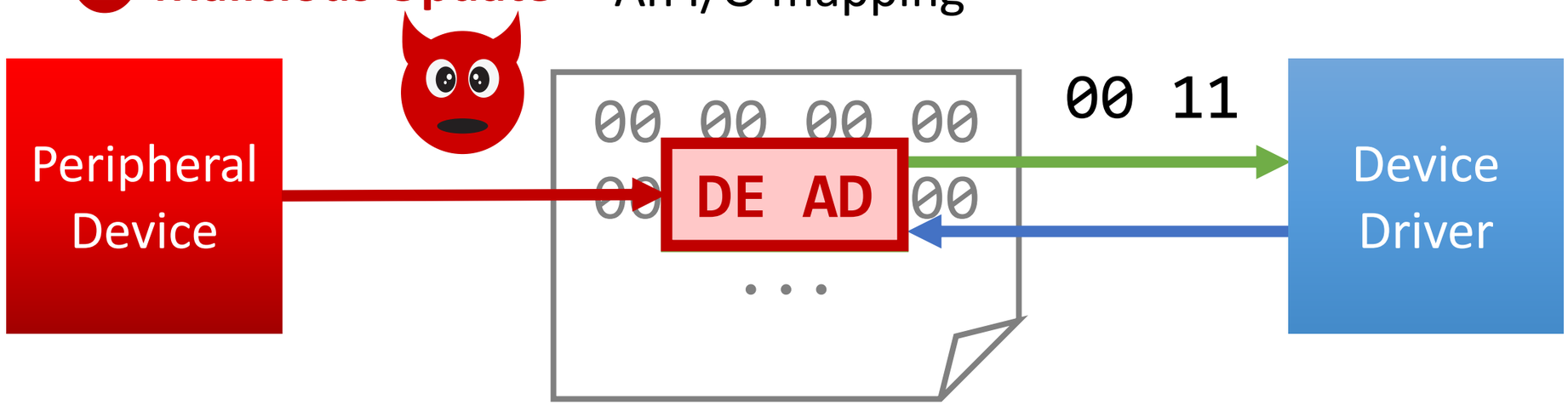


1 First fetch

& check passes

```
if (*map_ptr <= 0x00FF) {
  ...

  array[*map_ptr] = ...;
```

Potential Double-fetch Bugs in I/O Mappings



1 First fetch

& check passes

```
if (*map_ptr <= 0x00FF) {
   ...

  array[*map_ptr] = ...;
```

Potential Double-fetch Bugs in I/O Mappings

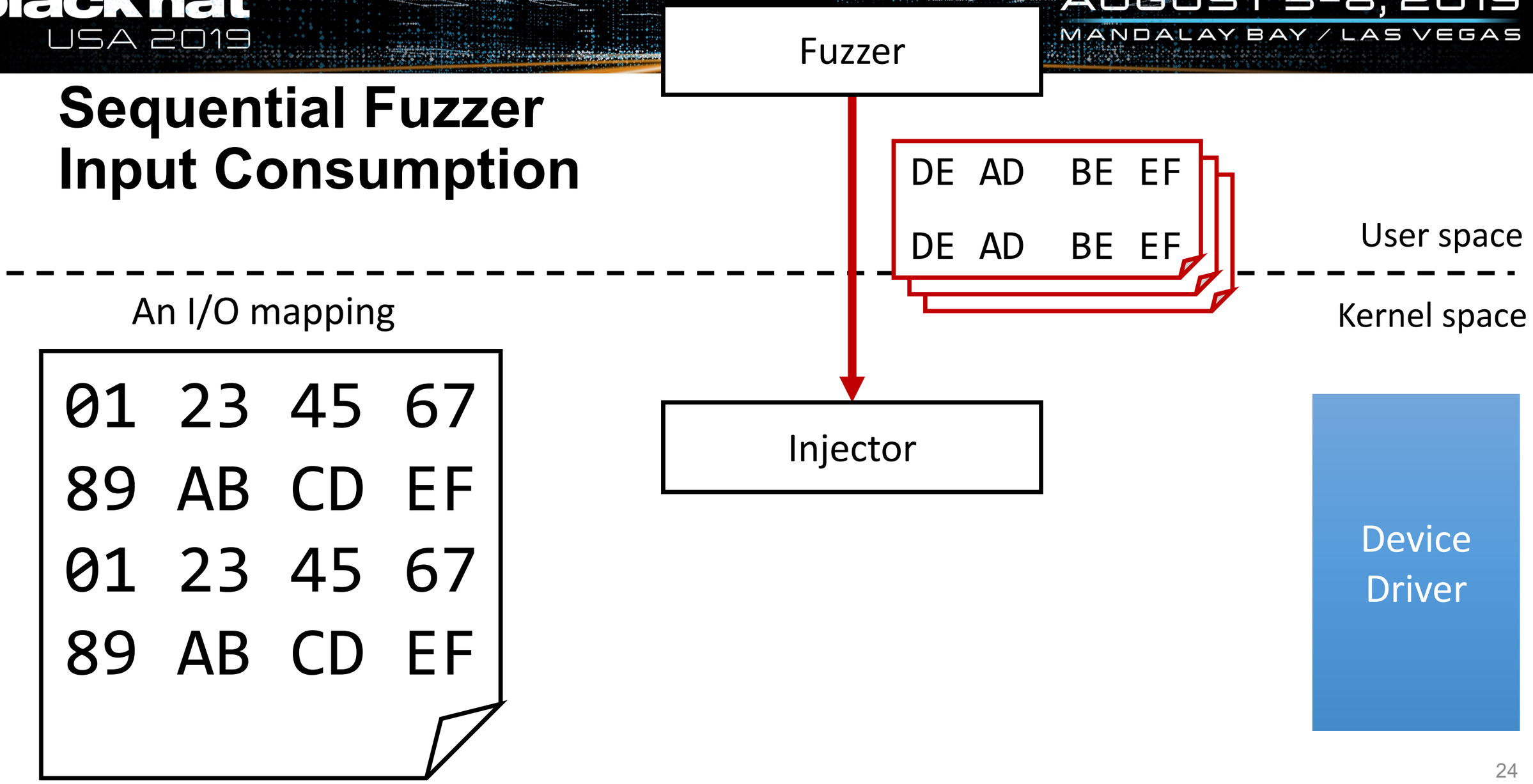
1 **First fetch**

& check passes

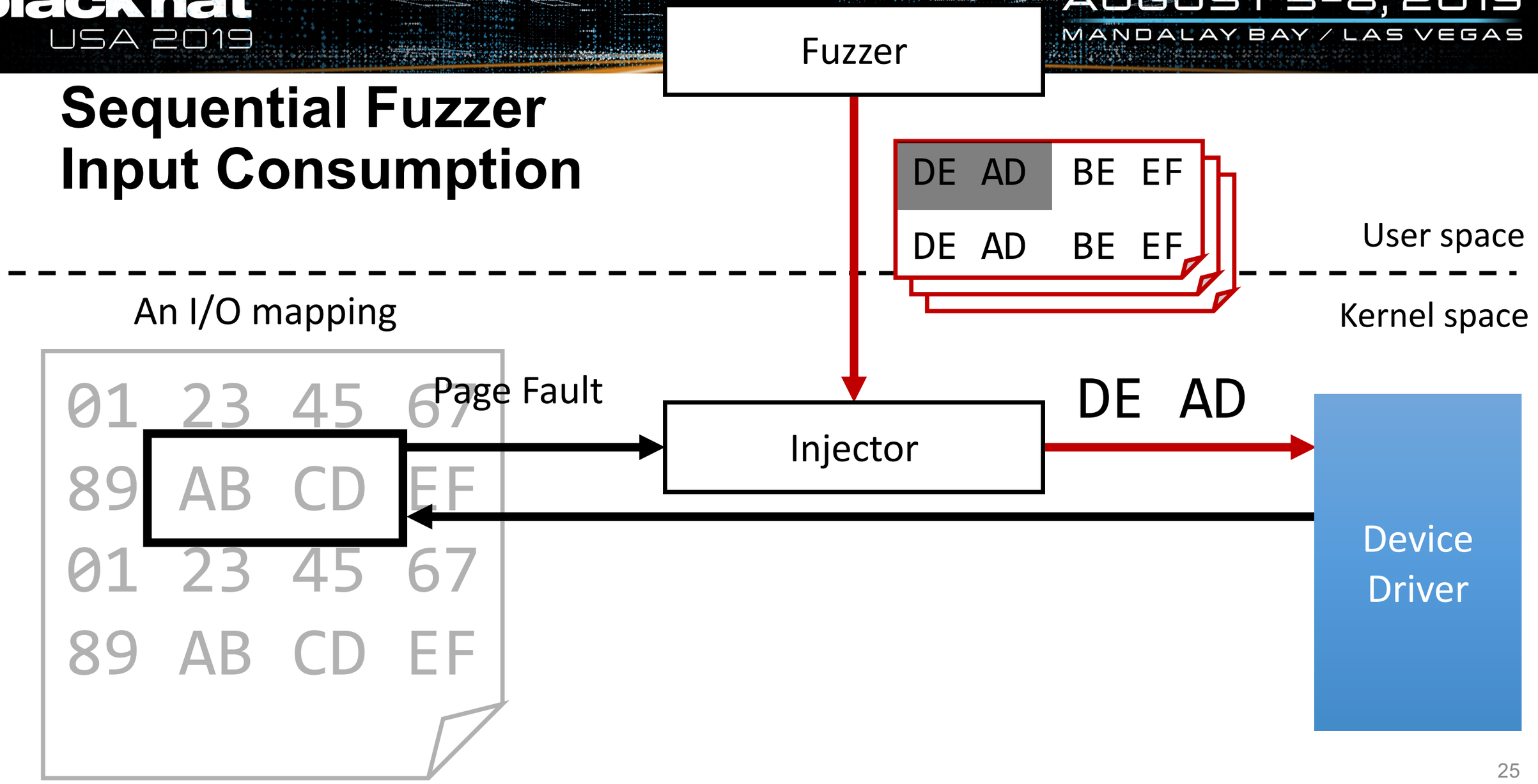
3 **Overlapping fetch (without rechecking)**

```
if (*map_ptr <= 0x00FF) {
  ...

  array[*map_ptr] = ...;
```

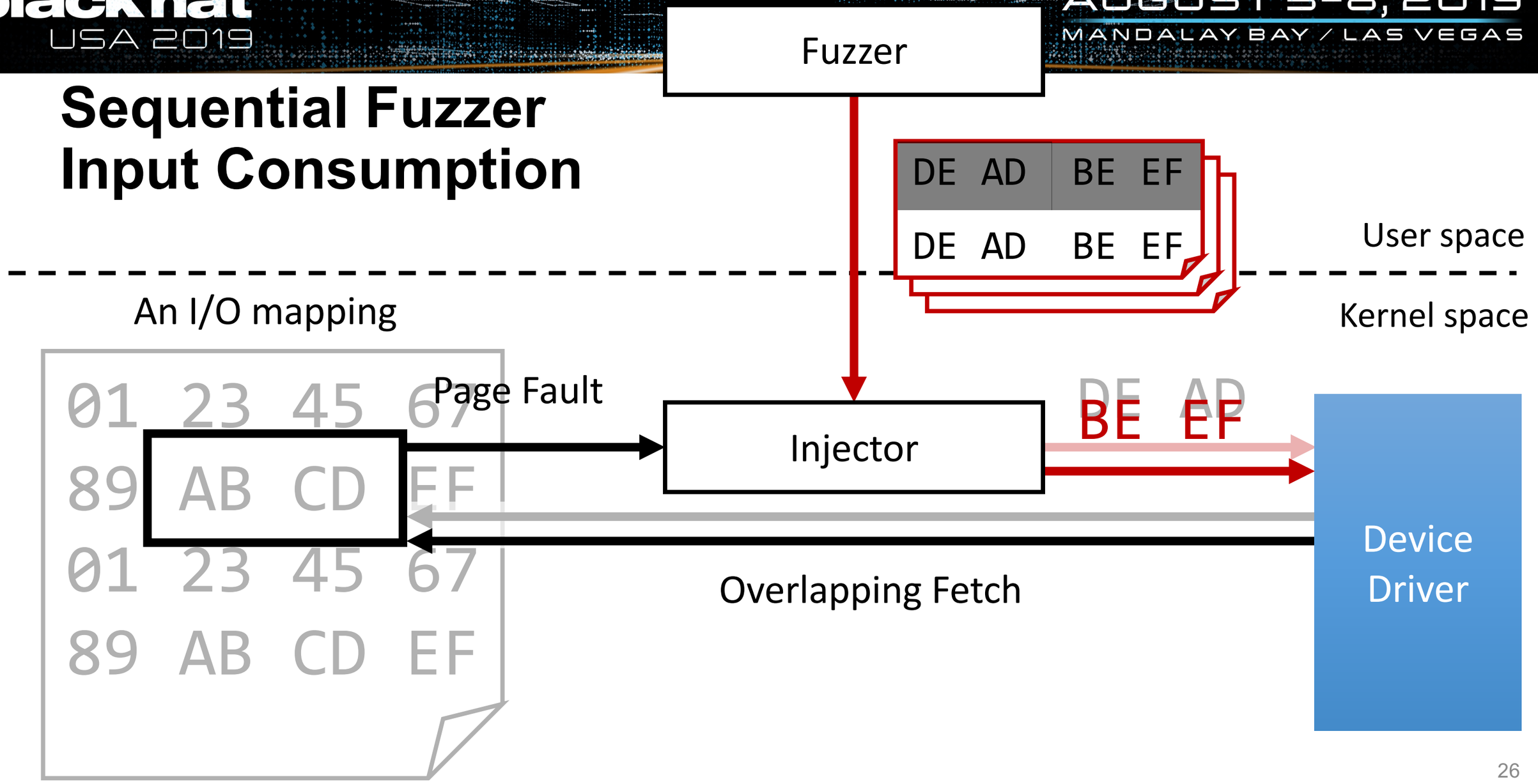
Sequential Fuzzer Input Consumption



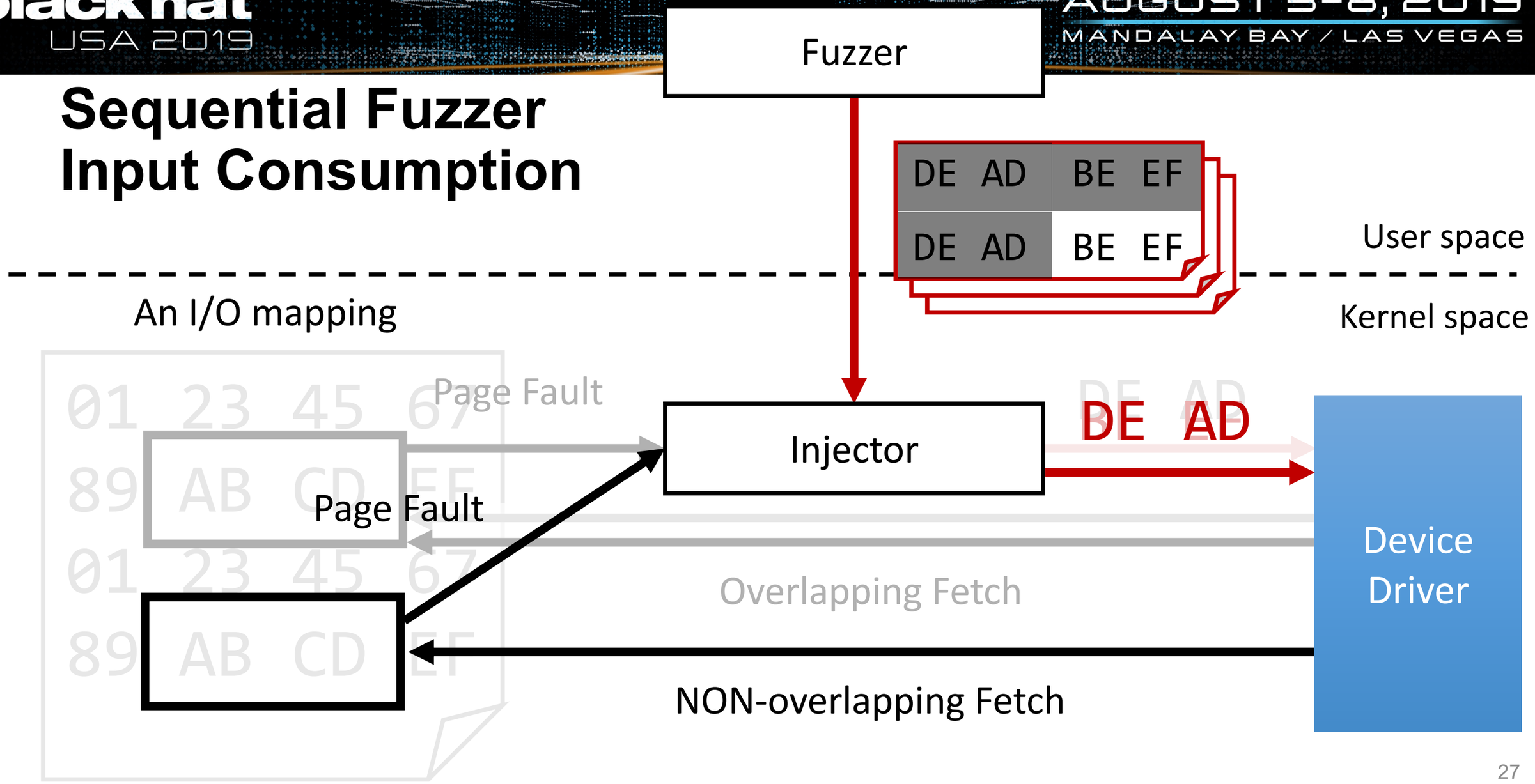
Sequential Fuzzer Input Consumption



Sequential Fuzzer Input Consumption

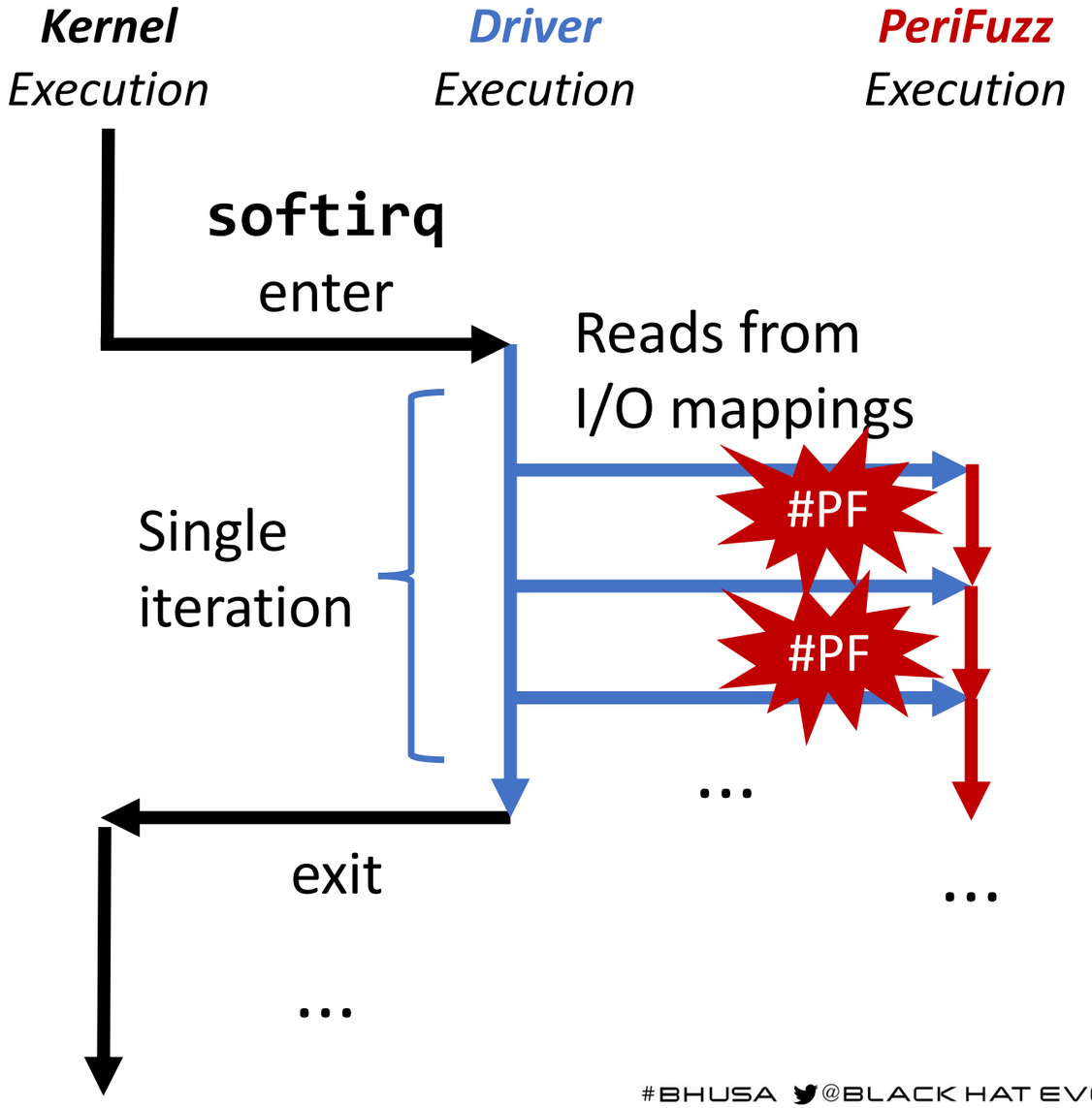


Sequential Fuzzer Input Consumption



Fuzzing Loop

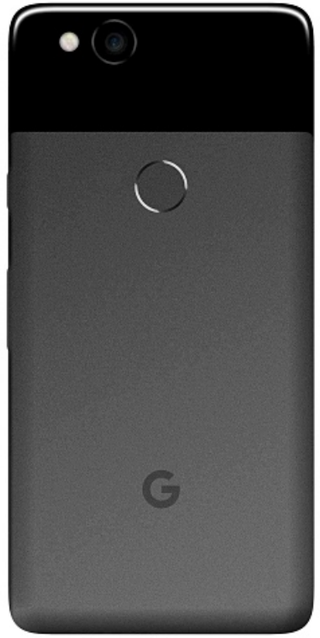
- Each iteration of the fuzzing loop consumes a single fuzzer-generated input
- aligned to the execution of software interrupt (`softirq`) handler's enter & exit
- can have **one or more reads** from I/O mappings.



Prototype Implementation

- Based on Linux kernel 4.4 for AArch64 (Google Pixel 2)
- Ported to 3.10 (Samsung Galaxy S6)
- AFL 2.42b as *PeriFuzz* front-end

Fuzzing Target: Wi-Fi Drivers



Qualcomm's Wi-Fi driver
in Google Pixel 2

Broadcom's Wi-Fi driver
in Samsung Galaxy S6

Fuzzing Target: Wi-Fi Drivers

1. Large codebase
   - Qualcomm's: 443,222 SLOC and Broadcom's: 122,194 SLOC
2. Highly concurrent
   - heavy use of bottom-half handlers, kernel threads, etc.
3. Lots of code runs in interrupt & kernel thread contexts
   - rather than system call contexts
4. No virtual device implementation available
5. No hypervisor support
   - EL2 not available in production smartphones

Bugs Found

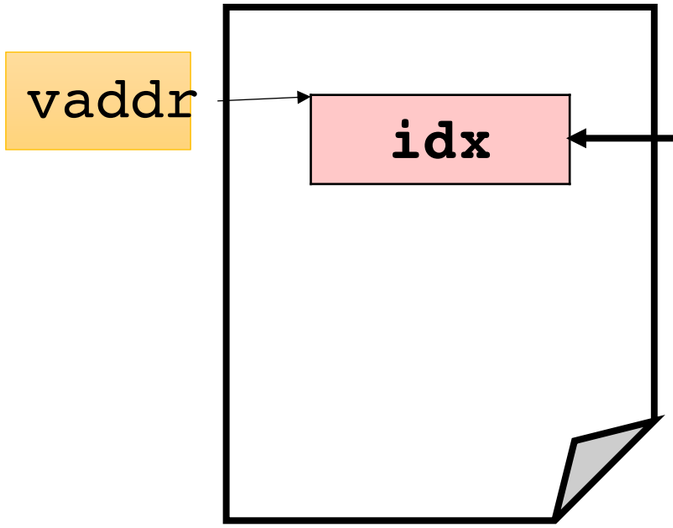
- Different classes of bugs
  - 9 buffer overreads or overwrites
  - 4 double-fetch issues
  - 1 kernel address leak
  - 3 reachable assertions
  - 2 null pointer dereferences

- In total, 15 vulnerabilities discovered
  - 9 previously unknown
  - 8 new CVEs assigned

Buffer Overflow (CVE-2018-11902)

Driver used a value read from a DMA mapping as an index into an array without validation (now patched!)

DMA I/O mapping



Driver Source Code

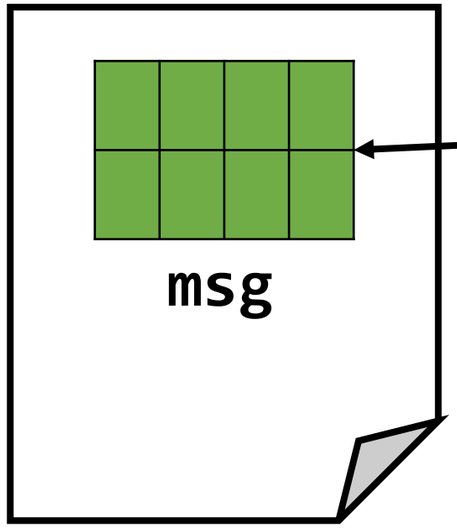
```
idx = *(pdev->rx_ring.alloc_idx.vaddr);

if ((idx < 0) || (idx > pdev->rx_ring.size_mask) ||
     (num > pdev->rx_ring.size))  {
QDF_TRACE(QDF_MODULE_ID_HTT,
  QDF_TRACE_LEVEL_ERROR,
  "%s:rx refill failed!", __func__);
return filled;
}

... // use of idx
```

Patch

Double-fetch Bug – Initial Fetch & Check

❶ The driver computes and verifies the checksum of a message

DMA I/O mapping



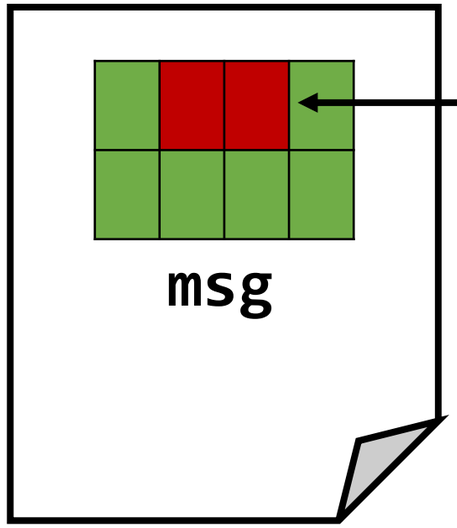
Driver Source Code

```
static uint8 dhd_prot_d2h_sync_xorcsum(...)
  ...
  prot_checksum = bcm_compute_xor32((volatile uint32 *)msg, num_words);
  if (prot_checksum == 0U) { /* checksum is OK */
    if (msg->epoch == ring_seqnum) {
      ring->seqnum++; /* next expected sequence number */
      goto dma_completed;
  ...
```

Double-fetch Bug – Overlapping Fetch & OOB

❷ The driver fetches the same bytes again from msg

DMA I/O mapping



Driver Source Code

```
ifidx = msg->cmn_hdr.if_id;
...
ifp = dhd->iflist[ifidx];
```

Overlapping fetch (fuzzed)

Out-of-bounds access

```
Unable to handle kernel paging request at virtual
address 2f6d657473797337

Kernel panic - not syncing: Fatal exception in
interrupt
```

Kernel Address Leak (CVE-2018-11947)

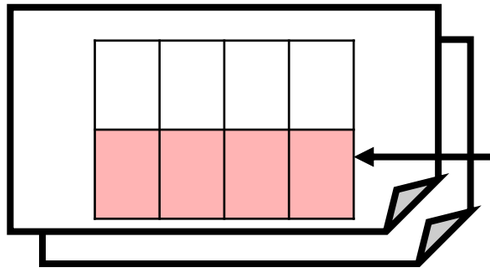
```
Unable to handle kernel paging request at virtual address
17000000d7ff0008

Kernel panic - not syncing: Fatal exception in interrupt
```

Symptom: A fuzzed value provided by *PeriFuzz* was *directly* being dereferenced.

Kernel Address Leak (CVE-2018-11947)

❶ Driver sends a kernel pointer to the device

DMA I/O mappings

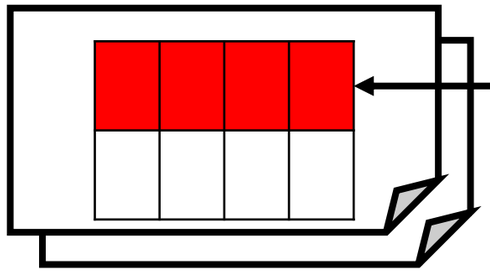


Write
cookie

Driver Source Code

```
non_volatile_req = qdf_mem_malloc(sizeof(*non_volatile_req));
...
// use pointer as cookie (which is later sent to the device)
cookie = ol_txrx_stats_ptr_to_u64(non_volatile_req);
...
```

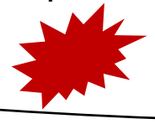
❷ Device sends the cookie back, which is then dereferenced by the driver



Read
cookie

(fuzzed)

```
req = ol_txrx_u64_to_stats_ptr(cookie);
...
req->... // A value read from I/O mapping is dereferenced
```



Fuzzing Throughput

- Fuzzing throughput is about 7~24 inputs/sec depending on the nature of the I/O mapping being fuzzed.
- The number of page faults is the main contributor. (e.g., 50 page faults per iteration gives around 20 inputs/sec)
- Rooms for improvement. (Details in the paper)

Phone/Driver	I/O Mapping	Peak Throughput (# of test inputs/sec)
Pixel 2 - QCACLD-3.0	QC1	23.67
	QC2	15.64
	QC3	18.77
	QC4	7.63
Galaxy S6 - BCMDHD4358	BC1	9.90
	BC2	14.28
	BC3	10.49
	BC4	15.92

cf) On Pixel 2, Syzkaller achieves on average 24 program executions per second (max: ~60).
(1 proc ADB-based configuration measured for a 15-min period)

Future Work

- Minimizing the impact of shallow bugs
  - All bugs found in less than 10,000 inputs
  - Shallow bugs frequently hit, which causes system restarts (reboot takes 1 min)
  - We had to manually disable subpaths rooted at bugs already found
- Improving throughput
  - Slower than, for example, typical user-space fuzzing
  - Possible optimizations and trade-offs outlined in the paper

Conclusion

- Remote peripheral compromise poses a serious threat to OS kernel security.
- PeriScope and PeriFuzz are practical dynamic analysis tools that can analyze large, complex drivers along the hardware-OS boundary.
- PeriScope and PeriFuzz are effective at finding vulnerabilities along the HW-OS boundary.
  - Memory overreads/overwrites, address leak, null pointer dereferences, reachable assertions, and double-fetch bugs

Q & A

Thank you!

Contact
Dokyung Song
Ph.D. Student at UC Irvine
dokyungs@uci.edu