Virtualisation for the Masses:

Exposing KVM on Android

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Introduction

Who am I and what am I hacking on?

- Active upstream kernel developer, co-maintaining the arm64 architecture port, locking, atomics, memory model, TLB, SMMU, ...
- Joined Android Systems Team at Google last year
- Leading the "Protected KVM" project to enable KVM on Android
  - Top contributors to KVM/arm64 for 5.9 and 5.10
  - Lots more to come (seems to be a hot topic)
- **Disclaimer: very much a work-in-progress! Upstreaming as we go.**

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The state of modern Android

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Generic Kernel Image (GKI)

- Problem: Separate kernel for each device does not scale and leads to fragmentation:
  - Difficult/expensive to provide updates
  - In-field release upgrades can be impossible
  - Bad for upstream

- GKI aims to maintain subset of kernel ABI within a given Android release and kernel version (e.g. `android11-5.4`)
  - GKI branches forked from android-mainline
    - Close to upstream
    - Updated with regular LTS merges
  - Vendors/OEMs can provide modules

https://source.android.com/devices/architecture/kernel/generic-kernel-image

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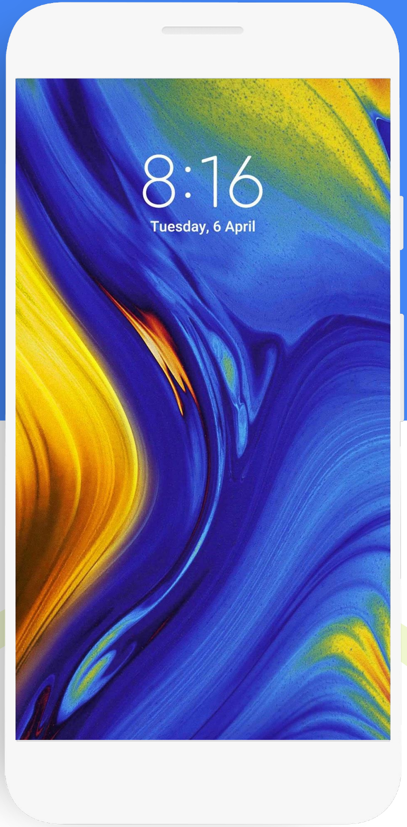
Virtualisation on Android today

tl;dr: It's the Wild West of fragmentation

When present, the hypervisor is treated as part of the device firmware and is typically supplied by the SoC vendor or OEM:

- Security enhancements for protecting the kernel
  - *"Mitigations are attack surface, too"*
    - Jann Horn, Project Zero
- Coarse-grained memory partitioning between devices using basic IOMMU-like hardware
- Running code outside of Android

Most of the time, there aren't even any virtual machines!



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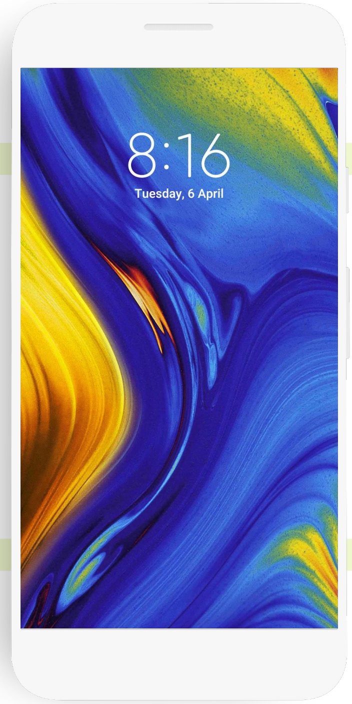
Security and functionality both lose out

Security

Increased TCB and difficulty/cost in providing streamlined updates across devices



Functionality

Unable to leverage hardware virtualisation capabilities from within Android

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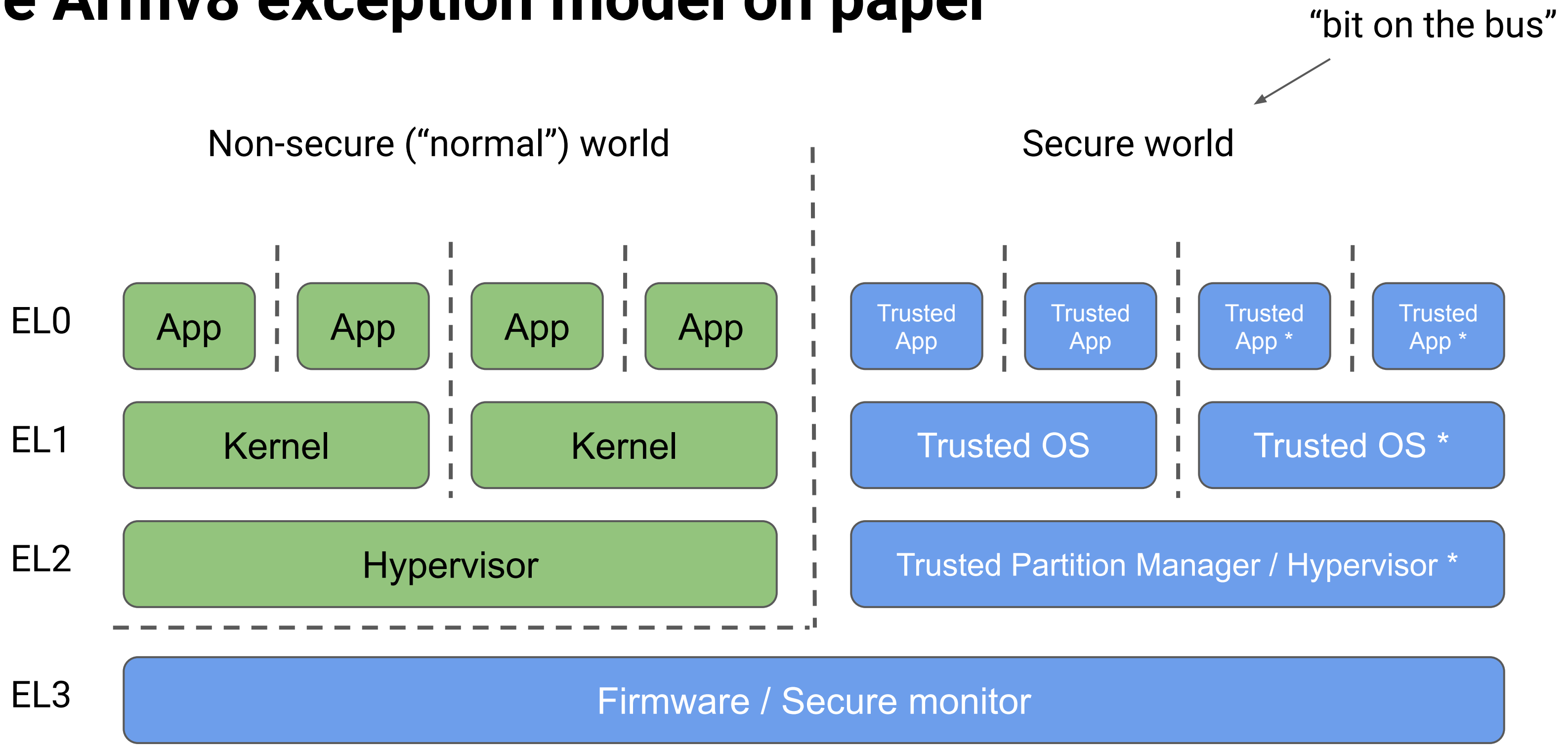
The Armv8 exception model on paper



* From Arm v8.4A

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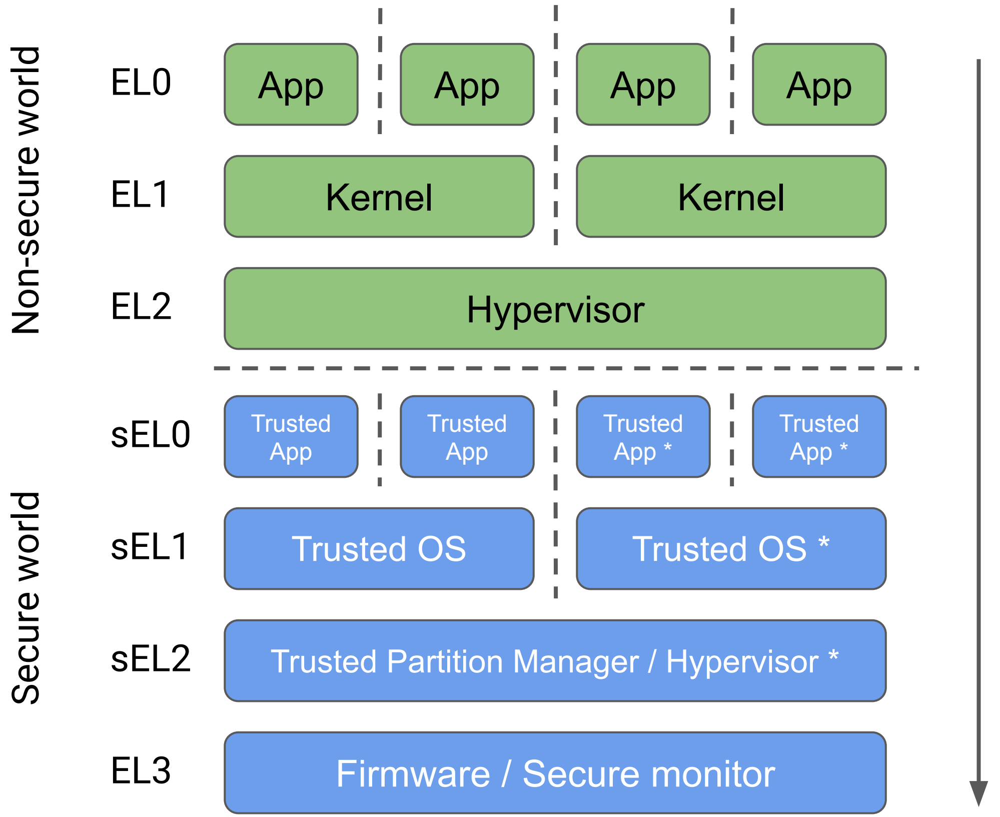
The Armv8 exception model sorted by privilege



Increasing privilege

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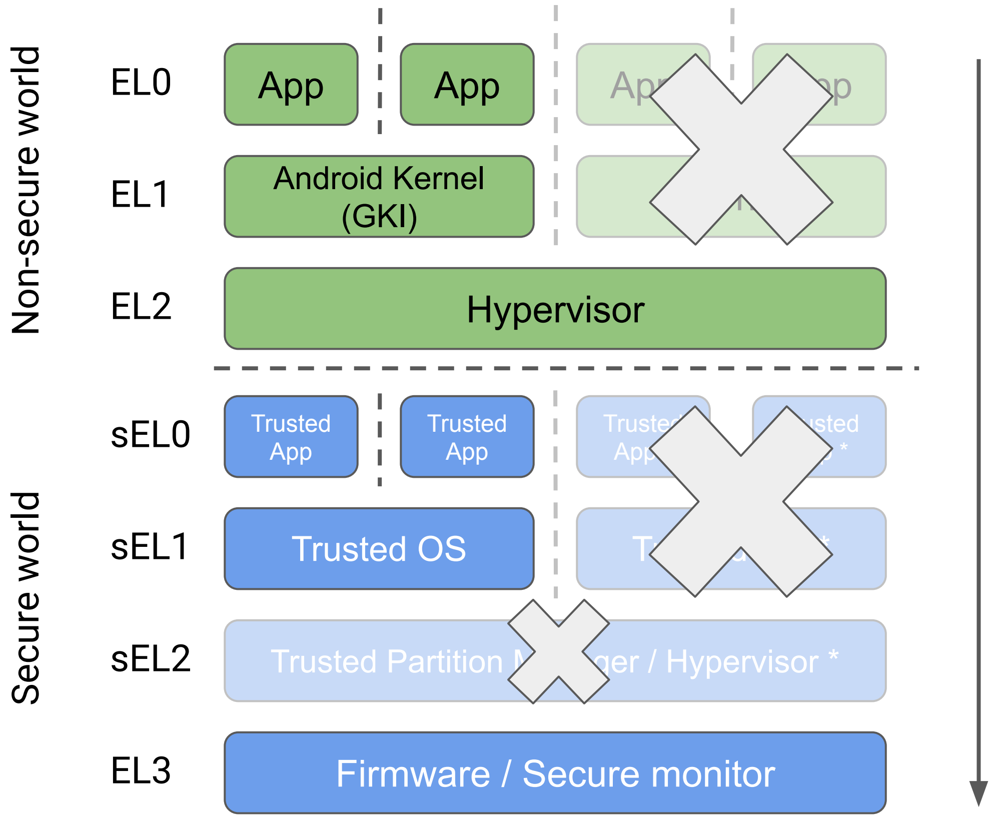
Mapping this to a modern Android system



Increasing privilege

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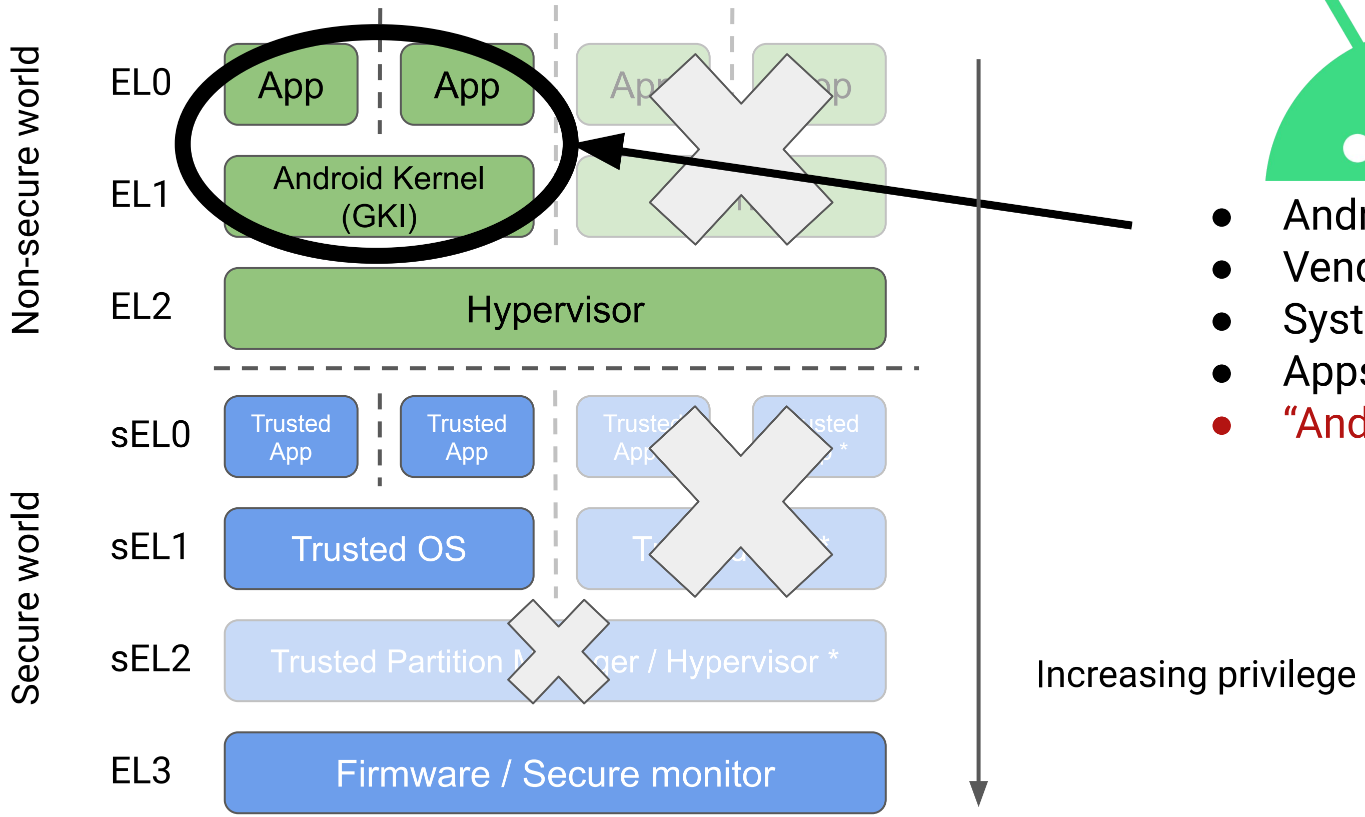

- Android kernel (GKI)
- Vendor modules
- System and libraries
- Apps
- “Android”

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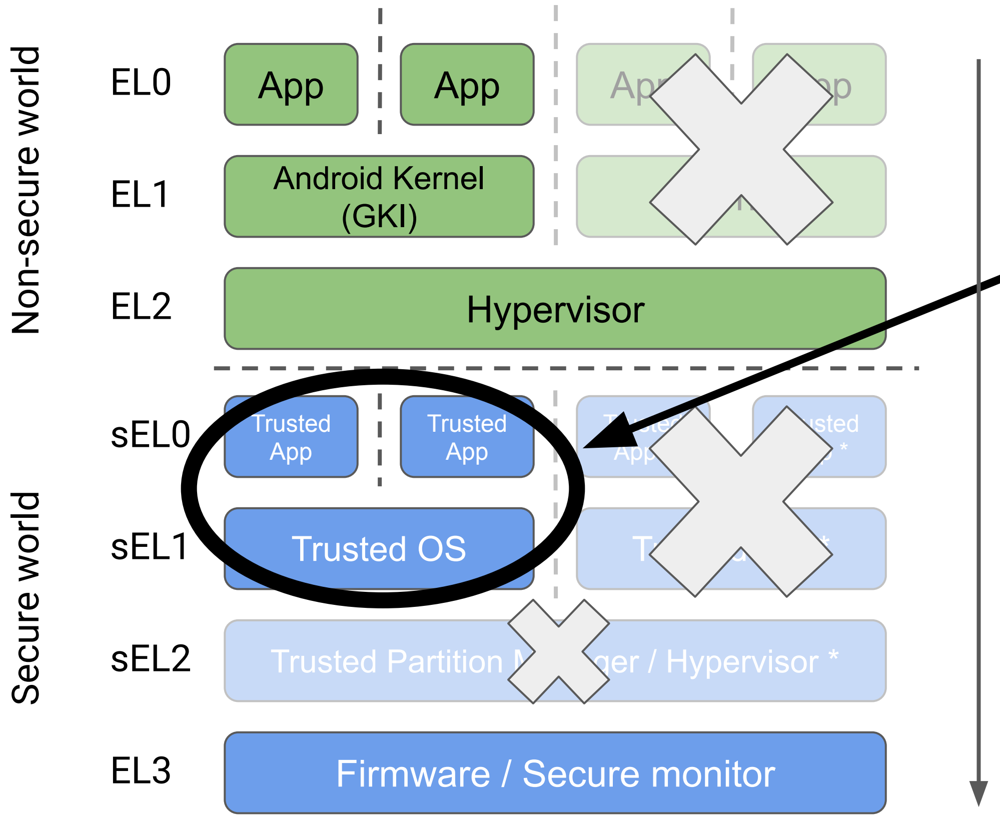
Mapping this to a modern Android system



- DRM, crypto, ...
- Third party OSes
- Opaque blobs
- Per-device integration

Increasing privilege

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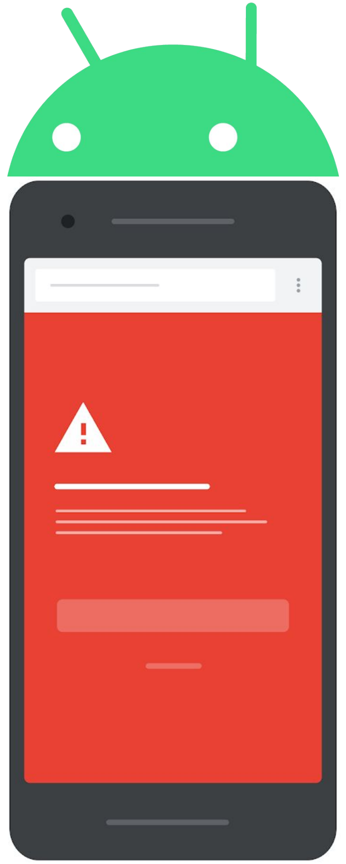
Trusted software

Definitions of trust (verb):

- *"To feel that something is safe and reliable"*
- *"To expect, hope or suppose"*

Android hopes that this software isn't malicious or compromised.

We need a way to de-privilege third party code and provide a portable environment in which to isolate services from each other and also from the rest of Android.



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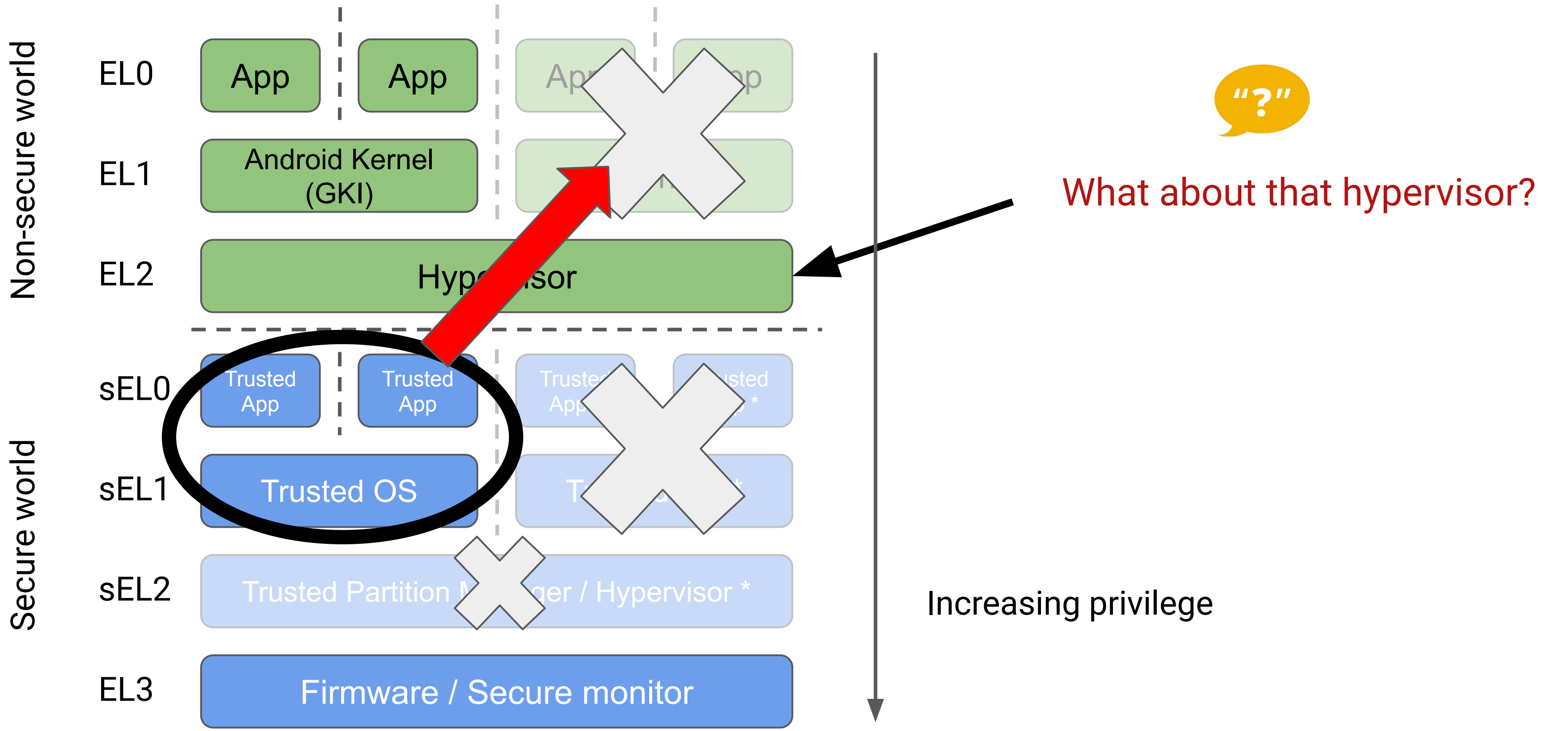
Virtualisation to the rescue?



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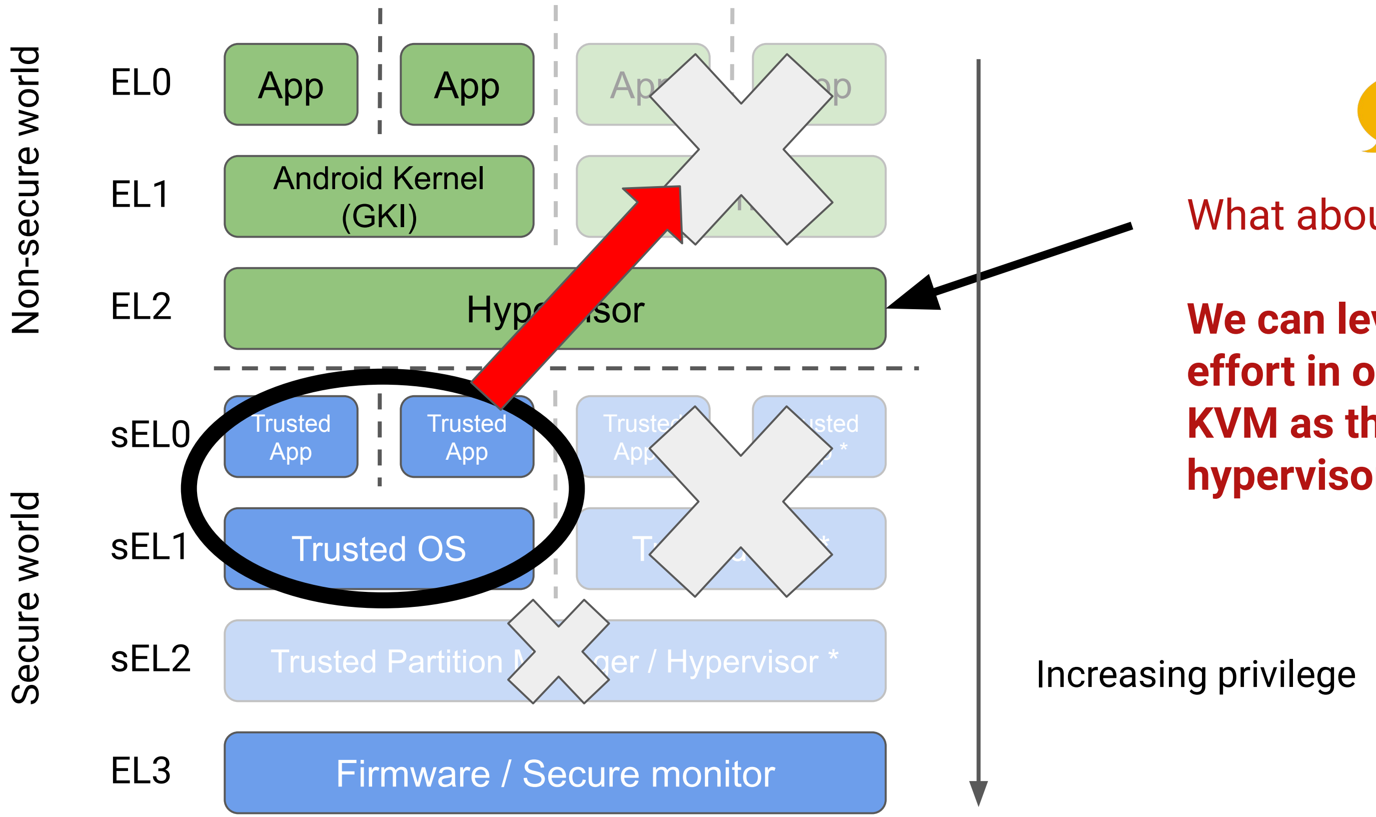
Virtualisation to the rescue?



What about that hypervisor?

We can leverage the GKI effort in order to deploy KVM as the common hypervisor.

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Virtualisation on arm64

(and how it’s used by KVM)

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Virtualisation checklist

Availability	All arm64 Android devices have support for hardware virtualisation and a two-stage MMU.
Isolation	Stage-2 page-tables provide memory isolation
Security	Move third-party code out of EL2/Trustzone and into non-secure virtual machines
Portability	Implement a common hypervisor in Android enabling new applications and virtual machines that require confidentiality of data and integrity of computation.

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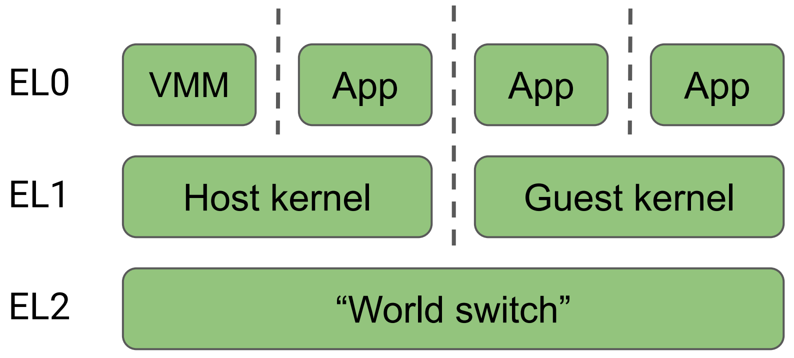
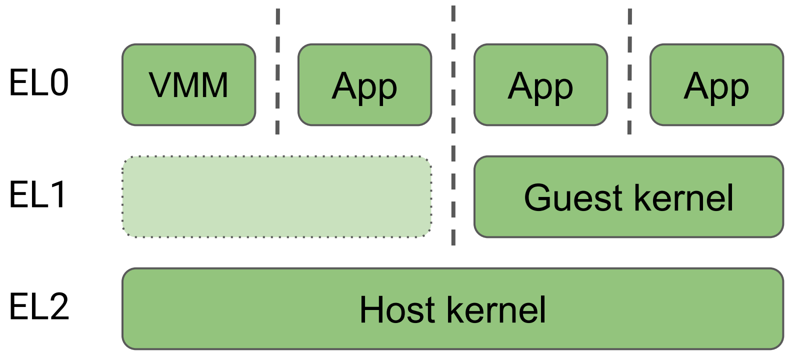
KVM on arm64

- Supported upstream on arm64 since v3.11
- Host kernel may reside at either EL1 or EL2:



nVHE (v8.0)



VHE (v8.1)
Blazingly fast!!1!

- Threat model places the entire host kernel (and VMM via `ioctl()`s) into the TCB; host has full access to guest memory.
    - This is a bit like “inverse Trustzone”

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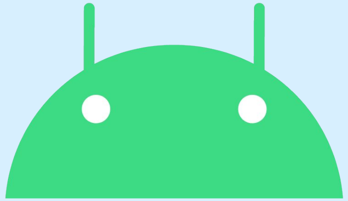
Big problem!

The threat model of Android is not aligned with the current design of KVM.



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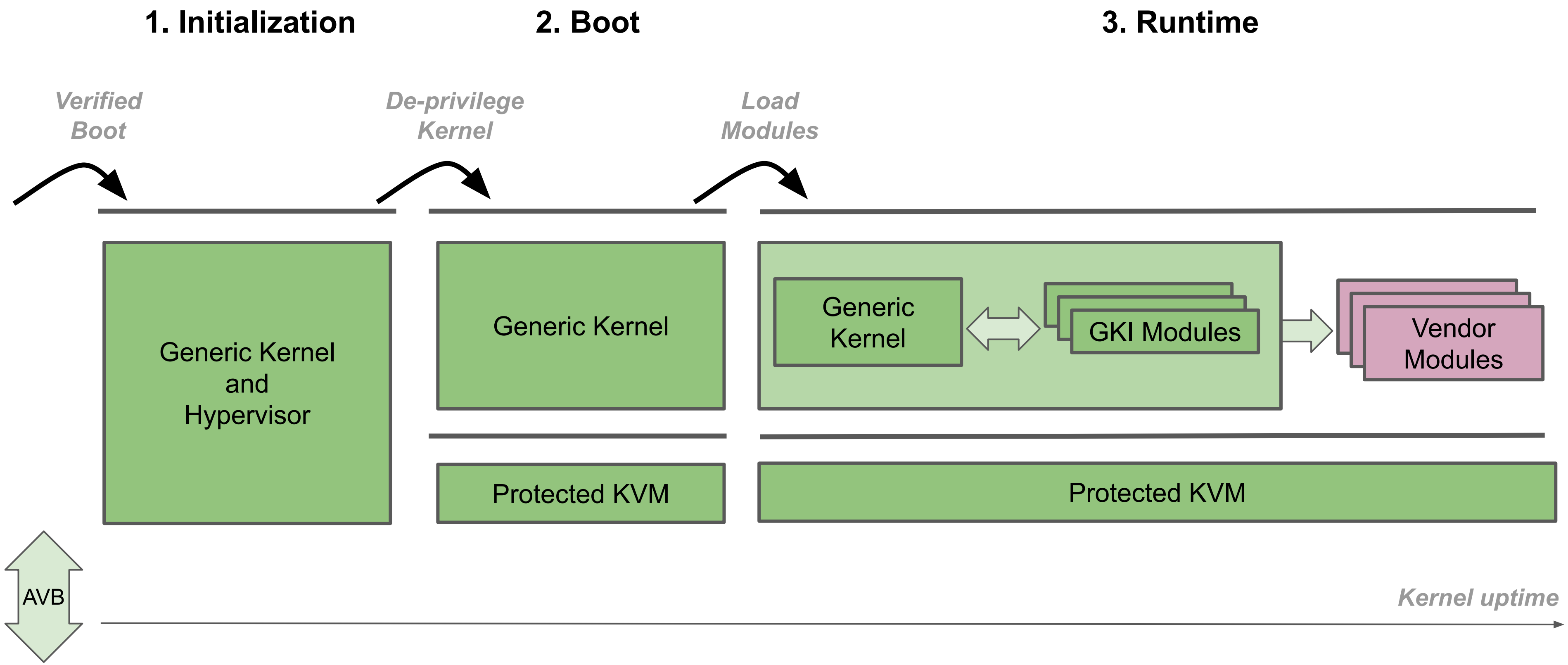
Revisiting nVHE with "Protected KVM"

Android's security model requires that guest data remains private even if the host kernel has been compromised. Maybe nVHE isn't so bad after all...

- Extend world-switch code at EL2 to manage stage-2 page-tables and guest state
- Install a stage-2 translation for the host kernel during boot before loading vendor modules
- Message passing between host and VM
- Template bootloader which accepts only signed VM images
- Formal verification techniques to reason about EL2 code

Q: Why not run Android in a VM instead?



Legend: 🟪 Vendor Specific 🟩 AOSP *AVB* - Android Verified Boot

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The taming of EL2

Executing at EL2

The KVM nVHE EL2 environment is a pretty horrible place: it has its own limited virtual address space and cannot run general kernel code:

- Not preemptible/interruptible and unable to block/schedule
- Can access all of normal memory if mapped
- Very limited device access; typically no console
- Basically just context-switches EL1 and allows host kernel to run functions with elevated privilege
- Tight coupling with host kernel is optimal for KVM's threat model

Prior to 5.9, Linux offered `#define kvm_call_hyp(f, ...)` to run kernel functions annotated with `__hyp_text` at EL2.

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Executing at EL2 (< 5.9)

```
// C code to run at EL2 (arch/arm64/kvm/hyp/tlb.c)
void __hyp_text __kvm_flush_vm_context(void)
{
    dsb(ishst);
    __tlbi(alle1is);
    if (icache_is_vpipt())
        asm volatile("ic ialluis");
    dsb(ish);
}

// EL2 entry dispatcher
kern_hyp_va     x0
do_el2_call                 // Indirect call to arbitrary address!!!
```

```
// EL1 hypercall (HVC #0)
#define kvm_call_hyp(f, ...)  __kvm_call_hyp(kvm_ksym_ref(f), ##__VA_ARGS__);

// Callsite
kvm_call_hyp(__kvm_flush_vm_context);
```

The EL2 object in 5.9/5.10

New threat model needs EL2 code to be self-contained & safe against compromised host kernel:

- Embed EL2 payload using separate ELF sections and symbol prefixing (similar to EFI stub)
- Fixed set of hypercalls rather than arbitrary function pointers
- Prior to de-privilege, host sets static keys and applies alternatives (one way switch)
- Following de-privilege, EL2 object no longer mapped for EL1

"Who needs namespaces when you have underscores?"

```
$ aarch64-linux-gnu-objdump -t -j .hyp.text arch/arm64/kvm/hyp/nvhe/kvm_nvhe.o
SYMBOL TABLE:
0000000000002000 g     F .hyp.text 00000000000000b4 __kvm_nvhe___host_exit
00000000000019e0 g     F .hyp.text 00000000000000c0 __kvm_nvhe___kvm_tlb_flush_vmid_ipa
0000000000004288 g     F .hyp.text 0000000000000048 __kvm_nvhe___vgic_v3_deactivate_traps
0000000000000048 g     F .hyp.text 00000000000000f0 __kvm_nvhe___sysreg_save_state_nvhe
00000000000043d0 g     F .hyp.text 0000000000000044 __kvm_nvhe___vgic_v3_init_lrs
0000000000001b30 g     F .hyp.text 0000000000000034 __kvm_nvhe___kvm_flush_vm_context
```

Symbol aliases created from "allowlist" of kernel symbols for use at EL2.

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Executing at EL2 (5.9/5.10)

```
// C code to run at EL2 (arch/arm64/kvm/hyp/nvhe/tlb.c)
void __kvm_flush_vm_context(void)
{
    [...]
}

// EL2 entry dispatcher (now in C!)
switch (func_id) {
case KVM_HOST_SMCCC_FUNC(__kvm_flush_vm_context):
    __kvm_flush_vm_context();
    break;
```

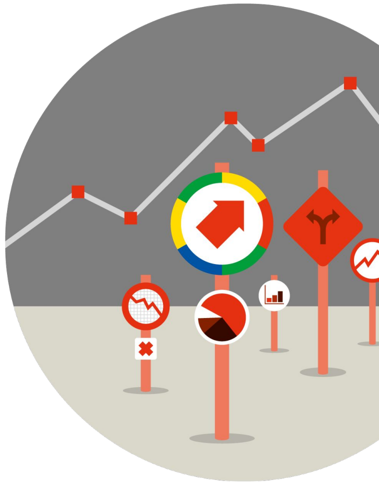
```
// EL1 hypercall (HVC #0)
#define __KVM_HOST_SMCCC_FUNC___kvm_flush_vm_context            2
arm_smccc_1_1_hvc(KVM_HOST_SMCCC_FUNC(f), ##__VA_ARGS__, &res);
#define kvm_call_hyp(f, ...)  kvm_call_hyp_nvhe(f, ##__VA_ARGS__);

// Callsite
kvm_call_hyp(__kvm_flush_vm_context);
```

Virtual memory at EL2 (without pKVM)

Today, the host kernel is trusted and therefore in control of the hypervisor virtual memory:

- Hypervisor stage-1 mappings created by the host
    - Hypervisor pages also mapped by the host linear mapping
    - KVM data structures (e.g `struct kvm`) mapped directly to EL2
    - More of the kernel gets mapped in over time! (no `hyp_unmap()`)
- Homebrew per-cpu implementation
    - Local CPU only
    - Directly reuses host per-cpu region
- Guest stage-2 page-tables also managed by the host kernel
    - Blindly installed by EL2 during VM world switch
- All page-tables constrained by host page-table configuration



Makes it trivial for a compromised host kernel to bypass new hypervisor restrictions.

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EL2 MM bootstrap (5.11?)

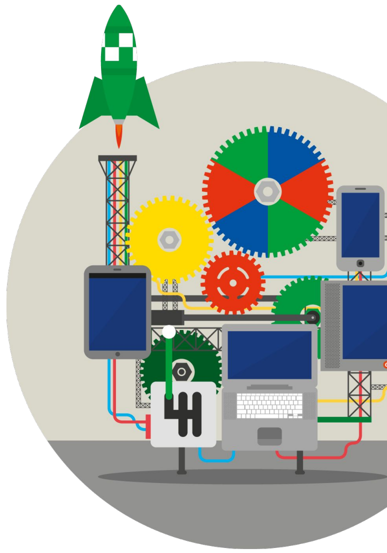
Allowing the host kernel to manipulate these page-tables breaks the revised security model:

- Page-tables must only be accessible to EL2
  - Stand-alone page-table walker merged for 5.10
  - http://lkml.kernel.org/r/20200911132529.19844-1-will@kernel.org

- Memory allocator needed for page-table pages
  - Hypervisor carveout donated from the host during boot
  - Trying to keep things as simple as possible
    - Host bootstraps EL2 prior to de-privilege
    - EL2 then transitions off temporary page-tables
  - https://android-kvm.googlesource.com/linux/+/refs/heads/pkvm

- Instantiate new per-cpu implementation at EL2 (also merged for 5.10)
  - https://lkml.kernel.org/r/20200922204910.7265-1-dbrazdil@google.com

- IOMMUs need to be kept in sync with the stage-2 page-tables



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EL2 MM bootstrap (5.11?)

```
#define hyp_vmemmap ((struct hyp_page *)__hyp_vmemmap)
struct hyp_pool {
        nvhe_spinlock_t lock;
        struct list_head free_area[HYP_MAX_ORDER + 1];
};

// Buddy allocator for page allocation at EL2
void *hyp_alloc_pages(struct hyp_pool *pool, gfp_t mask,
                      unsigned int order);
```

```
// kvm_hyp_setup() [Complete bootstrap and de-privilege host]
kvm_call_hyp_nvhe(__kvm_hyp_setup, base, kern_hyp_va(__va(base)), size,
                  kvm_get_bp_vect_pa(), num_possible_cpus(),
                  kern_hyp_va(per_cpu_base));
free_hyp_pgds();

// cpu_init_hyp_mode() [Install host vectors with temporary MMU setup]
vector_ptr = kern_hyp_va(kvm_ksym_ref(__kvm_hyp_host_vector));
arm_smccc_1_1_hvc(KVM_HOST_SMCCC_FUNC(__kvm_hyp_init), pgd_ptr, tpidr_el2,
                  hyp_stack_ptr, vector_ptr, &res);
```

Stage-2 for the host

- Memory will disappear from the host as it is assigned to a guest
  - "KVM protected memory extension" from Kirill Shutemov
  - Inject stage-1 abort or treat as RAZ/WI?
- IOMMU support
  - Unfortunate reliance on SoC design and sensible hardware
- Kernel self protection?
  - Looks to the host like the permissions have changed for *physical* memory
  - Allow host to change permissions for RW memory it owns?
- VMM will not be able to access guest state (including CPU registers and memory)
  - Negotiate shared memory regions with guest for virtio
  - **Q: How is a guest initialised to begin with?**

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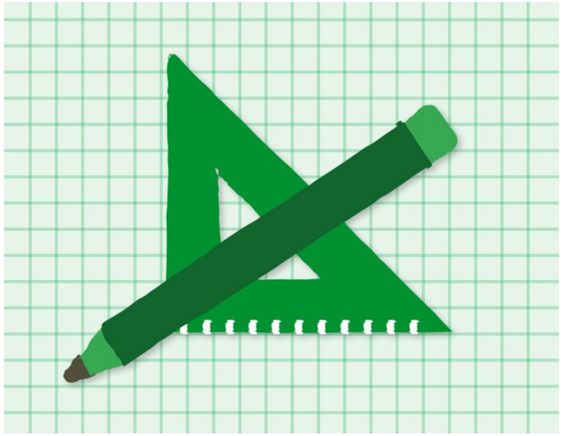
Template bootloader

Requiring VM images to reside in pre-populated carve-outs doesn't scale…

- … but we also need to ensure that guest payloads haven't been tampered with by the host
- Small first-stage bootloader installed in carve-out memory during host boot
  - Exploring bare-metal rust implementation
- Accessible only to EL2 and used as initial entry point for protected guests
  - Performs signature check on guest payload
  - **Q: Does this really need to be arm64-specific?**



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The virtual platform

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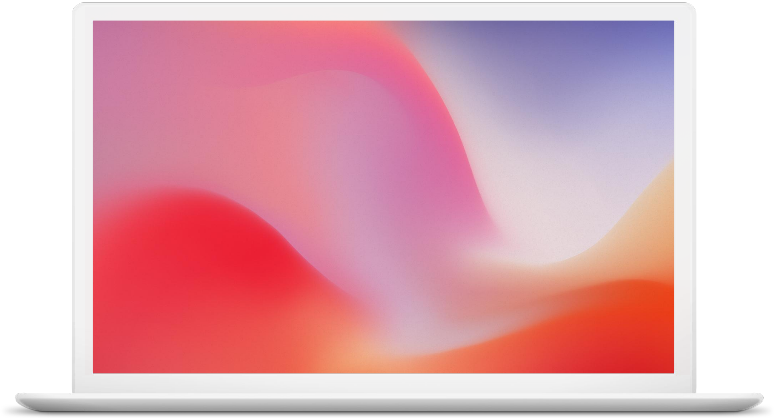
Adapt crosvm as the VMM

Reuse the Chrome OS Virtual Machine Monitor:

- Part of ChromeOS and now included in AOSP
- Lots of related talks at KVM Forum!
- Modern codebase written in Rust
- Focus on security and sandboxing
- Many virtio devices implemented
- Cross-architecture (surprisingly important!)
  - https://source.android.com/setup/create/cuttlefish



We provide a fairly basic arm64 virtual platform:

- Fixed memory map
- CPUs onlined via PSCI calls
- Arm architected timer
- RNG/entropy service
- **PV interrupt controller (rVIC) [Marc Zyngier's talk]**
- What about I/O?

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Just use virtio, stupid!

Virtio is the best thing since sliced bread and we should just use it for everything.
Job done?

- Strong desire to avoid changes to the spec
  - MMIO traps to the hypervisor
  - Re-use existing device/driver implementations

- Guest must use crypto (e.g. fs-verity) as host can intercept data due to lack of hardware memory encryption

- No shared-memory device?
  - Virtio assumes guest memory is shared with the host

https://www.kernel.org/doc/html/latest/filesystems/fsverity.html

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Bounce-buffering via shared windows

The Virtio 1.1 specification introduces the `VIRTIO_F_ACCESS_PLATFORM`reserved feature bit:

“[...] indicates that the device can be used on a platform where device access to data in memory is limited and/or translated.”

When set, causes a Linux guest to use the DMA API for virtio allocations.

- We can force the use of bounce-buffers by passing `swiotlb=force`
- We then just need to allow the host to access the bounce buffer pages
  - Expose SHARE/UNSHARE hypercalls to the guest to update host stage-2.
  - Hook the `set_memory_{decrypted,encrypted}()` API to share/unshare bounce buffer pages

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Zero-copy transfers using shared memory

Bounce buffers force the copying of all I/O data through a shared window:

- This is fine for many use-cases, but introduces undesirable overhead/incompatibility for others
  - e.g. Binder shared memory
- Need a handshake to share memory from host to guest
  - Don't want the guest to have access to all of host memory
  - Don't want the host to silently change guest stage-2
- Arm FF-A specification aims to solve this problem but is fairly heavyweight and not cross-architecture

Q: What should we be using here?

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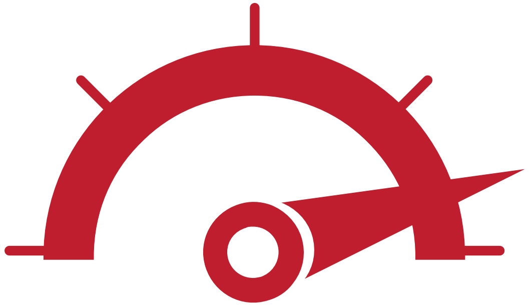
What’s next?

Still loads to do:

- Complete mm bootstrap
- Stabilise user ABIs
- Settle on solution for zero-copy I/O
- Move more guest state up to EL2
- Memory poisoning
- SMC proxying
- Attestation
- Ballooning
- Integration with rest of Android
- Continue upstreaming...



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Questions?

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