Lightweight Specification of Production Systems

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'exec spec'



+ Google

'caseMate'






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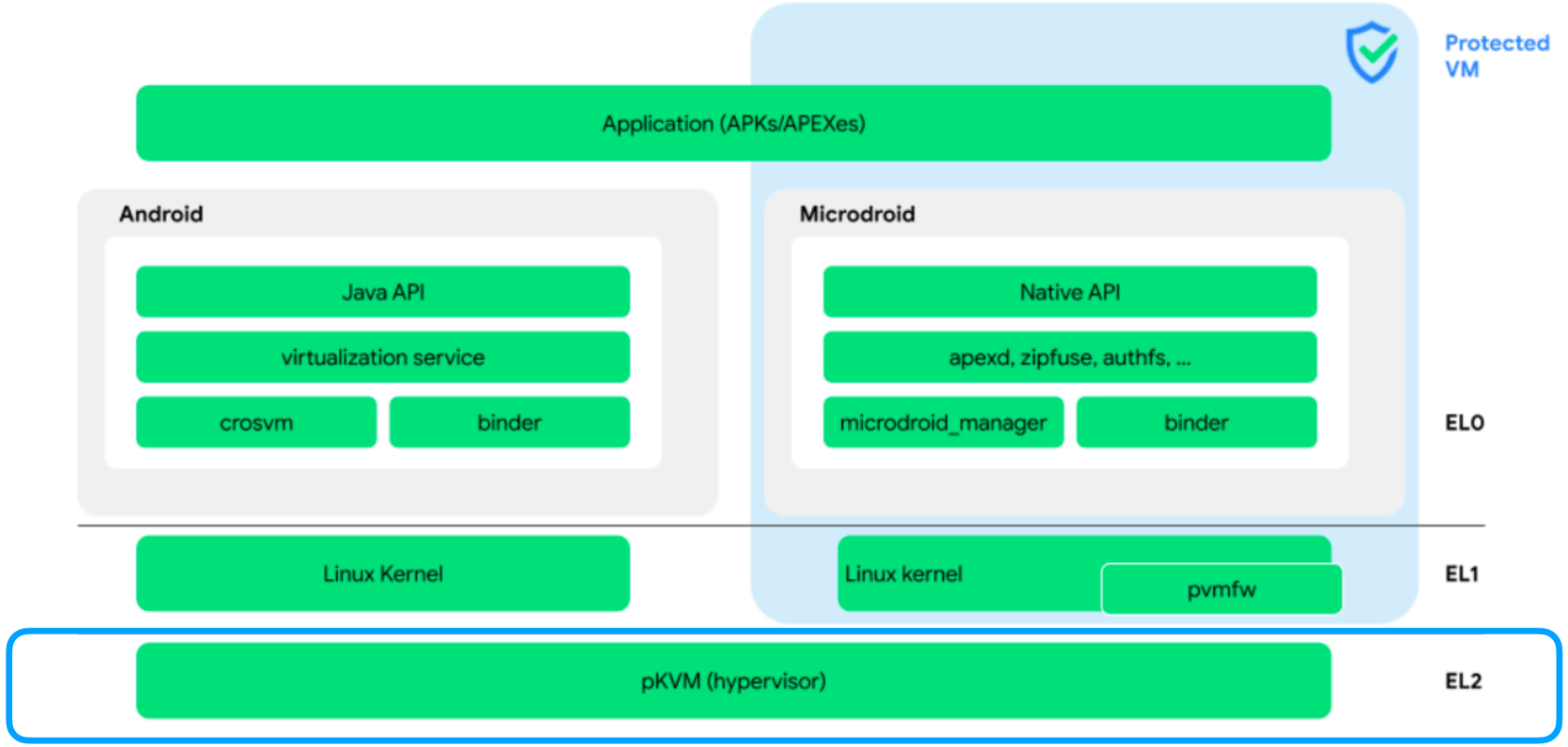
Android

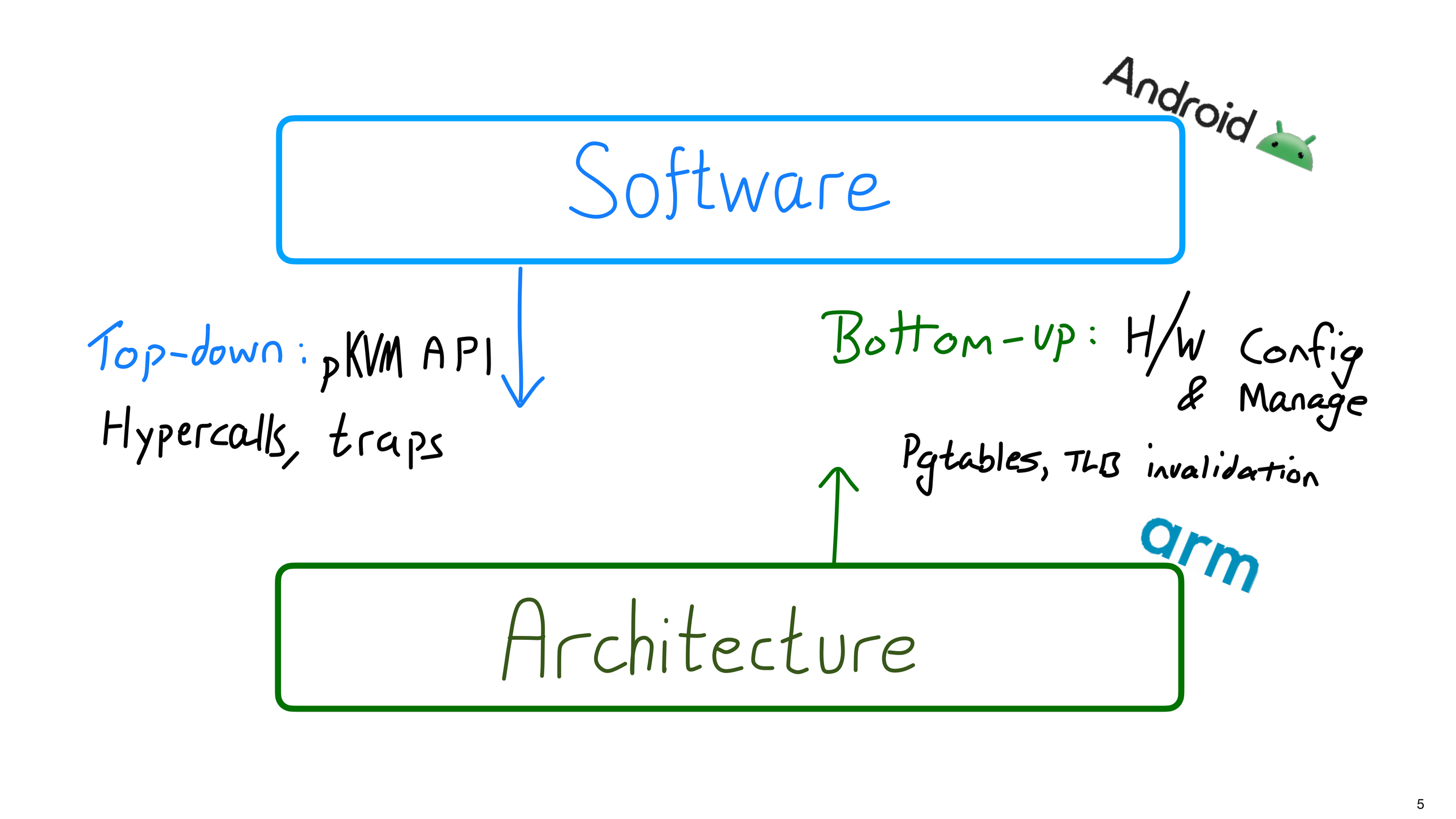


[https://source.android.com/docs/core/virtualization]

production systems?

can't prove? ... specify anyway!

use to test


Android
Software
Top-down: pKVM API
Hypercalls, traps
Bottom-up: H/W Config & Manage
Pgtables, TLB invalidation
arm
Architecture

Top-down: executable specifications of pKVM

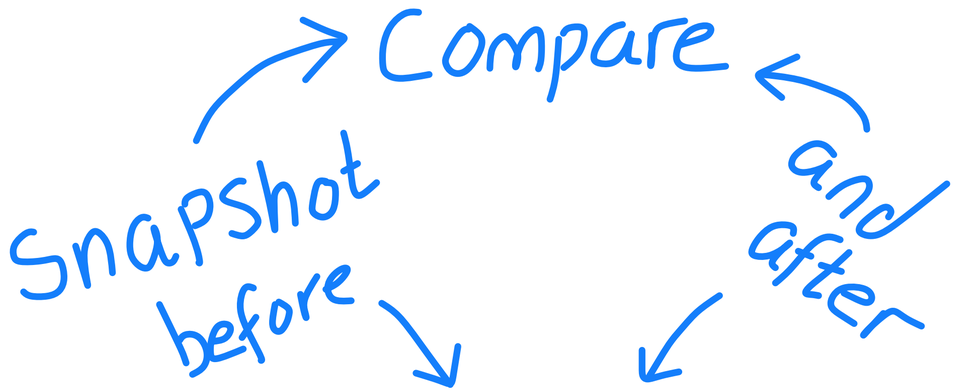
[Ghost in the Android Shell: Pragmatic Test-oracle Specification of a Production Hypervisor. SOSP 2025.
Kayvan Memarian, Ben Simner, David Kaloper-Meršinjak, Thibaut Pérami, and Peter Sewell.]

A Spec, Informally

A Spec, Precisely

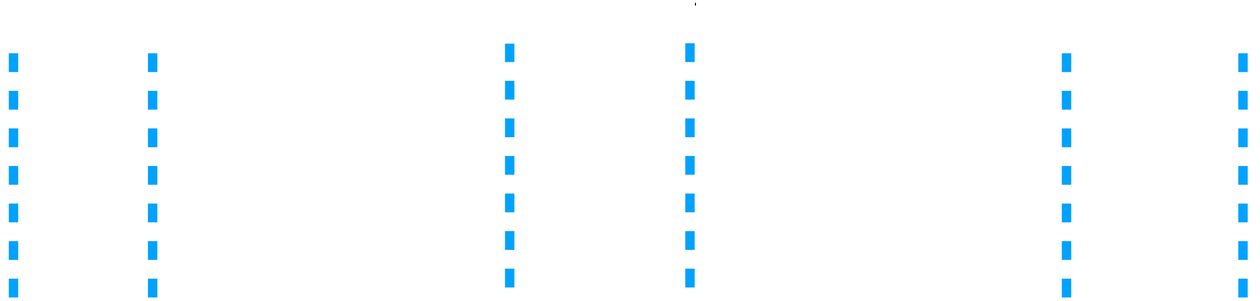
```
static bool compute_post__pkvm_host_share_hyp(
  struct ghost_state *g_post, struct ghost_state *g_pre,
  struct ghost_call_data *call)
{
  // Address space conversions
  u64 pfn = ghost_read_gpr(g_pre, 1);
  phys_addr_t phys = hyp_pfn_to_phys(pfn);
  host_ipa_t host_addr = host_ipa_of_phys(phys);
  hyp_va_t hyp_addr = hyp_va_of_phys(g_pre, phys);
  int ret = 0;

  // Permissions checks
  if (!is_owned_exclusively_by(g_pre, GHOST_HOST, phys)) {
    ret = -EPERM;
    goto out;
  }

  // Initialisation of the (partial) post-state
  copy_abstraction_host(g_post, g_pre);
  copy_abstraction_pkvm(g_post, g_pre);

  // Construction of abstract mapping attributes
  bool is_memory = ghost_addr_is_allowed_memory(g_pre, phys);
  struct maplet_attributes host_attrs =
    ghost_host_memory_attributes(is_memory, SHARED_OWNED);
  struct maplet_attributes hyp_attrs =
    ghost_hyp_memory_attributes(is_memory, SHARED_BORROWED);

  // Update abstract mappings with new targets
  mapping_update(
    &g_post->host.shared,
    g_pre->host.shared,
    MAP_INSERT_PAGE, GHOST_STAGE2, host_addr, 1,
    maplet_target_mapped_attrs(phys, 1, host_attrs)
  );
  mapping_update(
    &g_post->pkvm.pgt.mapping,
    g_pre->pkvm.pgt.mapping,
    MAP_INSERT_PAGE, GHOST_STAGE1, hyp_addr, 1,
    maplet_target_mapped_attrs(phys, 1, hyp_attrs)
  );

  // Epilogue: update the host register state
out:
  ghost_write_gpr(g_post, 1, ret);
  copy_registers_to_host(g_post);
  return true;
}
```

Making it executable ...



Android (EL1&0) ———

pKVM (EL2)



Finds bugs!

Just do it!

Computable abstraction

Bottom-up: casemate

Virtual Memory Discipline Checker

[Abstract architecture to catch concrete bugs: checking Android hypervisor TLB synchronisation. Preprint. *Ben Simner, Thomas Fourier, Yeji Han, David Kaloper Meršinjak, Thibaut Pérami, Peter Sewell, and Jean Pichon-Pharabod*.]

Free BSD

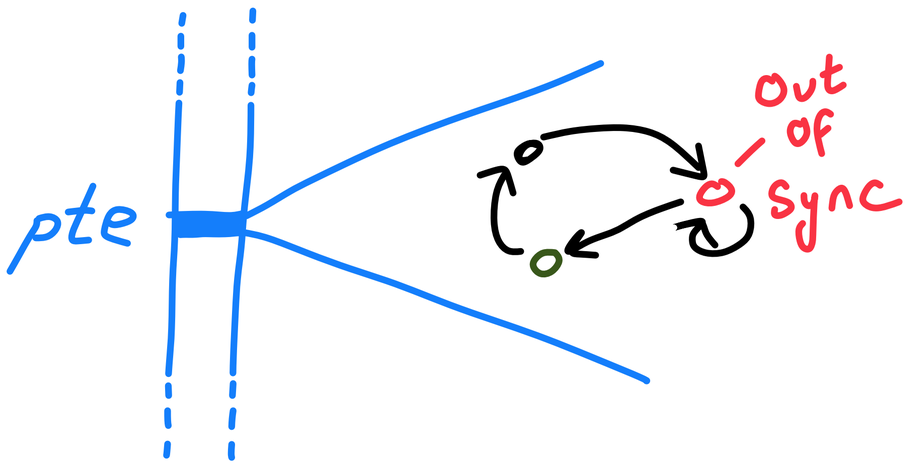
```
bool
vmmpmap_enter(vm_offset_t va, vm_size_t size, vm_paddr_t pa, vm_prot_t prot)
{
    pd_entry_t l3e, *l3;

    l3e = /* ... */

    while (size > 0) {
        l3 = vmmpmap_l3_table(va);
        if (l3 == NULL)
            return (false);

        atomic_store_64(&l3[pmap_l3_index(va)], l3e | pa);

        size -= PAGE_SIZE;
        pa += PAGE_SIZE;
        va += PAGE_SIZE;
    }

    return (true);
}
```

```
static pd_entry_t *
vmmpmap_l3_table(vm_offset_t va)
{
    /* ... */
    l2e = atomic_load_64(&l2[pmap_l2_index(va)]);
    if ((l2e & ATTR_DESCR_VALID) == 0) {
        /* Allocate a page for the level 3 table */
        m = vm_page_alloc_noobj(VM_ALLOC_WIRED | VM_ALLOC_ZERO);
        new_l2e = VM_PAGE_TO_PHYS(m) | L2_TABLE;
        mtx_lock(&vmmpmap_mtx);
        rv = atomic_cmpset_64(&l2[pmap_l2_index(va)], l2e, new_l2e);
        mtx_unlock(&vmmpmap_mtx);
        /* We may have raced another thread, try again */
        if (rv == 0)
            /* ... */
        /* The cmpset succeeded */
        l2e = new_l2e;
    }
    l3 = (pt_entry_t *)PHYS_TO_DMAP(l2e & ~ATTR_MASK);
    return (l3);
}
```

Racy with the H/W

Casemate

Pagetable update protocol



As sound abstraction

Casemate

Dynamic checking

```
        mtx_lock(&vmmpmap_mtx);
        rv = atomic_cmpset_64(&l0[pmap_l0_index(va)], l0e, new_l0e);
#if defined(__CASEMATE_FREEBSD__)
        casemate_model_step_lock((uint64_t)&vmmpmap_mtx);
        if (rv) {
            /* CASEMATE: success, wrote l0e */
            uint64_t __phys = DMAP_TO_PHYS((uint64_t)&l0[pmap_l0_index(va)]);
            casemate_model_step_write(WMO_plain, __phys, l0e);
        }
        casemate_model_step_unlock((uint64_t)&vmmpmap_mtx);
#endif
        mtx_unlock(&vmmpmap_mtx);
```

Violations = Security-critical bugs!

Annotate

```
****** TRAP (from  host) ****************************************************
__pkvm_host_share_hyp
[r1] pfn: 0x.........1372e2
W 0x........eabf9000 0x..............0 at arch/arm64/kvm/hyp/nvhe/page_alloc.c:84 in page_remove_from_list
W 0x........eabf9008 0x..............0 at arch/arm64/kvm/hyp/nvhe/page_alloc.c:84 in page_remove_from_list
W 0x........eaa8edc8 0x............400 at arch/arm64/kvm/hyp/nvhe/../pgtable.c:968 in stage2_try_set_pte
transition simplified model state diff:
mem:
-    *[0x........eaa8edc8]=0x.......1372007fd (pte_st:V       root:0x........eaa1b000)
+    *[0x........eaa8edc8]=0x.........400 (pte_st:IU n 0 root:0x........eaa1b000)
Wrel 0x........eaa8edc8 0x........eabf9003 at arch/arm64/kvm/hyp/nvhe/../pgtable.c:1040 in stage2_make_pte
! BBM invalid unclean->valid
[  162.133816] kvm [241]: nVHE hyp BUG at: arch/arm64/kvm/hyp/nvhe/ghost_simplified_model.c:1045!
```

Report Violations

Lessons!

- Specs are easy to write
  ... and useful!
- H/W protocols can be checked
  ... and S/W buggy!