Android Virtualization Framework
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Fuzzing Host-to-Guest Attack Surface in Android Protected KVM

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Agenda

- Introduction into Android pKVM
  - Overview & motivation
  - Attack surface
- Virtio driver stack in pKVM
  - Why fuzzing?
  - Challenges with fuzzing virtio front-end drivers
- Fuzzing virtio front-end drivers with LKL
  - Linux Kernel Library for fuzzing
  - Overview of the developed fuzzers for pVM
- Conclusion & Future work

Terminology

- ABL -- Android bootloader
- AVB -- Android verified boot
- AVF -- Android virtualization framework
- GKI -- Generic kernel image
- LKL -- Linux kernel library
- Microdroid -- a Google-provided mini-Android OS that runs in a pVM
- pKVM -- Protected KVM
- pVM -- Protected virtual machine
- PVMFW -- Protected virtual machine firmware
- SMP -- Symmetric multiprocessing

Who we are

Will Deacon

- Active upstream kernel developer, co-maintaining aarch64 architecture port, locking, atomics, memory model, TLB, SMMU, ...
- Leading the Protected KVM project to enable KVM on Android

Eugene Rodionov

- Android Red Team security engineer
- Focused on finding & exploiting vulnerabilities in low-level software in AOSP and Pixel devices

Android Protected KVM

Android Protected KVM: Overview

- **Protected KVM introduces a new security model where the host and the deprivileged guest VMs mutually distrust each other.**

- **Mutual distrust:**
  - Protected KVM provides security for the guest VMs even if the host kernel is compromised
  - A malicious guest cannot escape into the host (Android) or cannot compromise another guest VM

- **Deprivileged guests:**
  - Guest VMs don't need TrustZone privileges and run in non-secure world EL1/EL0

- **Protected KVM on Arm64: A Technical Deep Dive** by Quentin Perret
- **Now You See Me, Now You Don't: Splitting pKVM Into Discrete, Mutually Exclusive Address Spaces** by Marc Zyngier
- **All Bark and no Bite: vCPU Stall Detection for KVM Guests** by Sebastian Ene
- **Panel discussion: KVM-based virtualization contributor Q&A** by Will Deacon, et al

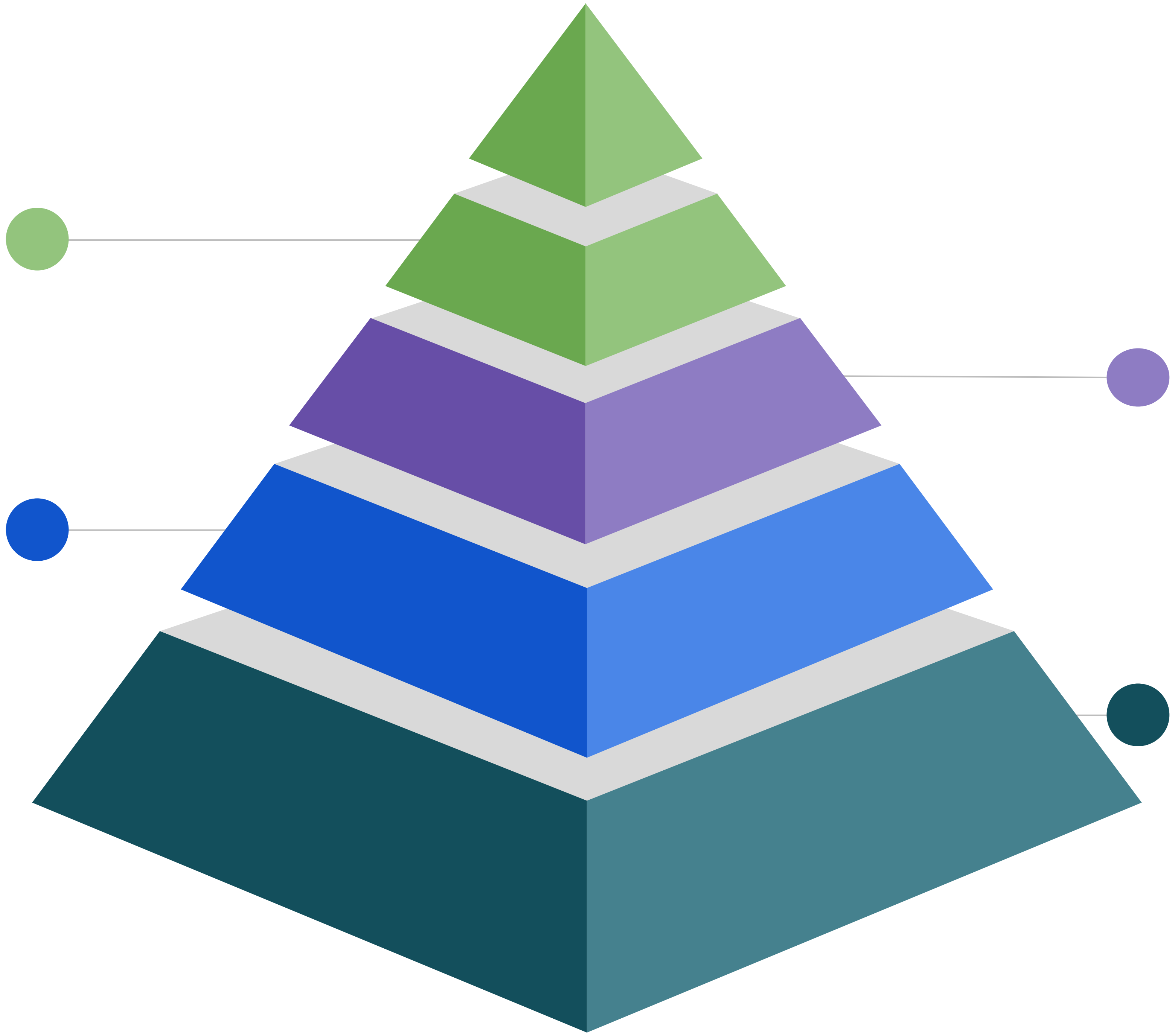
Building pillars of pKVM security

Host & guest VM software

- VMM and protected VM payload
- Process **untrusted input** received from the host/guest respectively
- **Prioritizing host-to-guest attacks**

Hypervisor

- Enforces isolation of the guests between each other and from the host
- Protects pVM bootloader and sealing keys.



Attestation & Sealing

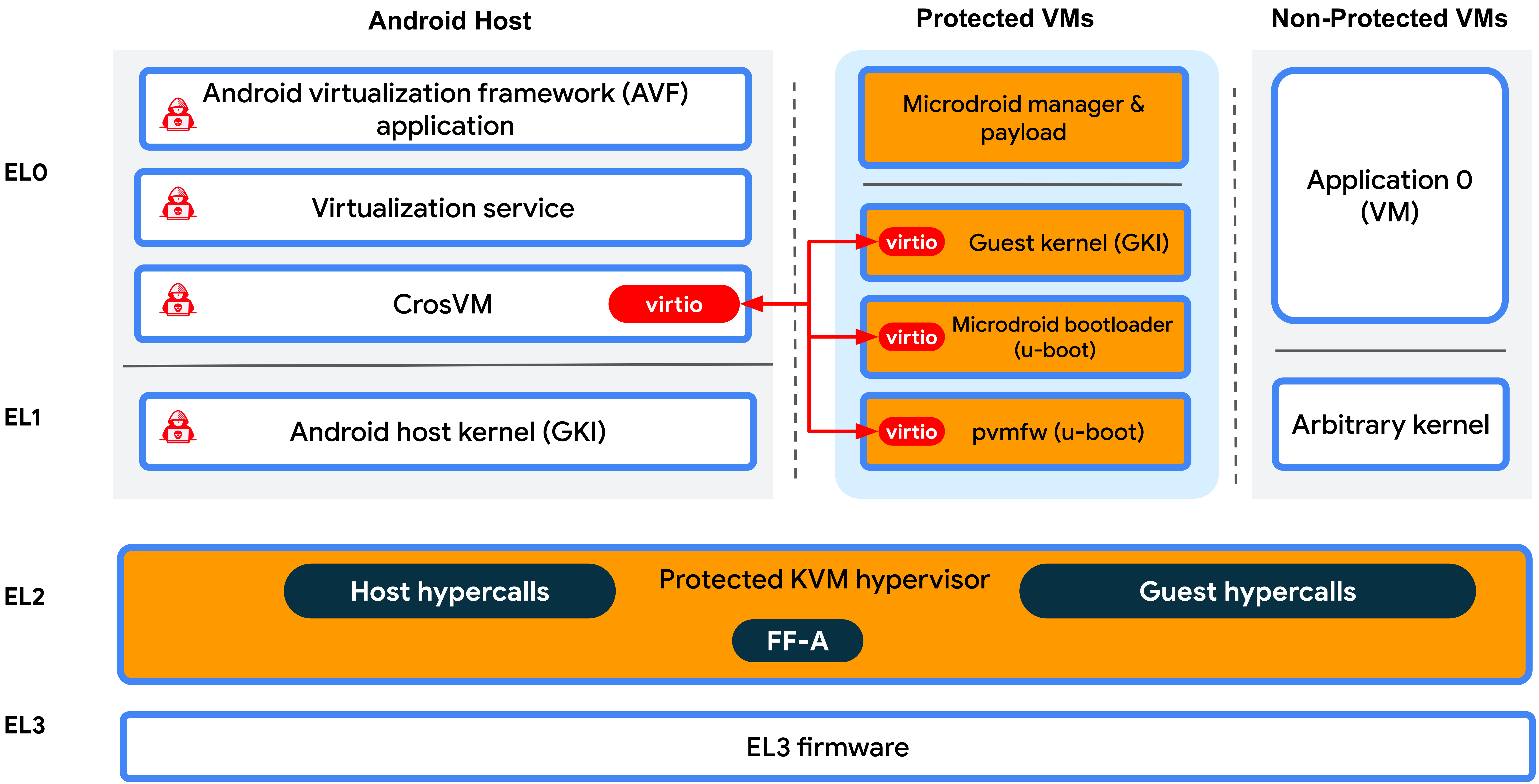
- Enable external services to attest the integrity of protected VMs
- Enable per-VM instance secret data

Secure boot & AVB

- Enforces authenticity of the hypervisor and Android kernel
- Provides attestation services and protects sealing keys

Virtio attack surface

Android Protected KVM Attack Surface



Attacking guests via virtio

Host:
virtio back-end

Host <==> guest shared memory

Virtio descriptors			
buffer PA	buffer len	flags	next desc
0x7fff..800	0x100	0x0	1
...	...	...	2
...	...	...	...

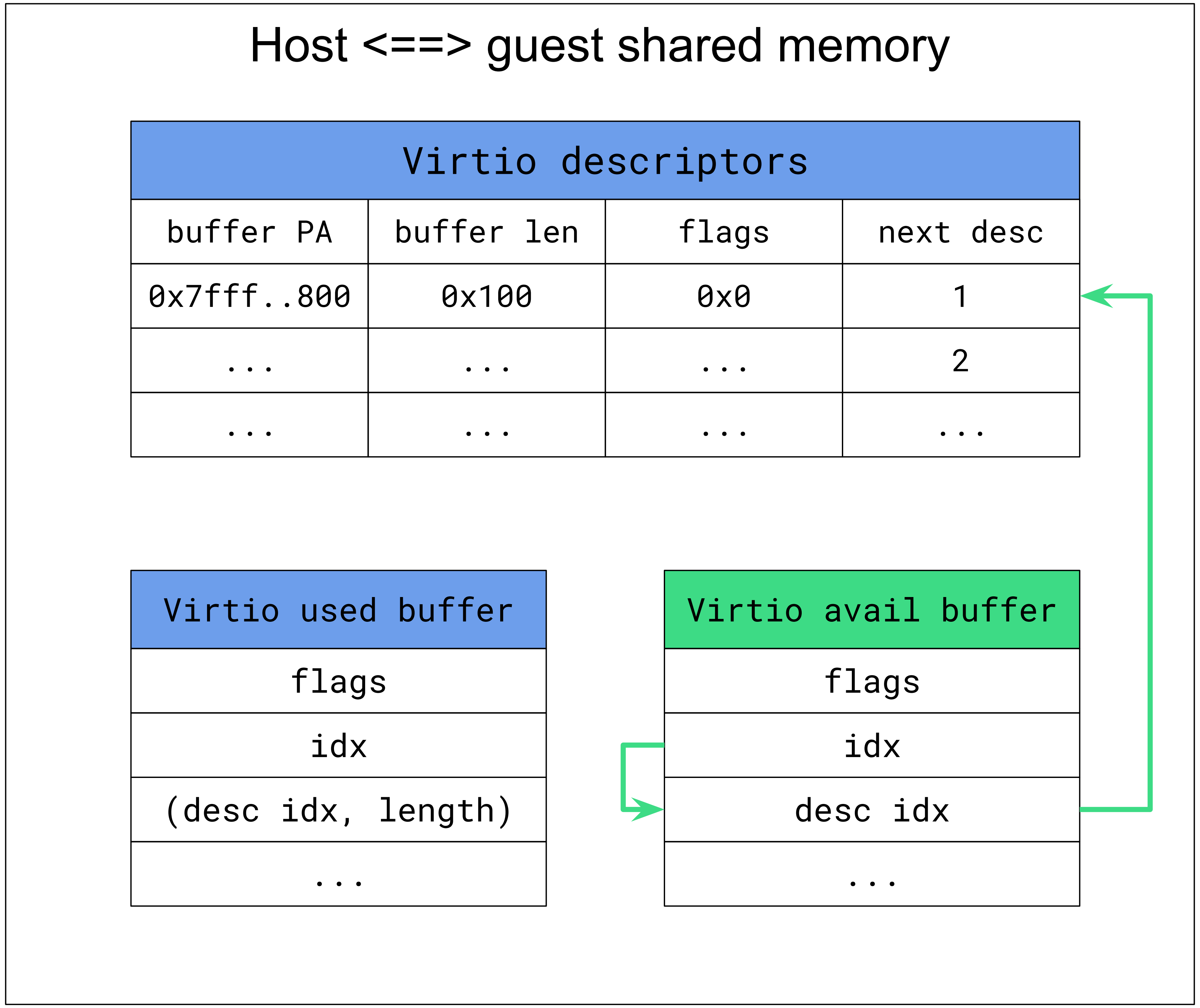
Virtio used buffer
flags
idx
(desc idx, length)
...

Virtio avail buffer
flags
idx
desc idx
...

Guest:
virtio front-end

Attacking guests via virtio

Host:
virtio back-end



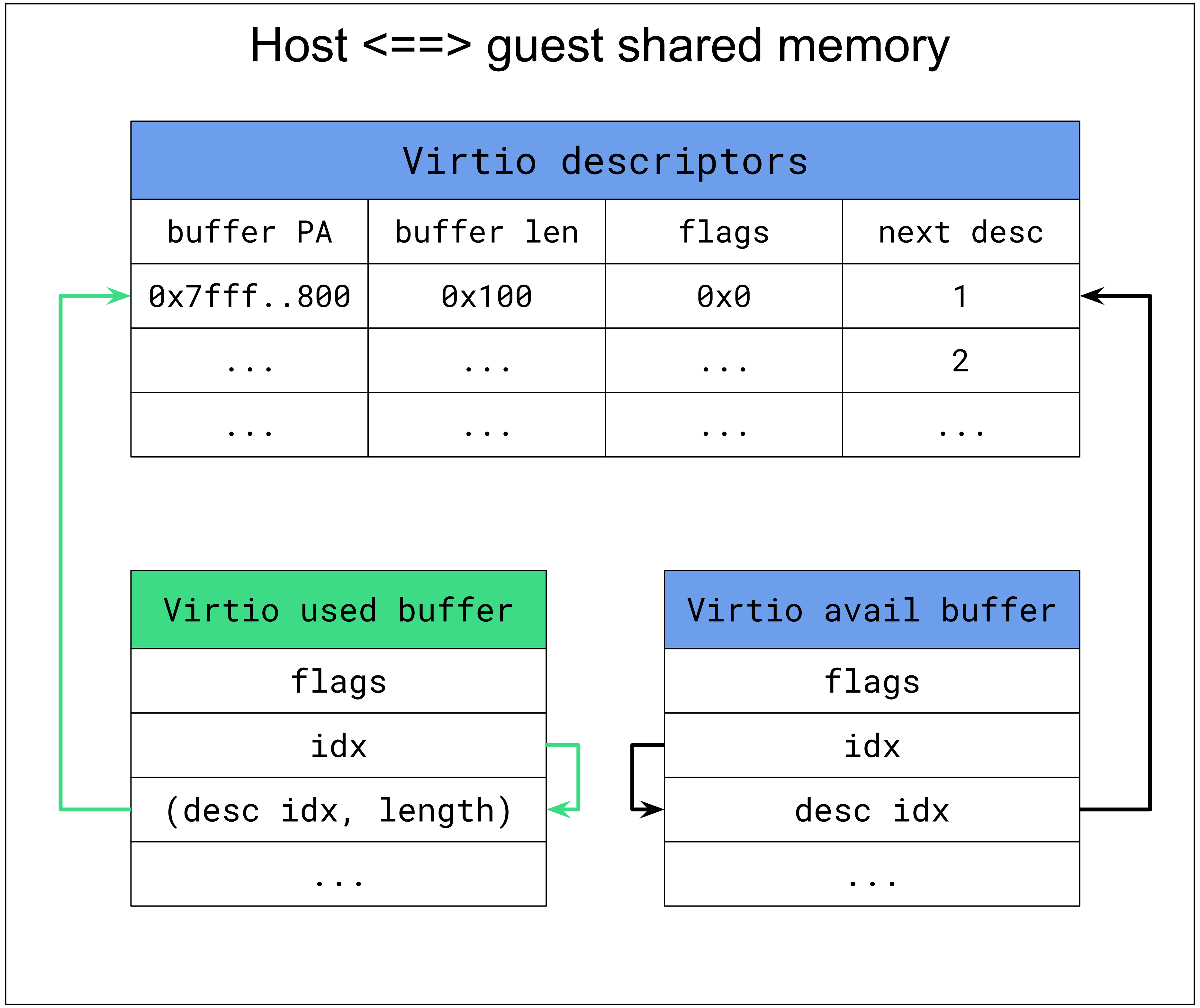
Guest:
virtio front-end

1. Put request in the virtio queue

Attacking guests via virtio

Host: virtio back-end

2. Process request from the queue
3. Put response in the virtio queue



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Attacking guests via virtio

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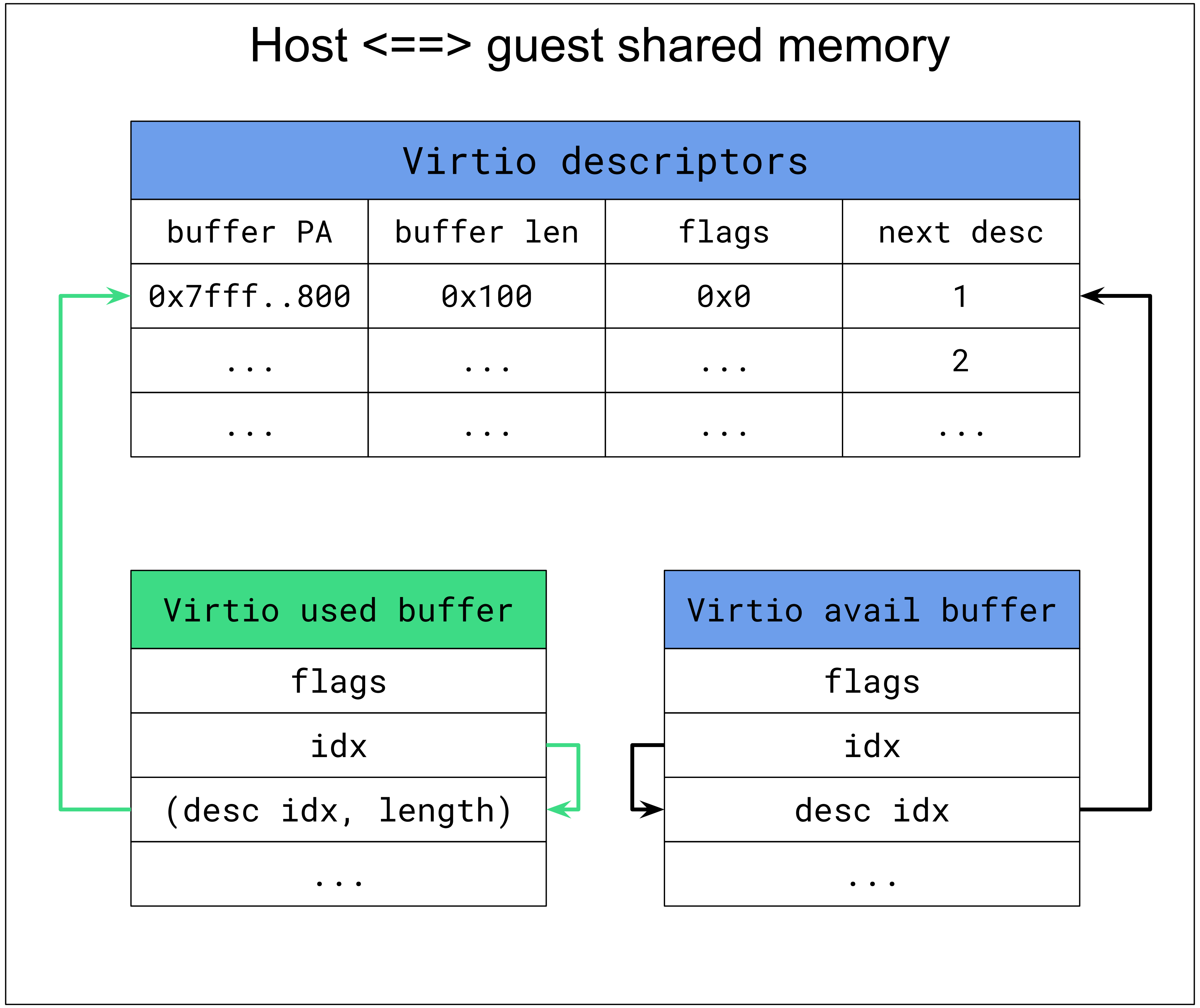
2. Process request from the queue

3. Put response in the virtio queue



Guest: virtio front-end

1. Put request in the virtio queue

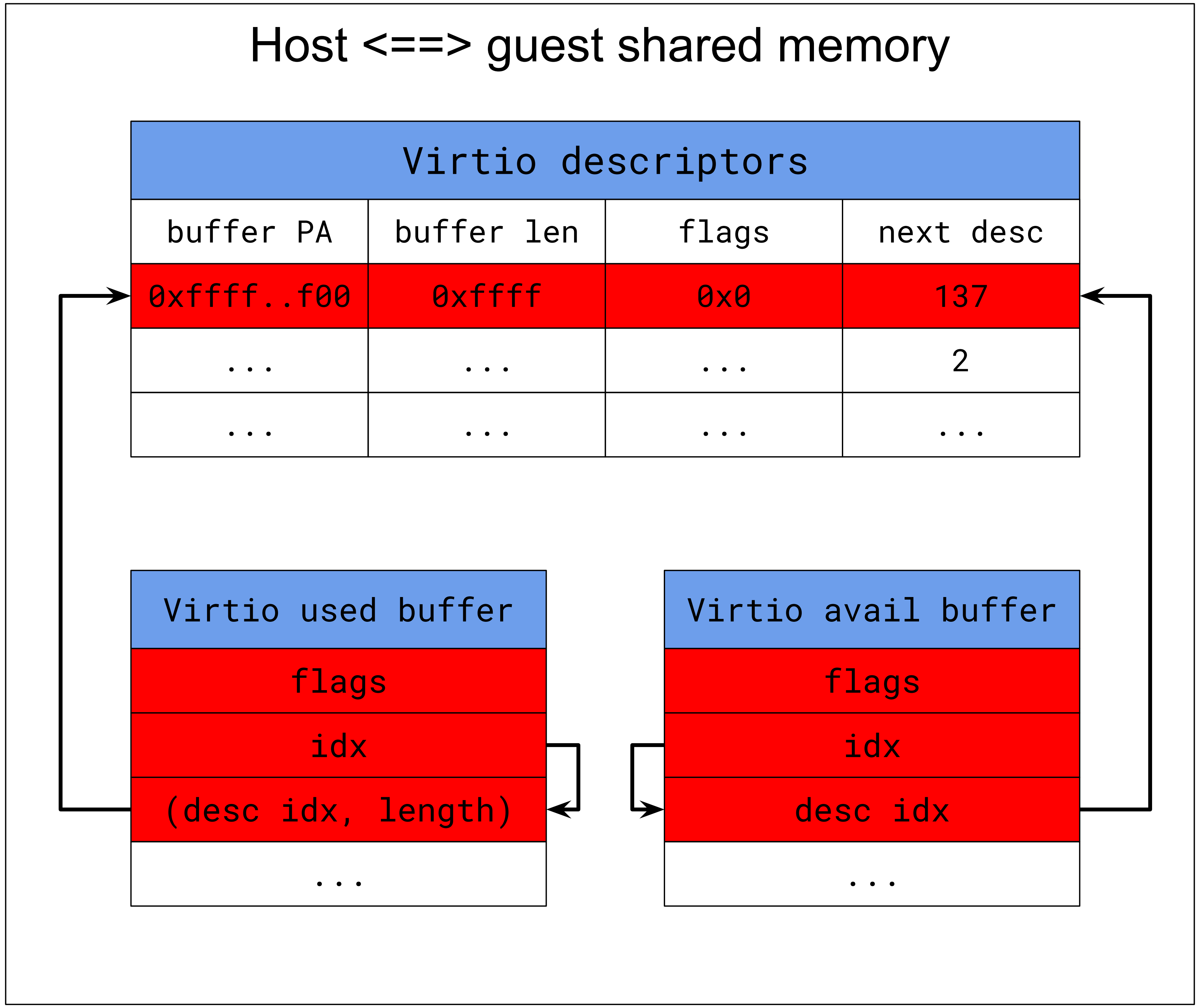
4. Process response from the virtio queue

Attacking guests via virtio

Host:
virtio back-end

2. Process request from the queue

3. Put response in the virtio queue



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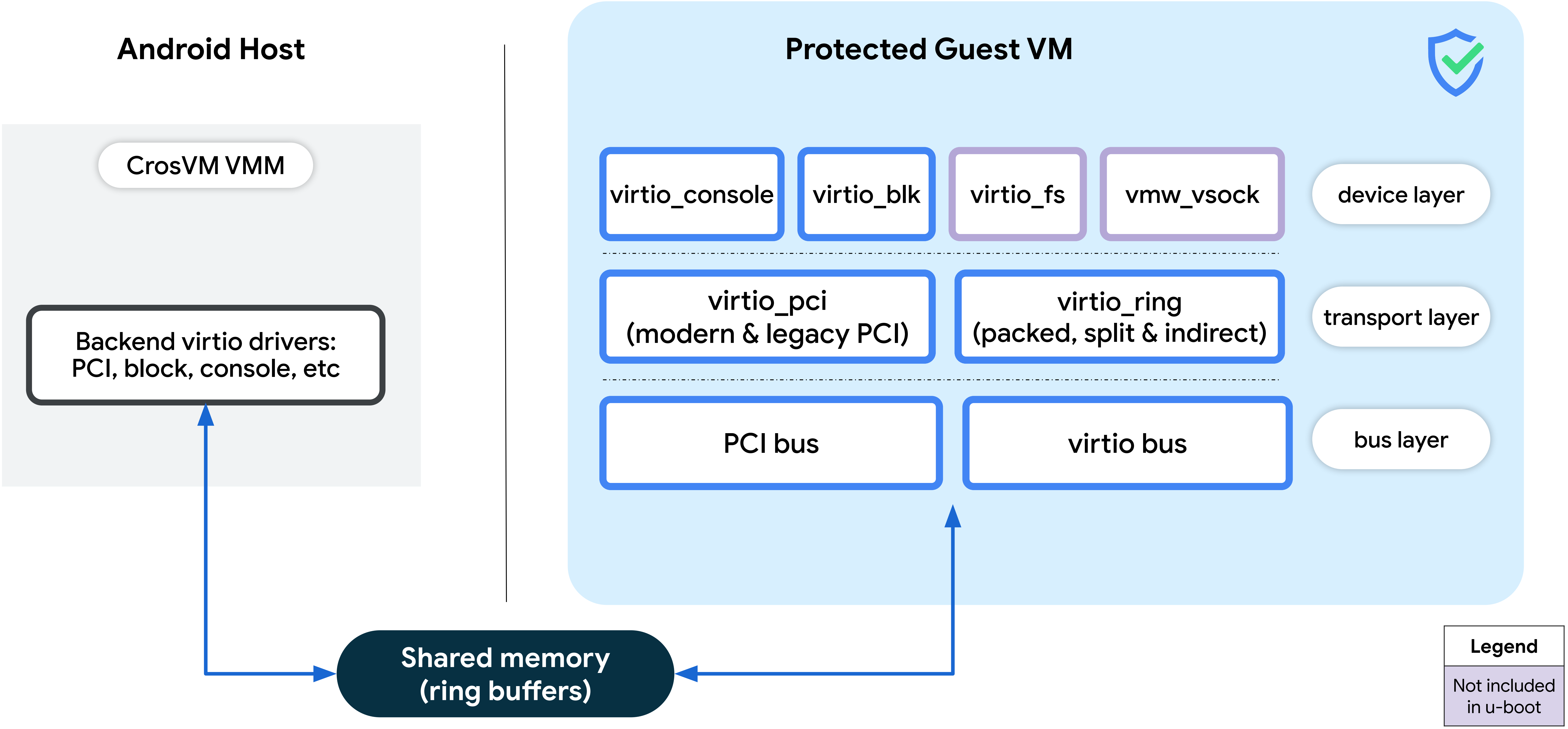
Protected VM virtio attack surface



Virtio hardening in Linux mainline & u-boot

Host-to-guest attack vector **isn't new** for Linux mainline.[1]

However, this attack vector **is new for Android** and pKVM, in particular.

Virtio implementation in u-boot **wasn't hardened** against malicious host.[2]

[1] Hardening virtio, https://lwn.net/Articles/865216
[2] virtio: [Harden and test vring]() patch series

Fuzzing virtio front-end drivers in the Linux kernel

Why fuzzing virtio drivers?

- **One of the most effective ways to find stability and security issues in C/C++ code**

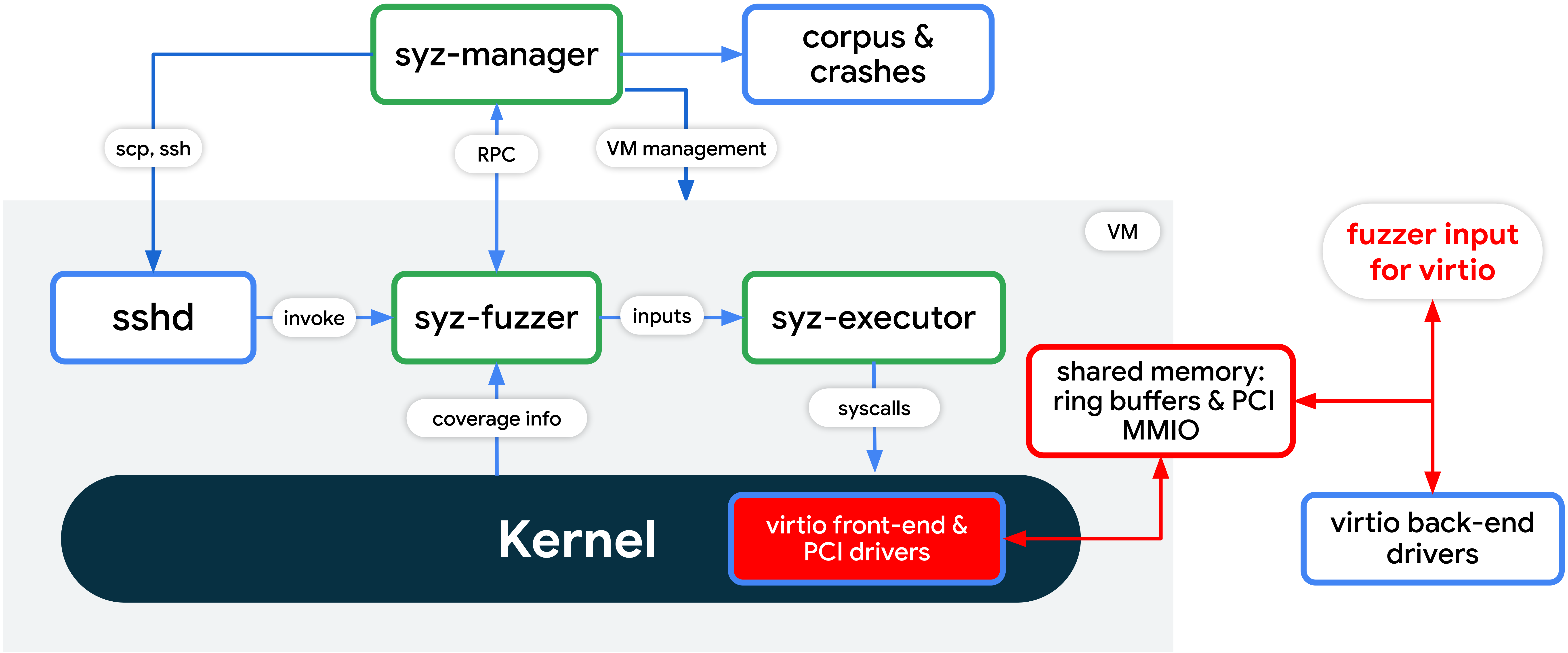
- **Fuzzing provides continuous security**

- **Fuzzer harness could be potentially reused across GKI/u-boot**
  - as long as the same fuzzing engine is used

- **Not too many security tools for Linux/Android kernel to choose from:**
  - syzkaller[1] & syzbot[2] is a 'de-facto standard' fuzzing tools for kernel

[1] https://github.com/google/syzkaller
[2] https://syzkaller.appspot.com/upstream

Virtio fuzzing: challenges



https://github.com/google/syzkaller/blob/master/docs/internals.md

LKL Overview

Linux kernel library (LKL)[1] builds Linux kernel as a user-space library

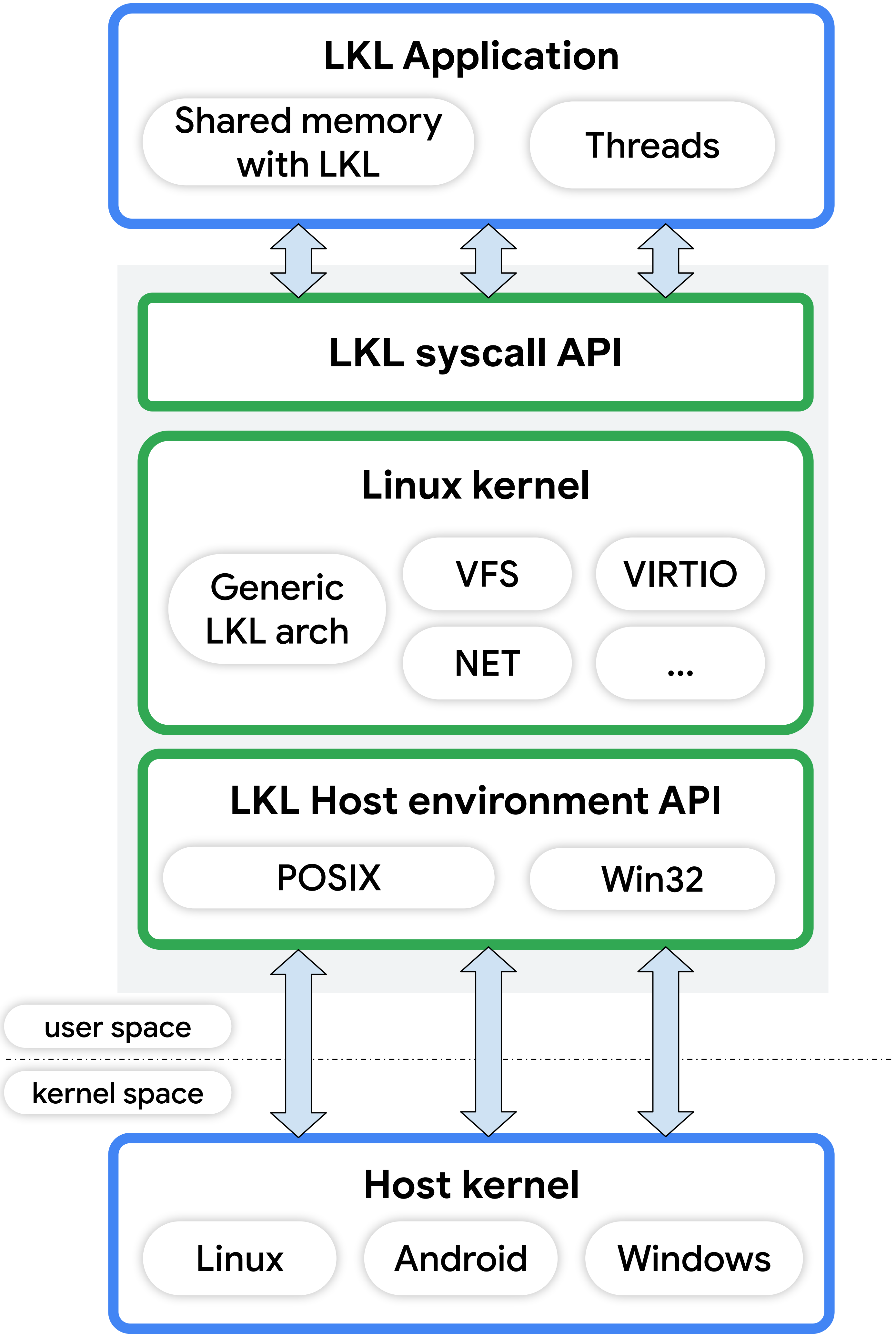
- Implemented as Linux arch-port
- LKL vs UML

LKL building blocks:

- Host environment API -- portability layer
- Linux kernel code
- LKL syscall API exposed to the user-space application

Run kernel code without launching a VM:

- kernel unit testing
- fuzzing![2,3]



[1] https://github.com/lkl/linux
[2] Xu et al., Fuzzing File Systems via Two-Dimensional Input Space Exploration
[3] https://github.com/atrosinenko/kbdysch

Using LKL from your C program

```
int ret = lkl_start_kernel(&lkl_host_ops, "mem=50M");

lkl_mount_fs("sysfs");
lkl_mount_fs("proc");
lkl_mount_fs("dev");

dev_t dev = makedev(MISC_MAJOR, UHID_MINOR);
int mknod_result = lkl_sys_mknodat(AT_FDCWD, "/dev/uhid",
        S_IFCHR | S_IRUSR | S_IWUSR, dev);

int fd = lkl_sys_open("/dev/uhid", O_RDWR | O_CLOEXEC, 0);
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Anatomy of LKL fuzzer

LKL enables fuzzing Linux kernel code in user-space

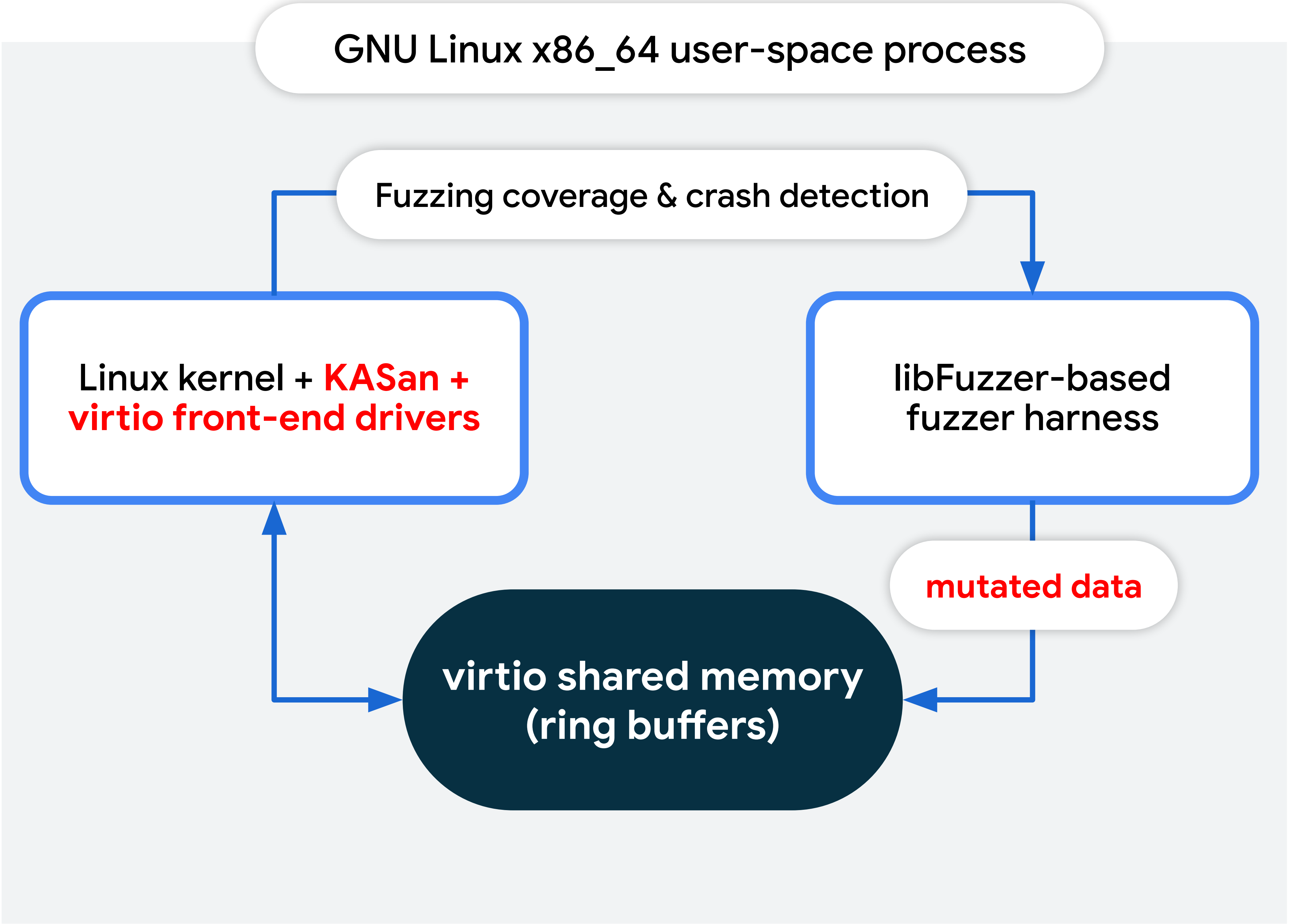
- use in-process fuzzing engine, such as libFuzzer

Advantages:

- high fuzzing performance on x86_64 cores
- lightweight fuzzers (no need to run VMs)
- easy debugging & crash reproducing (i.e. gdb)
- hardware emulation (e.g. PCI)

Limitations:

- no SMP in LKL
- x86_64 vs aarch64 -- potential false positives, true negatives



Virtio front-end fuzzers

Kernel under test:

- android13-5.10

virtio_ring:

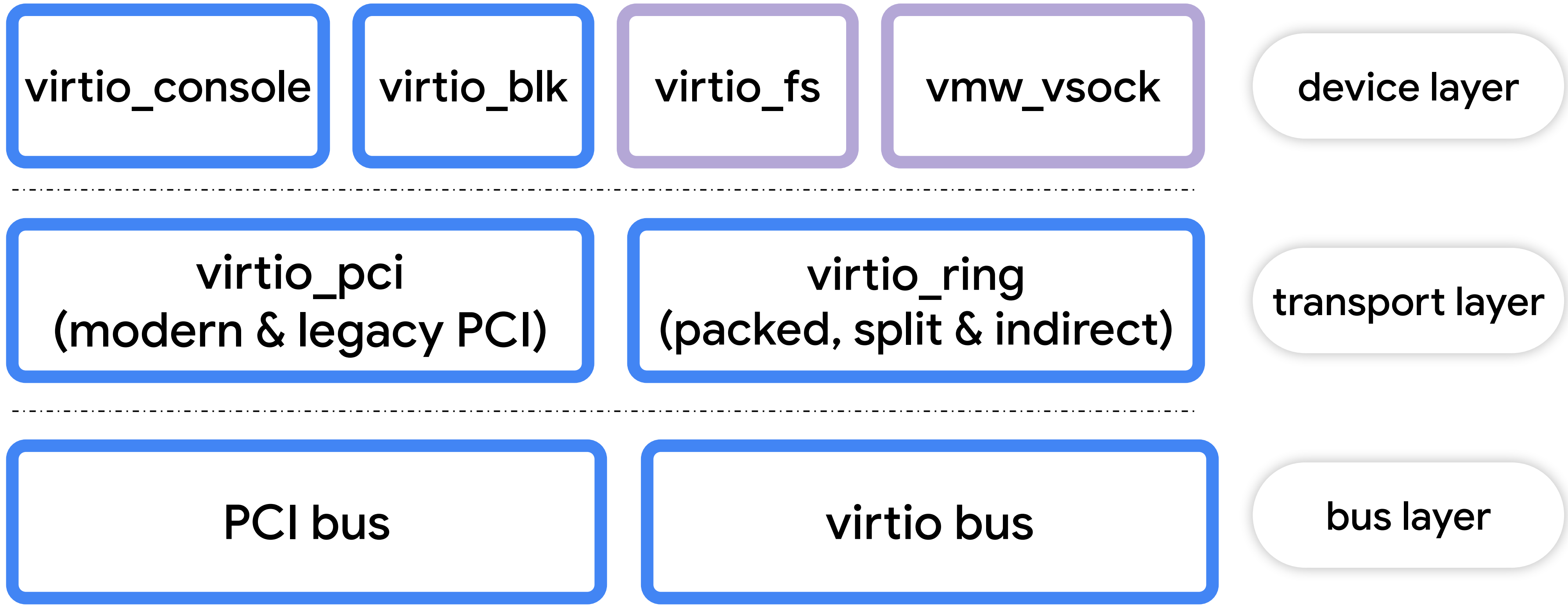
- fuzzes ring-buffer processing functionality
- handles both split & packed mode

virtio_pci:

- fuzzes PCI configuration space
- LKL arch-specific implementation of PCI bus
- mock-out PCI MMIO in the fuzzer harness

virtio_blk:

- mutates the virtio_blk configuration block



Virtio_blk fuzzer finding

```
int block_read_full_page(struct page *page, get_block_t *get_block)
{
   struct buffer_head *bh, *head, *arr[MAX_BUF_PER_PAGE];

   ...
   do {
      if (buffer_uptodate(bh))
         continue;

      if (!buffer_mapped(bh)) {
         int err = 0;

         ...
         if (buffer_uptodate(bh))
            continue;
      }

      arr[nr++] = bh;

   } while (i++, iblock++, (bh = bh->b_this_page) != head);
   ...
}
```

OOB write on stack

Virtio_blk fuzzer finding

- With the block size `0xe5e5e5e5`:
  - `inode->i_blkbits == 32`
  - `1 << READ_ONCE(inode->i_blkbits)` is undefined behavior in C
  - `1 << READ_ONCE(inode->i_blkbits) == 1` on x86 architecture

```
static struct buffer_head *create_page_buffers(struct page *page, ...)
{
  BUG_ON(!PageLocked(page));
  if (!page_has_buffers(page))
    create_empty_buffers(page, 1 << READ_ONCE(inode->i_blkbits), b_state);
  return page_buffers(page);
}
```

Fuzzing virtio driver stack in u-boot

- **Both pvmfw (1st stage) and microdroid bootloader (2nd stage) are based on u-boot**
  - rely on virtio_blk to get boot configuration and virtio_console for debug output

- **Fuzzing and ASAN for sandbox patch series enable fuzzing for virtio front-end drives:**
  - works for u-boot in sandbox mode
  - provide coverage-guided libFuzzer-based fuzzing
  - enables AddressSanitizer for the fuzz target

- **Findings:**
  - virtio: Harden and test vring patch series

Fully controlled OOB write in u-boot

```
static void detach_buf(struct virtqueue *vq, unsigned int head)
{
  ...
  while (vq->vring.desc[i].flags & nextflag) {
    virtqueue_detach_desc(vq, i); // <== i is OOB
    i = virtio16_to_cpu(vq->vdev, vq->vring.desc[i].next);
    vq->num_free++;
  }
  ...
}

int bounce_buffer_stop(struct bounce_buffer *state)
{
  ...
  // state is OOB and point to a fully attacker-controlled memory
  if (state->flags & GEN_BB_WRITE)
    memcpy(state->user_buffer, state->bounce_buffer, state->len);

  free(state->bounce_buffer);
  return 0;
}
```

Conclusion

LKL-based virtio fuzzers
continuously run in Google's internal ClusterFuzz engine.

Virtio fuzzing effort
led to identification and **proactive mitigation** of multiple security and stability issues in GKI and u-boot.

Need your support
in **improving fuzzing** for virtualized interfaces.

Future work

- **Write more fuzzers targeting virtio front-end and PCI drivers**

- **Upstreaming LKL to Linux mainline:**
  - first attempt in 2015
  - restarted in 2020[1] -- still ongoing to integrate LKL as a submodule of UML

- **Currently focusing on upstreaming LKL to Android Common Kernel mainline:**
  - effort to upstream LKL as a separate architecture is WIP
  - share LKL fuzzing work with the open-source community

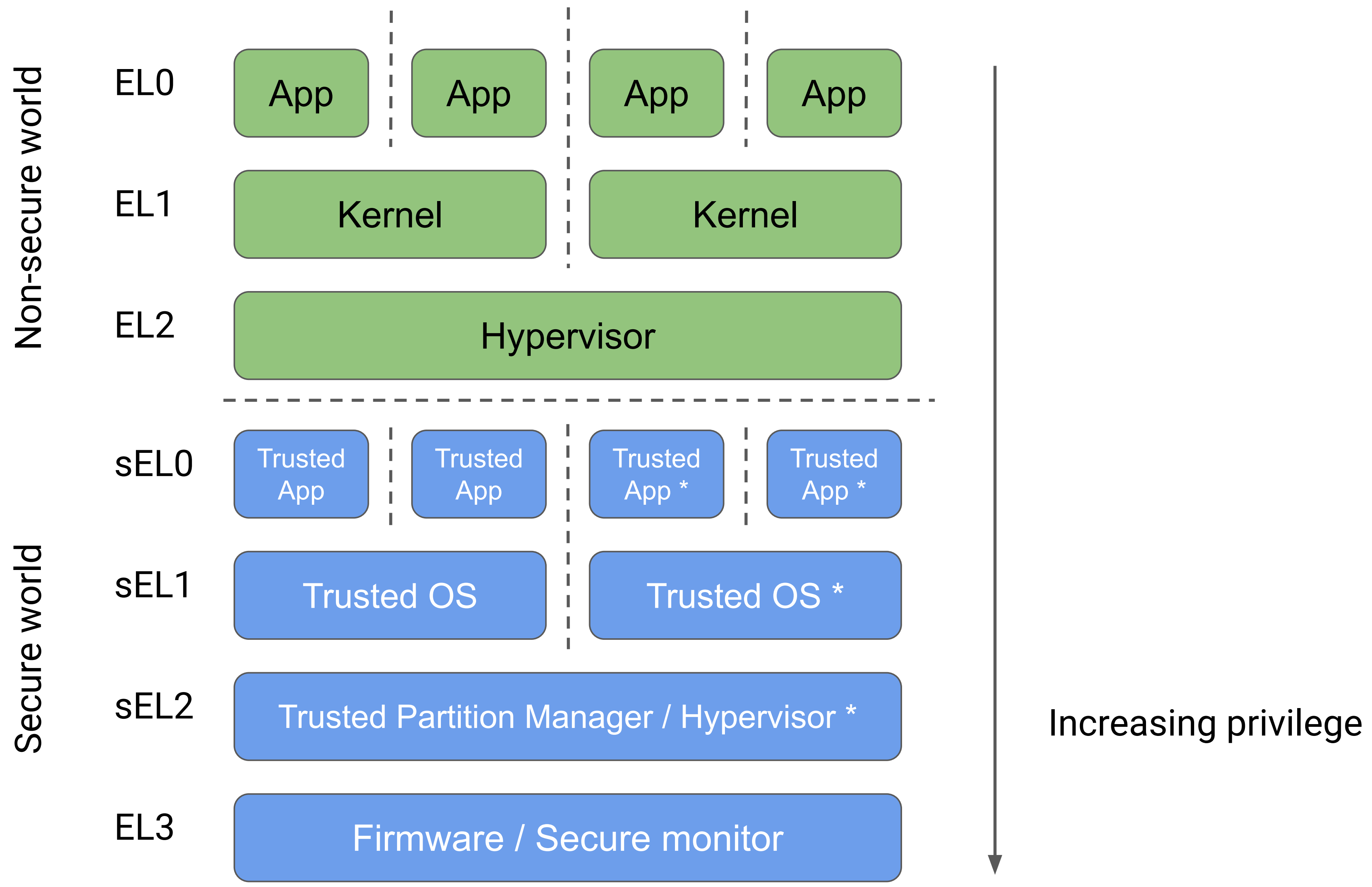
[1] https://lwn.net/Articles/811575/

Thank you!

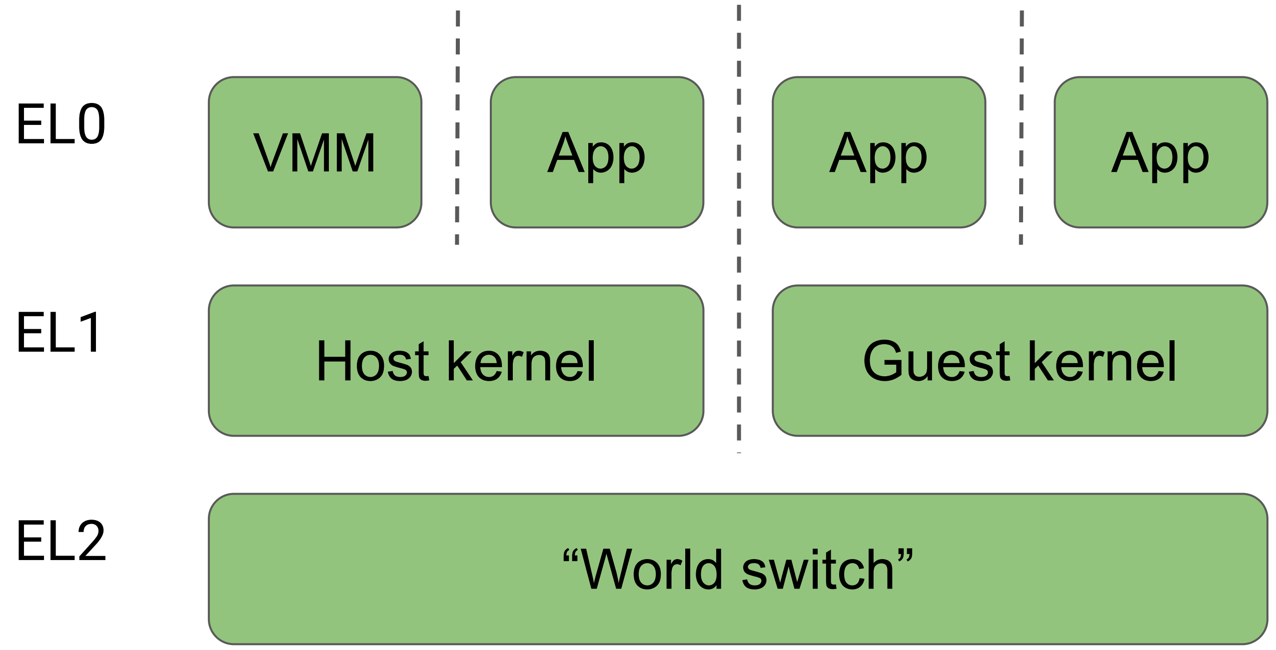
Appendix

Android Protected KVM: Motivation

TrustZone is currently used whenever host isolation is needed



Historically, a guest VM is completely controllable by the host



Prioritizing host-to-guest attacks in pKVM

Guest-to-host VM escapes is a traditional threat model for modern VMMs and hypervisors.

Android Virtualization Framework in Android 13 doesn't allow running arbitrary guest VMs.

LKL KASan details

KASan provides actionable reports for invalid memory access:

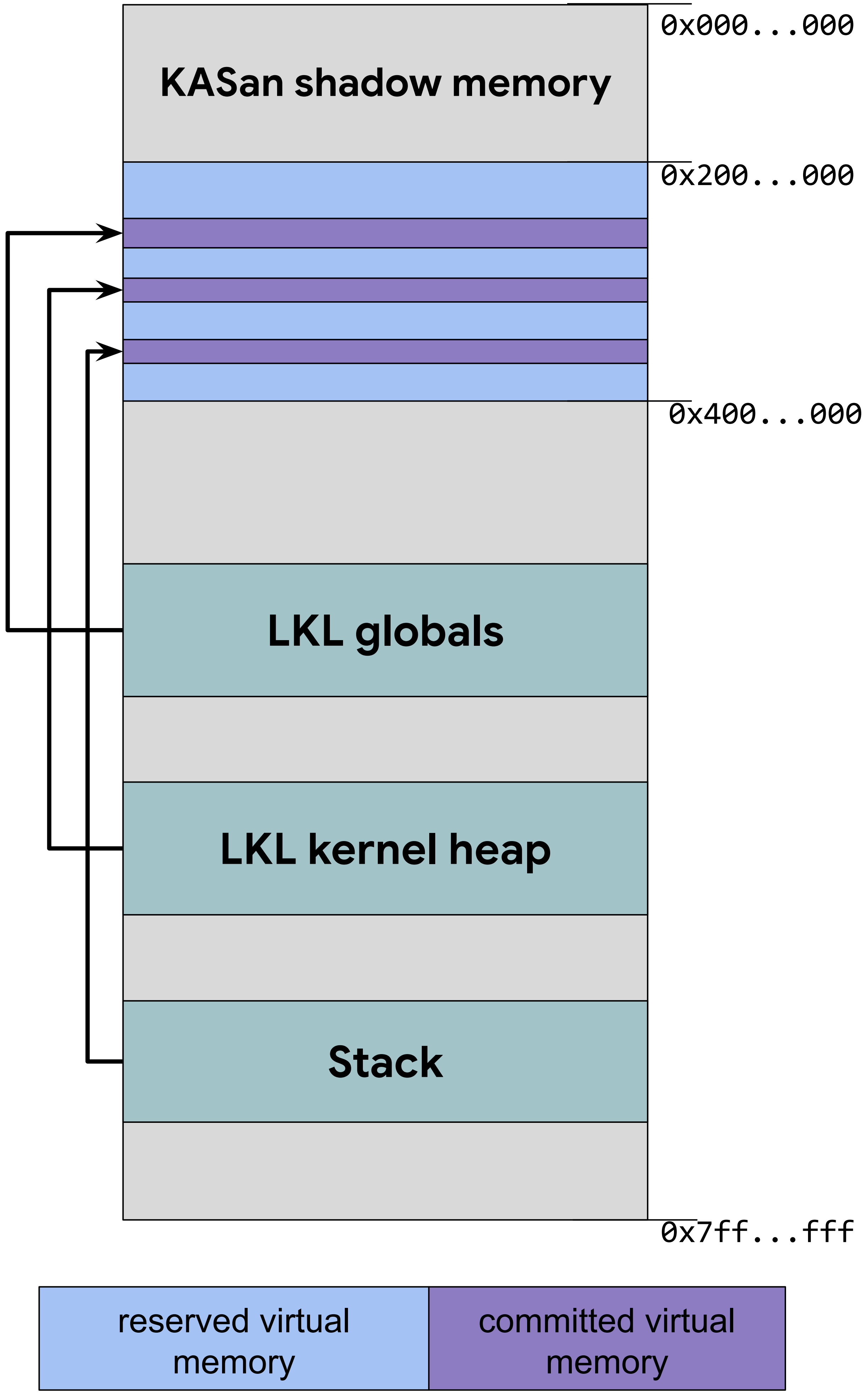
- OOB, user-after-free, double-free
- covers stack, heap and globals

User-space ASan in LKL:

- ASan shadow memory poisoning routines are invoked in global constructors
- Which might be problematic due to specifics of globals initialization in Linux kernel

LKL implements generic KASan:

- -fsanitize=kernel-address
- arch-specific KASan implementation

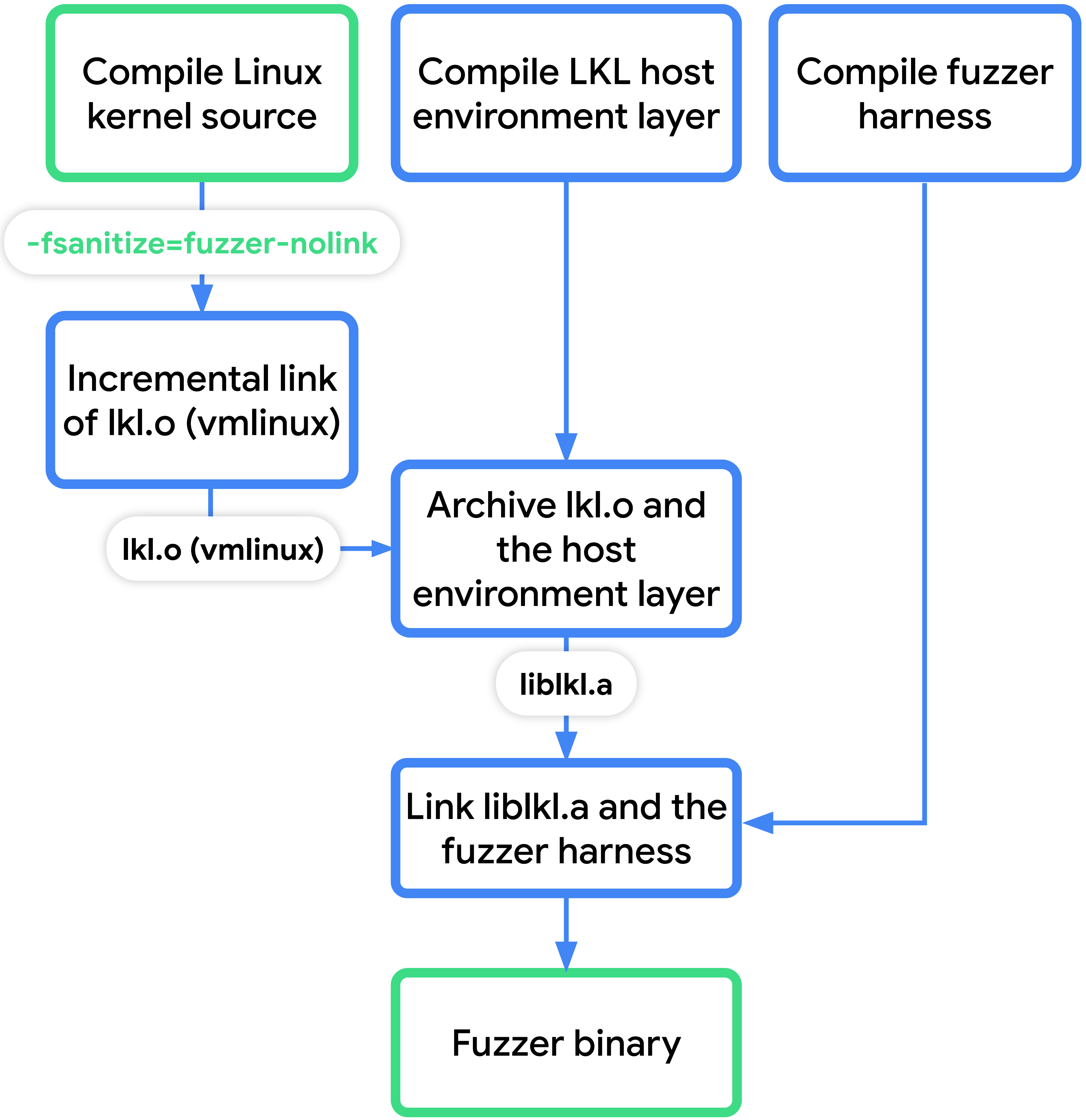


LKL fuzzing coverage

LKL relies on libFuzzer-based fuzzing code coverage instrumentation.

KCOV is an alternative solution:

- needs additional implementation to feed the coverage feedback to libFuzzer engine



How to develop an LKL fuzzer

- **Identify an interface to fuzz**
  - use ‘realistic’ attack surface (i.e. reachable from user-space or from the hardware)
- **Enable the kernel feature under test in the kernel config**
  - which doesn’t depend on aarch64 features or SMP
- **Mock-out low-level interfaces if needed**
  - LKL already comes with virtio back-end and arch-specific PCI implementations
- **Provide fuzzer harness which sends the fuzzer’s entropy to the target kernel interface**

Output of virtio_blk fuzzer

```
./virtio_blk-fuzzer -close_fd_mask=3
...

#455 NEW  cov: 3662 ft: 6239 corp: 92/178b lim: 4 exec/s: 455 rss: 96Mb L: 2/4 MS: 1
#472 NEW  cov: 3662 ft: 6248 corp: 93/180b lim: 4 exec/s: 472 rss: 96Mb L: 2/4 MS: 2
#495 NEW  cov: 3662 ft: 6249 corp: 94/184b lim: 4 exec/s: 495 rss: 96Mb L: 4/4 MS: 3
#496 NEW  cov: 3662 ft: 6250 corp: 95/185b lim: 4 exec/s: 496 rss: 96Mb L: 1/4 MS: 1
#510 NEW  cov: 3662 ft: 6252 corp: 96/188b lim: 4 exec/s: 510 rss: 96Mb L: 3/4 MS: 4
#511 NEW  cov: 3662 ft: 6260 corp: 97/190b lim: 4 exec/s: 511 rss: 96Mb L: 2/4 MS: 1
#521 NEW  cov: 3662 ft: 6261 corp: 98/194b lim: 4 exec/s: 521 rss: 96Mb L: 4/4 MS: 5
#525 NEW  cov: 3662 ft: 6267 corp: 99/198b lim: 4 exec/s: 525 rss: 96Mb L: 4/4 MS: 4
...
```