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Adaptive Android Kernel Live Patching

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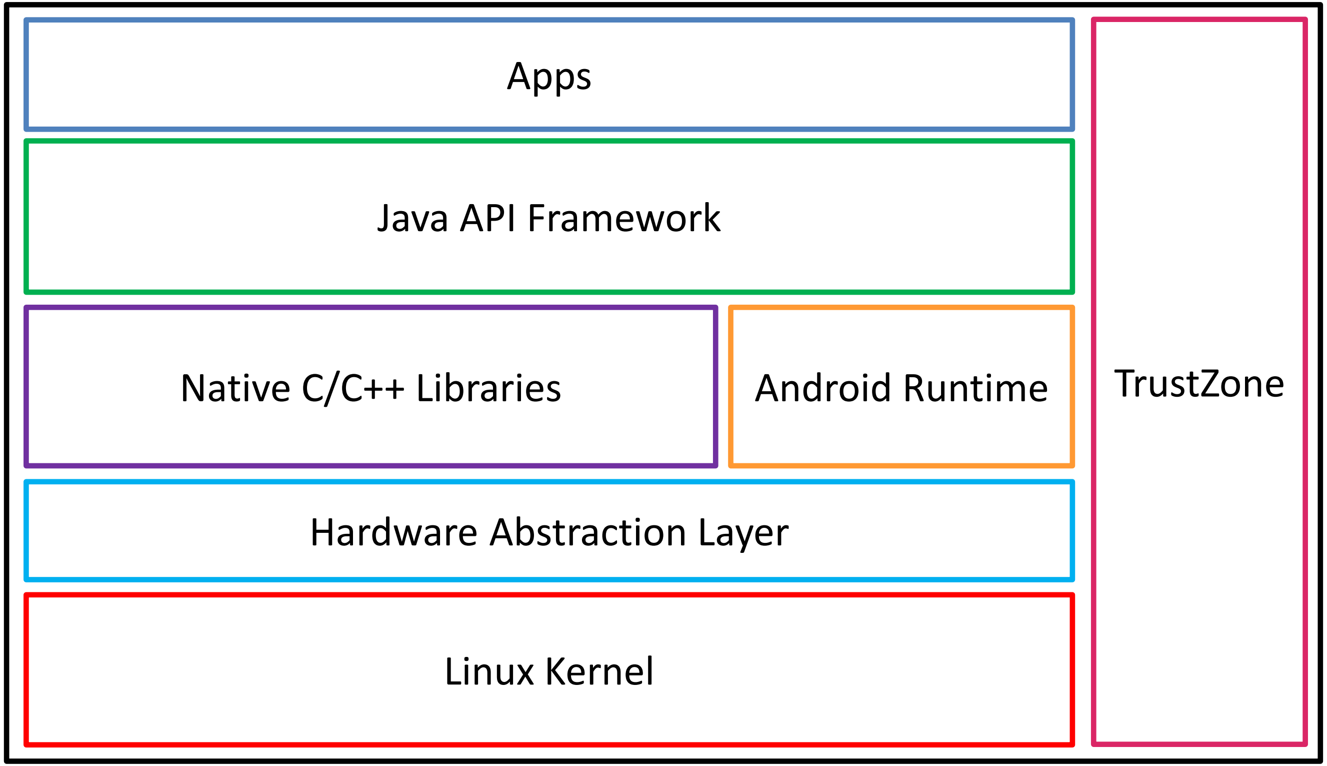
Android Kernel Vulnerabilities



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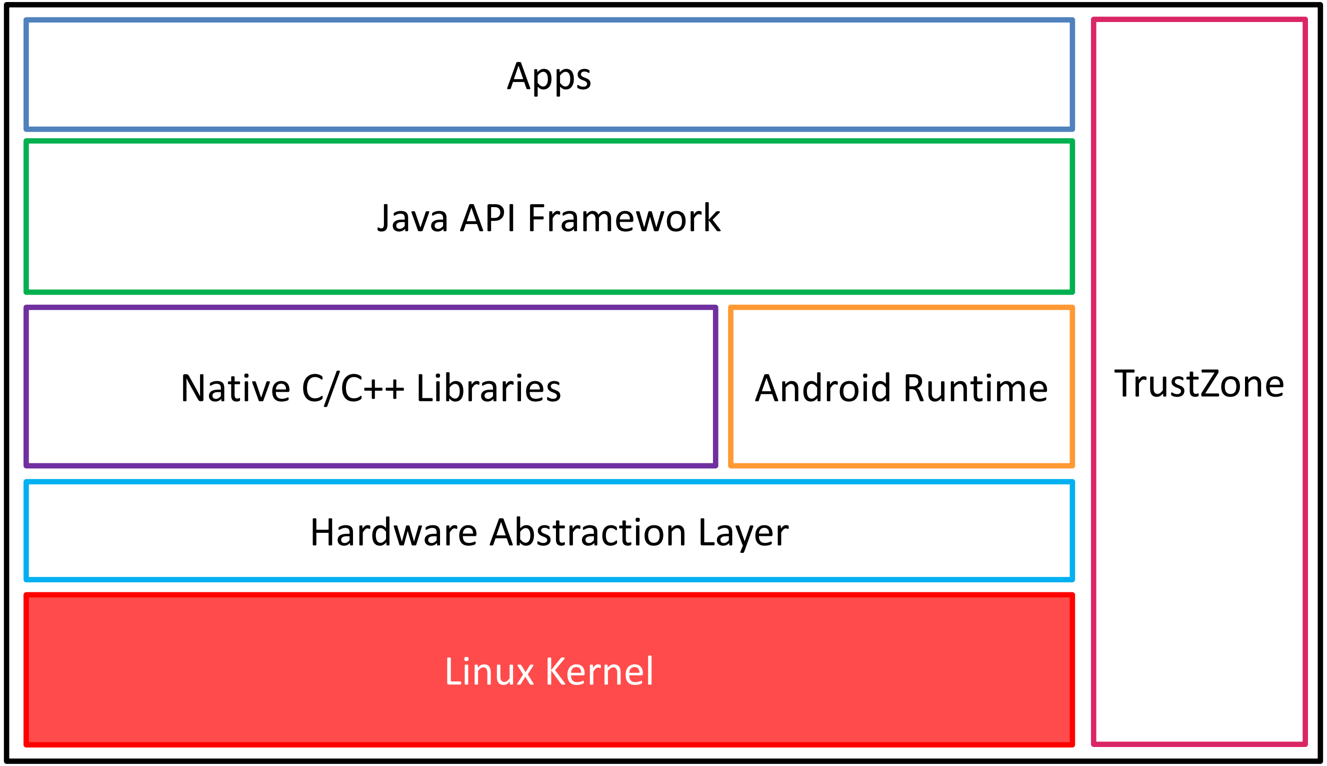

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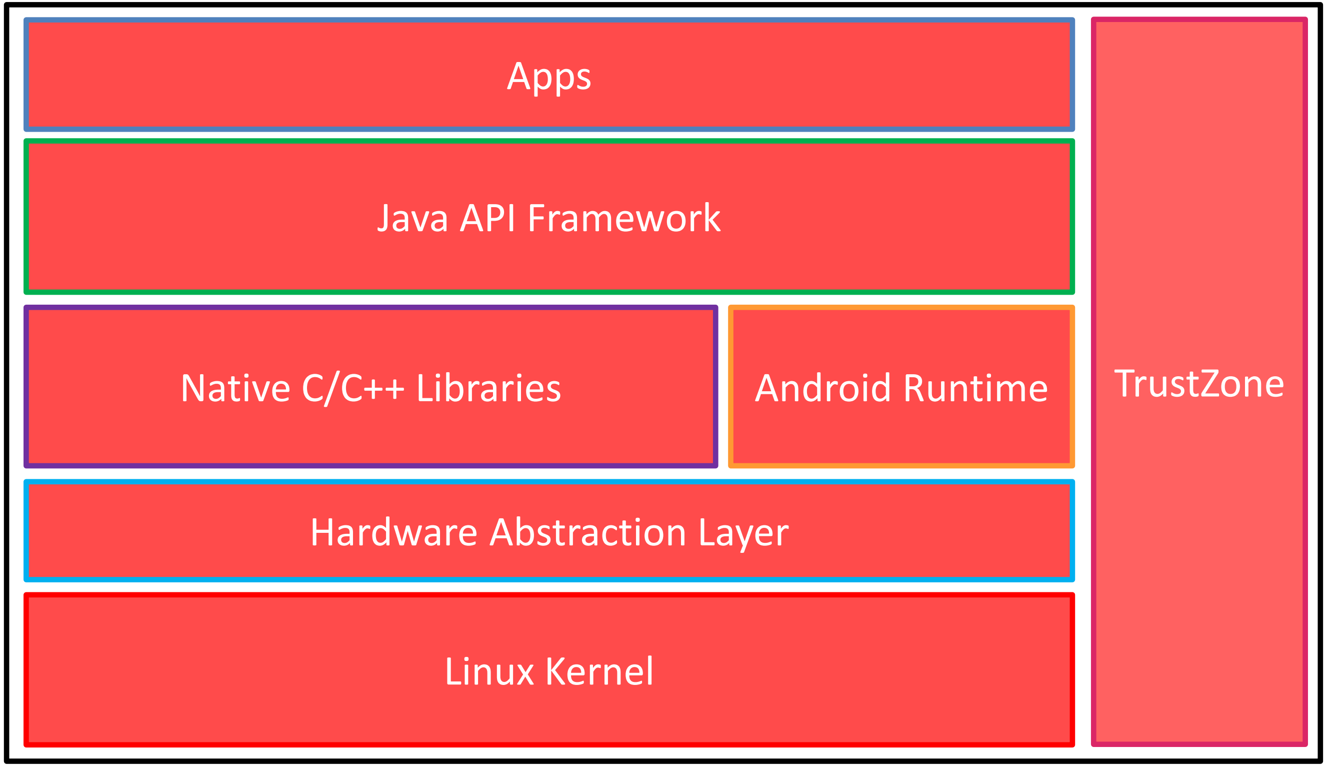
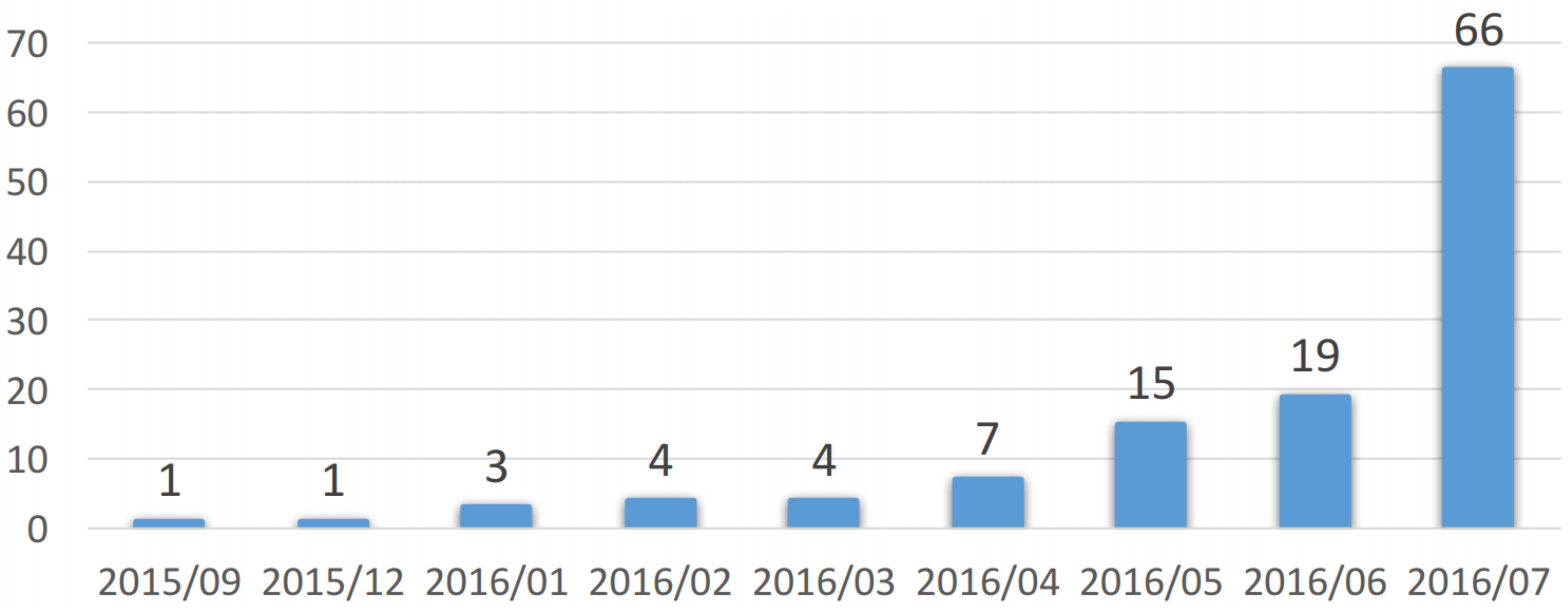


Number of Disclosed Android Kernel Vulnerabilities



Problem: Old Exploits Remain Effective

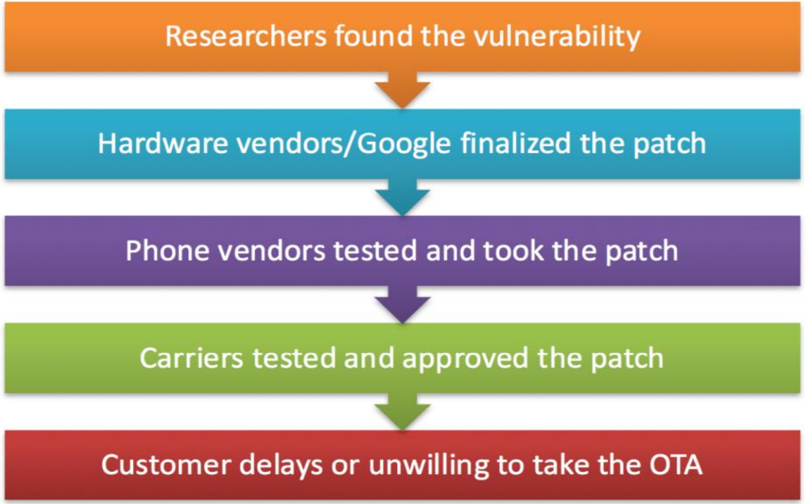
CVE ID	Release Date	Months	% Vulnerable Devices
CVE-2015-3636	Sep. 2015	14	30%
CVE-2015-1805	Mar. 2016	8	47%

Number of devices vulnerable to two root exploits as of Nov. 2016

- Android 5.0 released in November **2014**
- **46.3%** of devices run an older version in September **2016**

Challenges

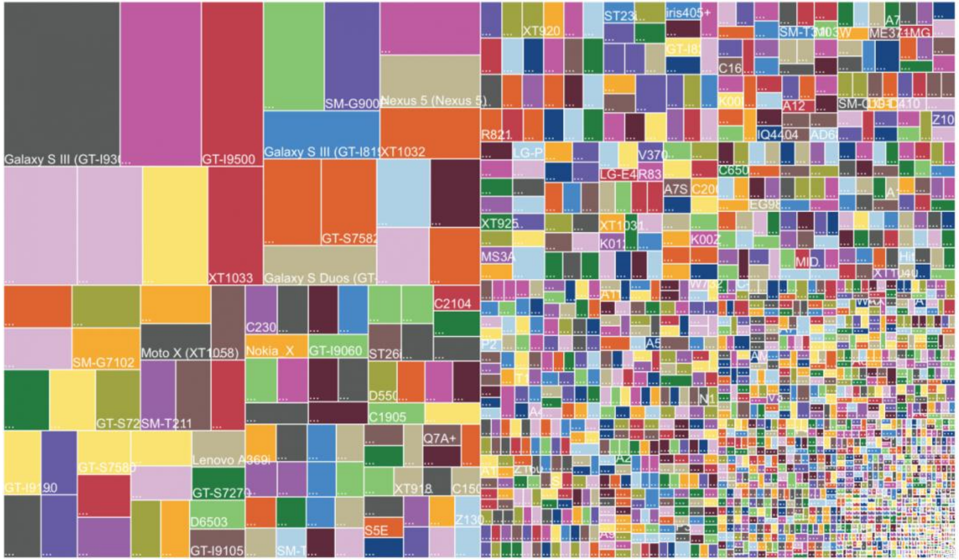
- *Officially* patching an Android device is a long process → **Third-party**



- Delayed/non-existing kernel source code → **Binary-based**

Challenges

- Severely fragmented Android ecosystem → **Adaptive**



http://d.ibtimes.co.uk/en/full/1395443/android-fragmentation-2014.png

Solution

Third-party Binary-based Adaptive Kernel Live Patching

Key requirements:

- **Adaptiveness**
  - It should be adaptive to various device kernels
- **Safety**
  - Patches should be easy to audit
  - Their behaviors must be *technically* confined
- **Timeliness**
  - Response time should be short, after disclosed vulnerability or exploit
- **Performance**
  - The solution should not incur non-trivial performance overhead

Feasibility Study: Dataset

- Studied **1139** Android kernels

Vendor	#Models	#Images
Samsung	192	419
Huawei	132	217
LG	120	239
Oppo	74	249
Google Nexus	2	15
Total	520	1139

Category	Statistics
Countries	67
Carriers	37
Android Versions	4.2.x, 4.3.x, 4.4.x, 5.0.x, 5.1.x, 6.0.x, 7.0.x
Kernel Versions	2.6.x, 3.0.x, 3.4.x, 3.10.x, 3.18.x
Kernel Architectures	ARM (77%), AArch64 (23%)
Kernel Build Years	2012, 2013, 2014, 2015, 2016

Feasibility Study: Observations

- Most kernel functions are **stable** across devices and Android releases
- Most vulnerabilities triggered by **malicious inputs**
- Many functions return **error codes**
  - Return a pointer → ERR_PTR

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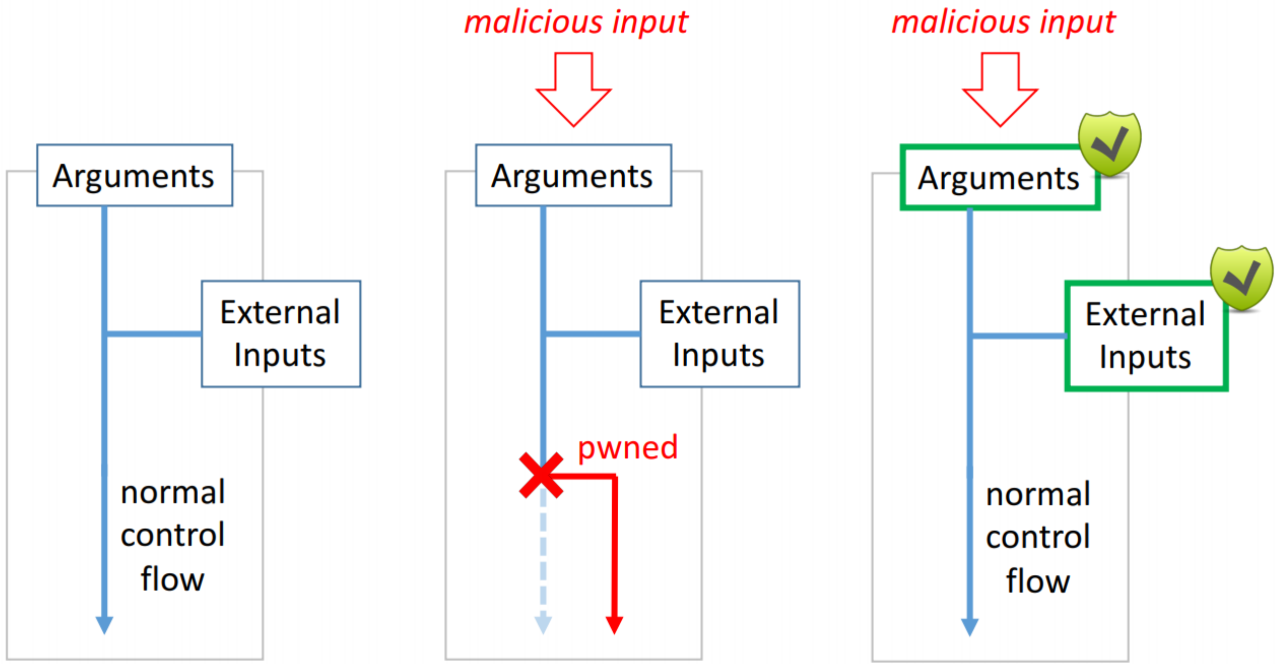
Filter them

Gracefully return

Overall Approach: Input Validation



KARMA

KARMA: **K**ernel **A**daptive **R**epair for **M**any **A**ndroids

- ✓ **Adaptive** – Automatically adapt to various device kernels
- ✓ **Memory-safe** – Protect kernel from malicious (misused) patches
- ✓ **Multi-level** – Flexible for different vulnerabilities

KARMA Design: Safety

- Patches are written in Lua, confined by Lua VM at runtime
- A patch can only be placed at designated locations
- Patched functions must return error codes or void
  - Use existing error handling to recover from attacks
- A patch can read but not write the kernel memory
  - Confined by KARMA APIs
  - Prevent malicious (misused) patches from changing the kernel
  - Prevent information leakage

KARMA Design: Multi-level Patching

- A patch can only be placed at designated locations
  - **Level 1**: Entry or return point of a (vulnerable) function
  - **Level 2**: Before or after the call site to a callee
    - e.g., copy_from_user
  - **Level 3**: Binary-based patch
- 76 critical Android kernel vulnerabilities
  - **Level 1**: 49/76 (64.5%)
  - **Level 2**: 22/76 (28.9%)
  - **Level 3**: 5/76 (6.6%)

KARMA Patch Example

```
 	if (requeue_pi) {
 		/*
+		 * Requeue PI only works on two distinct uaddrs. This
+		 * check is only valid for private futexes. See below.
+		 */
+		if (uaddr1 == uaddr2)
+			return -EINVAL;
+
+		/*
 		 * requeue_pi requires a pi_state, try to allocate it now
 		 * without any locks in case it fails.
 		 */
```

Part of the official patch of CVE-2014-3153 (Towelroot)

KARMA Patch Example

```
function kpatcher(patchID, sp, cpsr, r0, r1,
    r2, r3, r4, r5, r6, r7, r8, r9, r10, r11,
     r12, r14)
    if patchID == 0xca5269db50f4 then
        uaddr1 = r0
        uaddr2 = r2
        if uaddr1 == uaddr2 then
            return -22
        else
            return 0
        end
    end
end
kpatch.hook(0xca5269db50f4,"futex_requeue")
```

-EINVAL

More *complex* examples in the paper

KARMA API

API	Functionality
hook	Hook a function for live patching
subhook	Hook the calls to sub-functions for live patching
alloc_mem	Allocate memory for live patching
free_mem	Free the allocated memory for live patching
get_callee	Locate a callee that can be hooked
search_symbol	Get the kernel symbol address
current_thread	Get the current thread context
read_buf	Read raw bytes from memory with the given size
read_int_8	Read 8 bits from memory as an integer
read_int_16	Read 16 bits from memory as an integer
read_int_32	Read 32 bits from memory as an integer
read_int_64	Read 64 bits from memory as an integer

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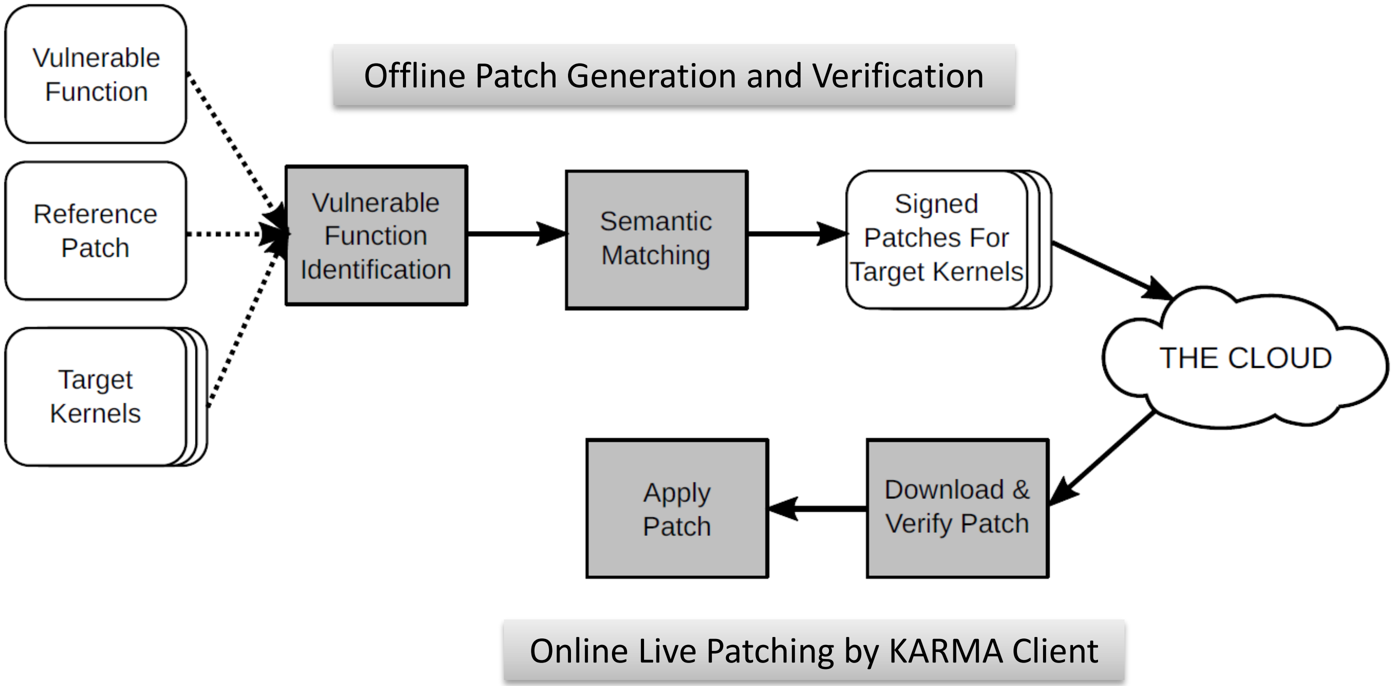
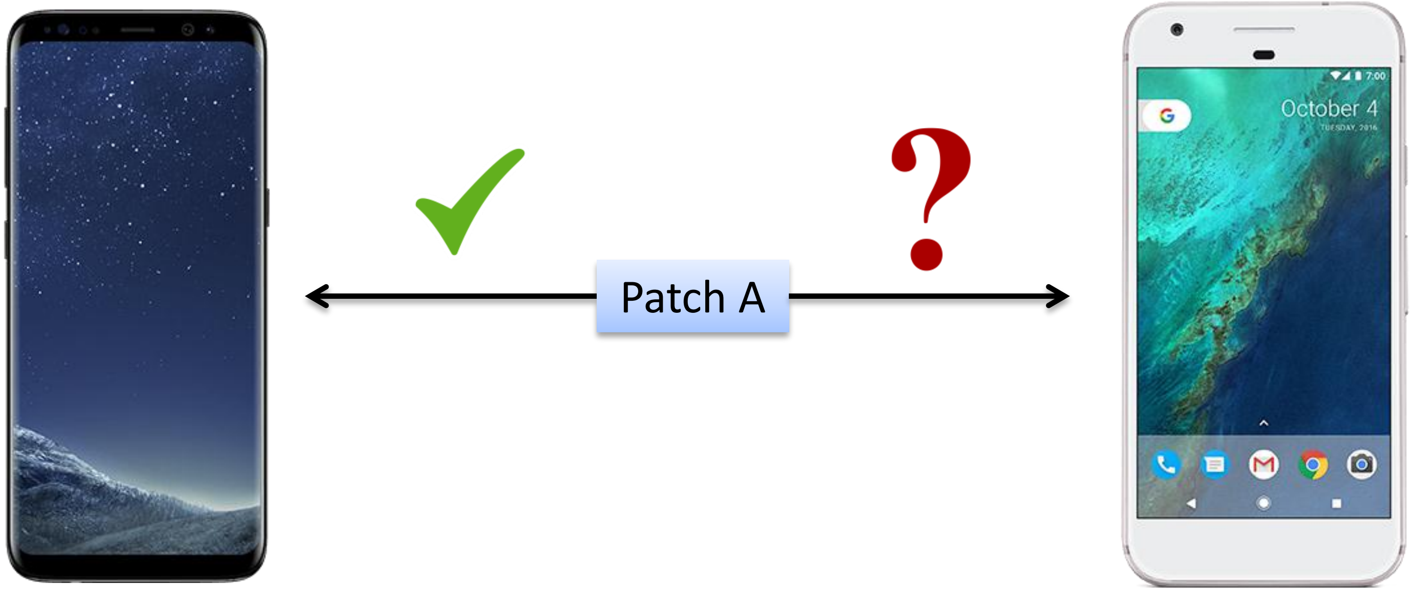
Available to patches

KARMA Architecture



Offline Patch Adaptation



Offline Patch Adaptation

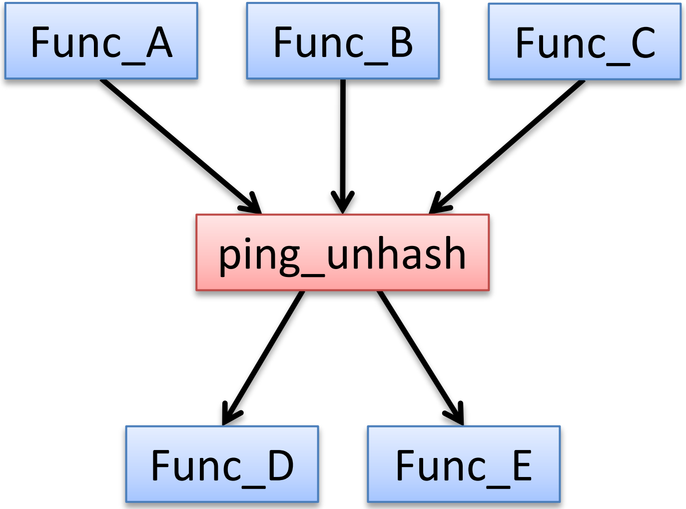
Three steps:

1. **Identify** the vulnerable functions in the target kernel
   - Same function but different names
   - Inlined
2. **Check** if the reference patch works for the target kernel
   - Same function but different semantics
3. **Adapt** the reference patch for the target kernel

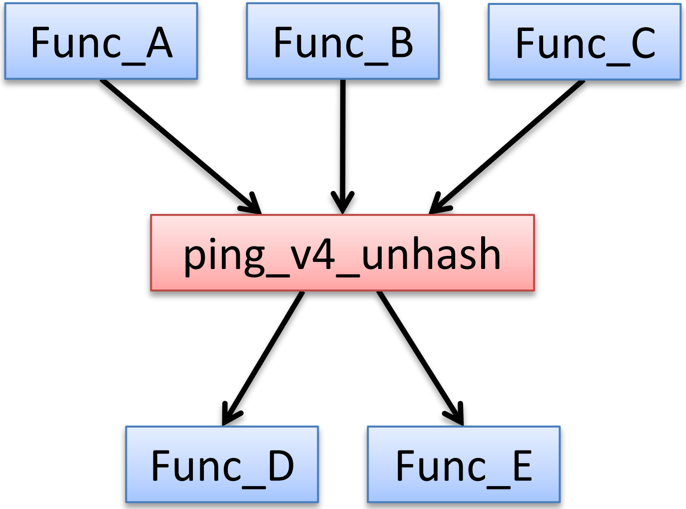
Vulnerable Function Identification Example

CVE-2015-3636 (PingPong Root)

Device A: ping_unhash



Device B: ping_v4_unhash

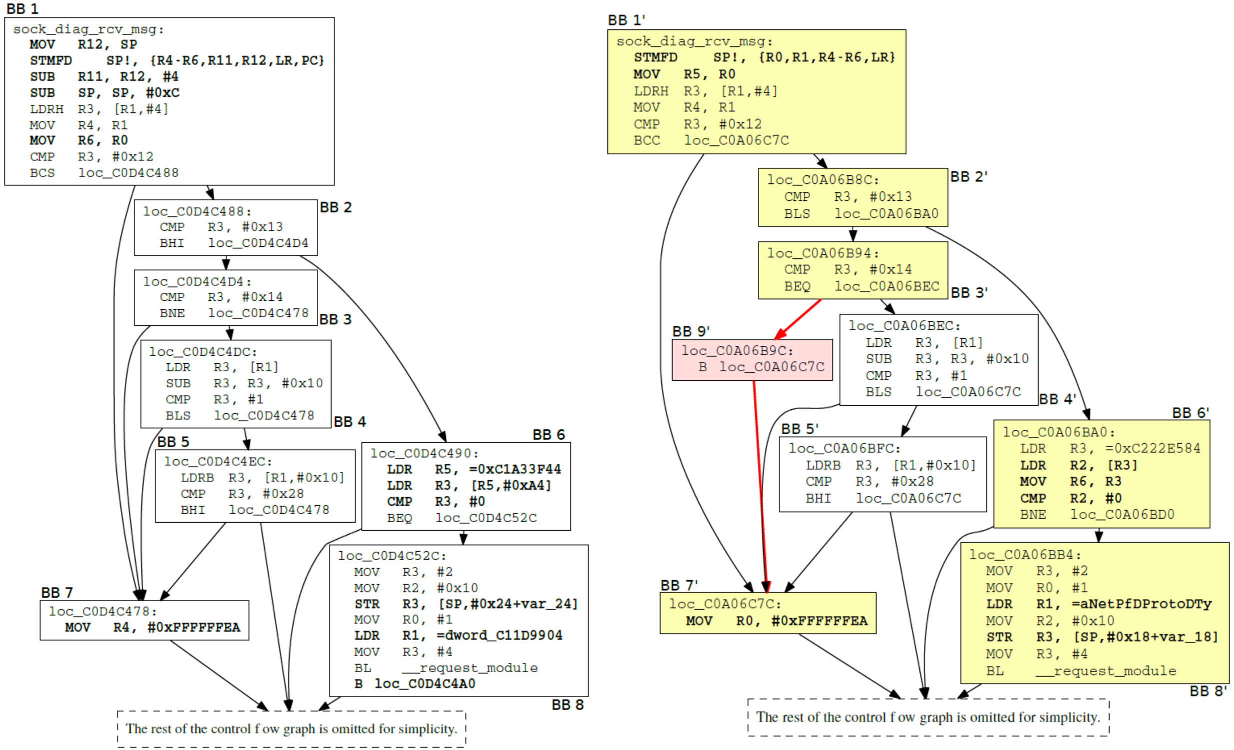


Call graph based similarity comparison

Semantic Matching

- Check if two functions are semantically equivalent
- If so, adapt the reference patch to the target kernel
- Syntactic matching is too strict
  - Different compilers can generate different code with same semantics
    - Instruction order, register allocation, instruction selection, code layout

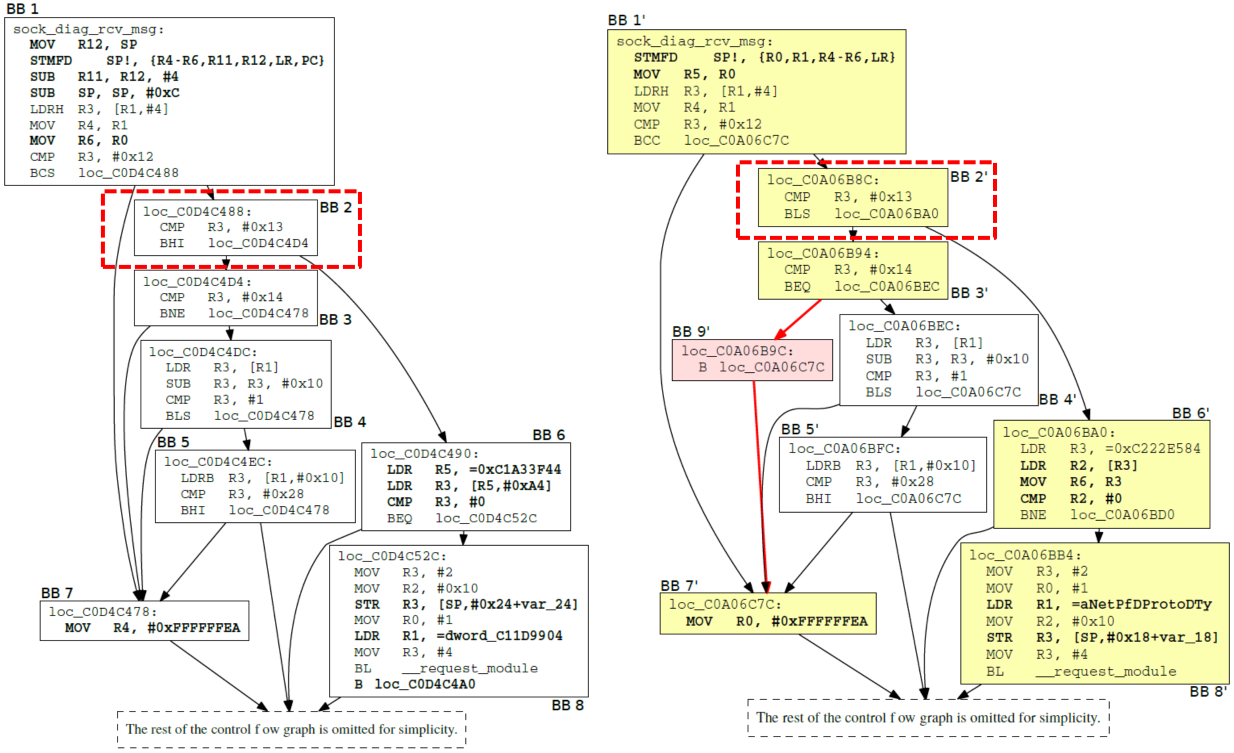
Semantic Matching



(a) (b)

Same semantics with different syntax

Semantic Matching



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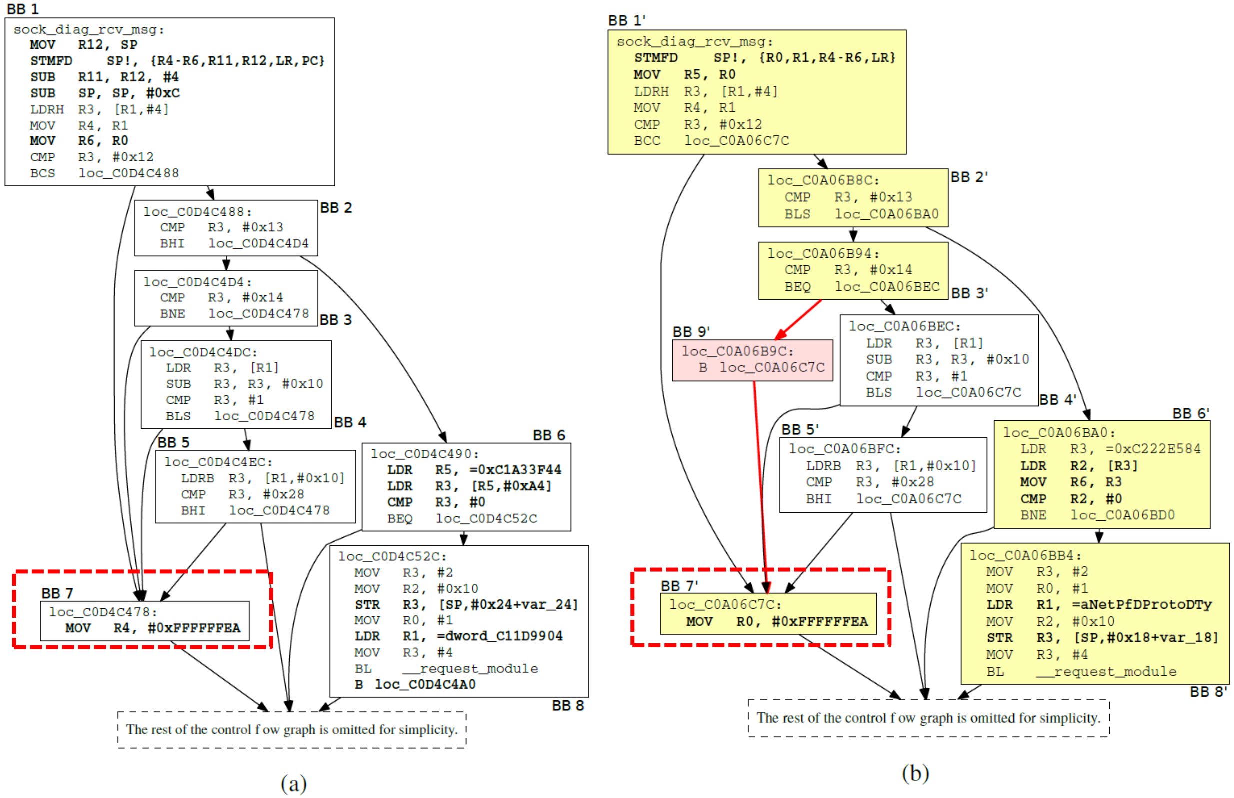

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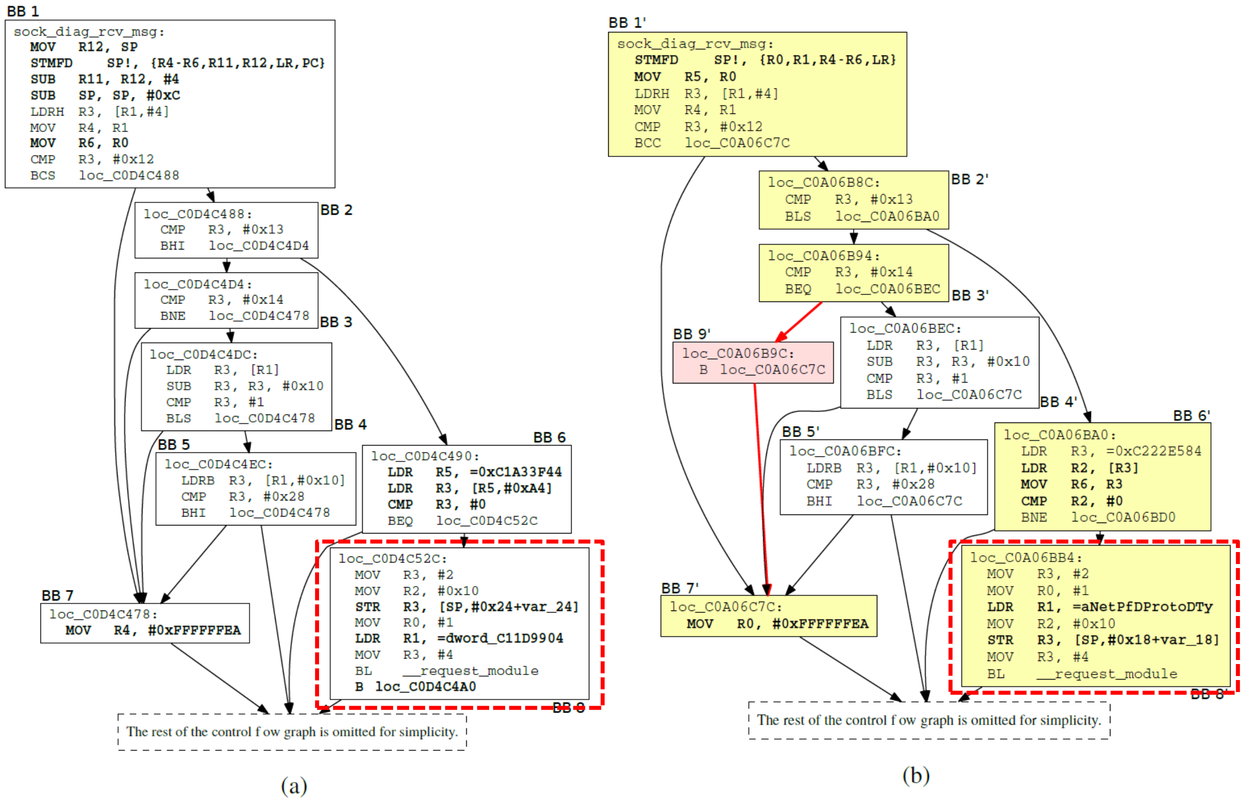

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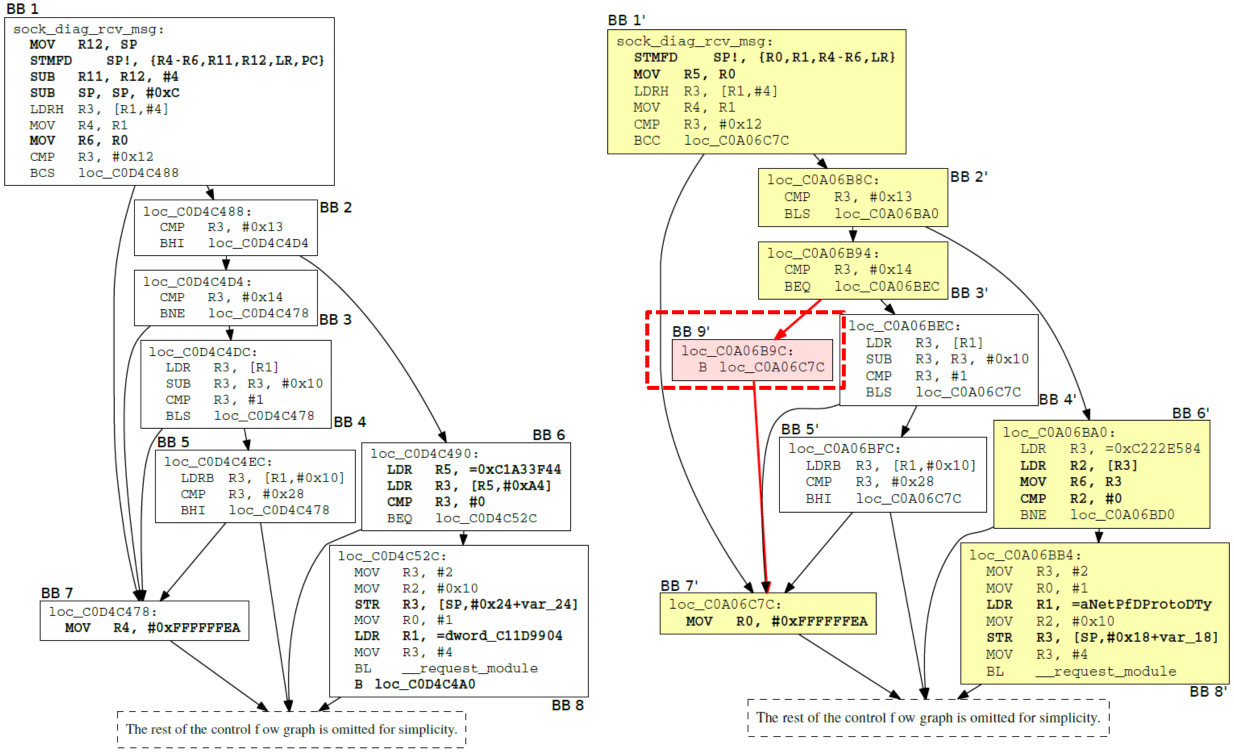

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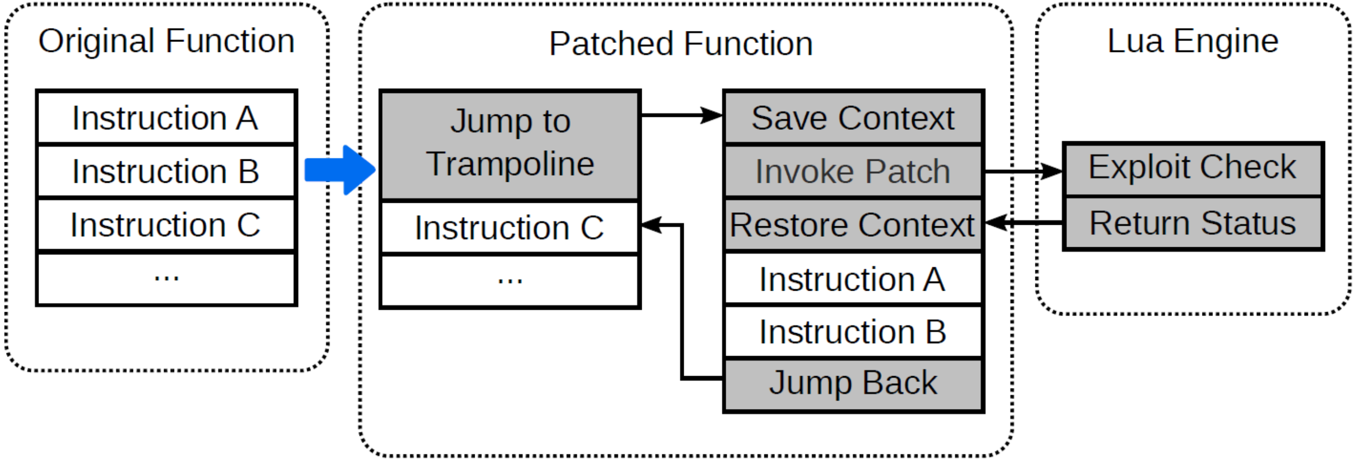
Same semantics with different syntax

Semantic Matching

- Check if two functions are semantically equivalent
- If so, adapt the reference patch to the target kernel
- Syntactic matching is too strict
  - Different compilers can generate different code with same semantics
    - Instruction order, register allocation, instruction selection, code layout
- Use symbolic execution to abstract these differences and adapt patches
  - Use approximation to improve scalability (details in the paper)

Online Patch Application



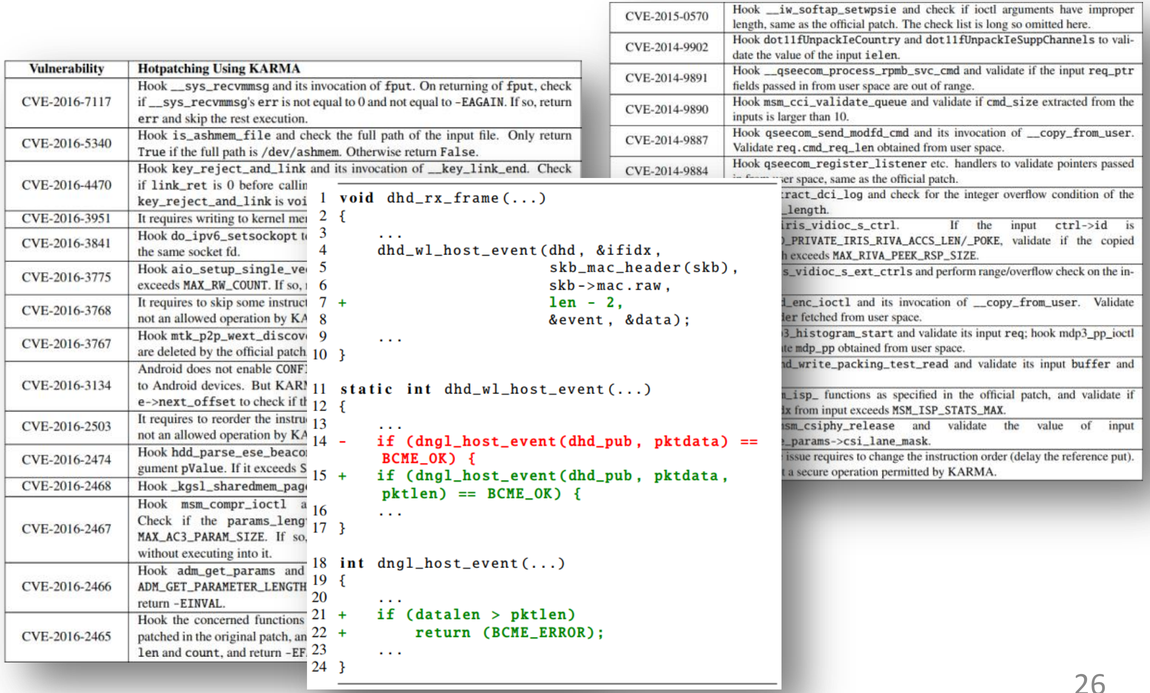
Function entry point hooking

Prototype Implementation

- Lua engine in kernel (11*K* SLOC)
  - Simple
  - Memory-safe
  - Easy to embed and extend
  - 24 years of development
- Semantic matching
  - angr

Evaluation: Applicability

- Evaluated **76** critical vulnerabilities in the last three years
- Patch level:
  - Level-1: 49
  - Level-2: 22
  - Level-3: 5



Evaluation: Adaptability

Kernel Function	CVE ID	# of Opcode Clusters	% of the Largest Opcode Cluster	# of Syntax Clusters	% of the Largest Syntax Cluster	# of Semantic Clusters	% of Largest Semantic Cluster	Semantic Matching Time Cost	# of Instructions	# of Basic Blocks
sock_diag_rcv_msg	2013-1763	35	25.0%	7	73.5%	3	75.5%	10.5s	72	16
perf_swevent_init	2013-2094	9	55.9%	5	55.9%	2	96.3%	24.6s	81	22
fb_mmap	2013-2596	26	20.2%	7	44.4%	5	66.9%	12.2s	102	15
__get_user_1	2013-6282	3	92.4%	2	92.4%	2	98.0%	3.2s	6	2
futex_requeue	2014-3153	54	14.8%	9	71.0%	3	99.3%	35.8s	459	107
msm_isp_proc_cmd	2014-4321	42	22.0%	5	66.5%	3	42.8%	8.8s	385	68
send_write_packing_test_read	2014-9878	12	57.6%	4	61.2%	1	100%	4.9s	25	4
msm_cci_validate_queue	2014-9890	6	59.5%	4	84.9%	2	72.4%	6.7s	77	8
ping_unhash	2015-3636	36	12.5%	5	75.7%	3	50.5%	4.6s	54	8
q6lsm_snd_model_buf_alloc	2015-8940	29	34.0%	9	36.6%	5	44.2%	9.9s	104	20
sys_perf_event_open	2016-0819	22	36.3%	6	46.9%	6	84.2%	34.6s	569	118
kgsl_ioctl_gpumem_alloc	2016-3842	16	35.4%	3	88.8%	4	46.0%	4.7s	79	11
is_ashmem_file	2016-5340	6	89.6%	2	93.9%	2	98.1%	0.8s	23	3

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Types and frequencies of instruction opcodes

Evaluation: Adaptability

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Number of function calls and conditional branches (to abstract CFG)

Evaluation: Adaptability

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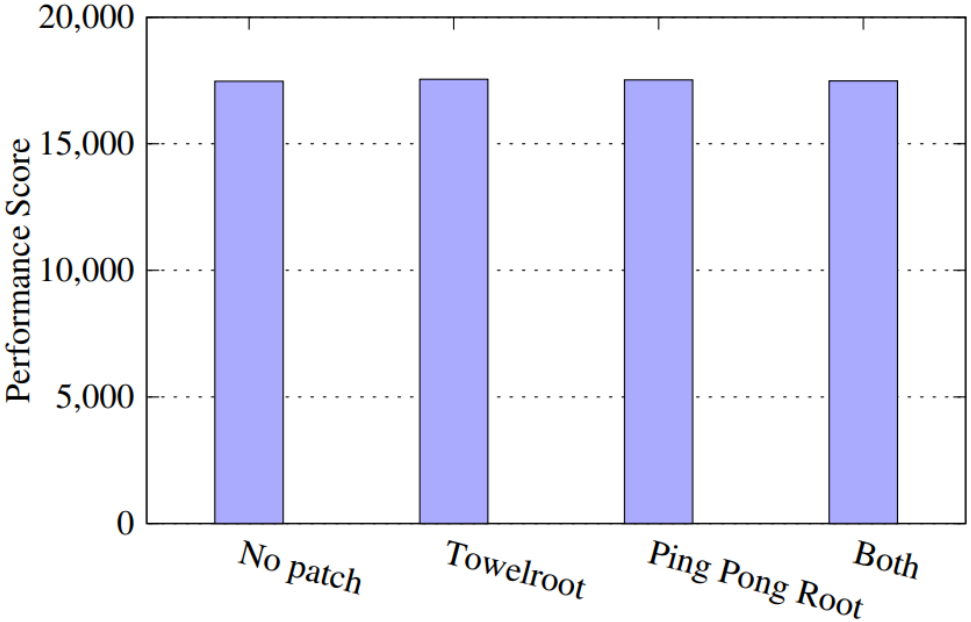
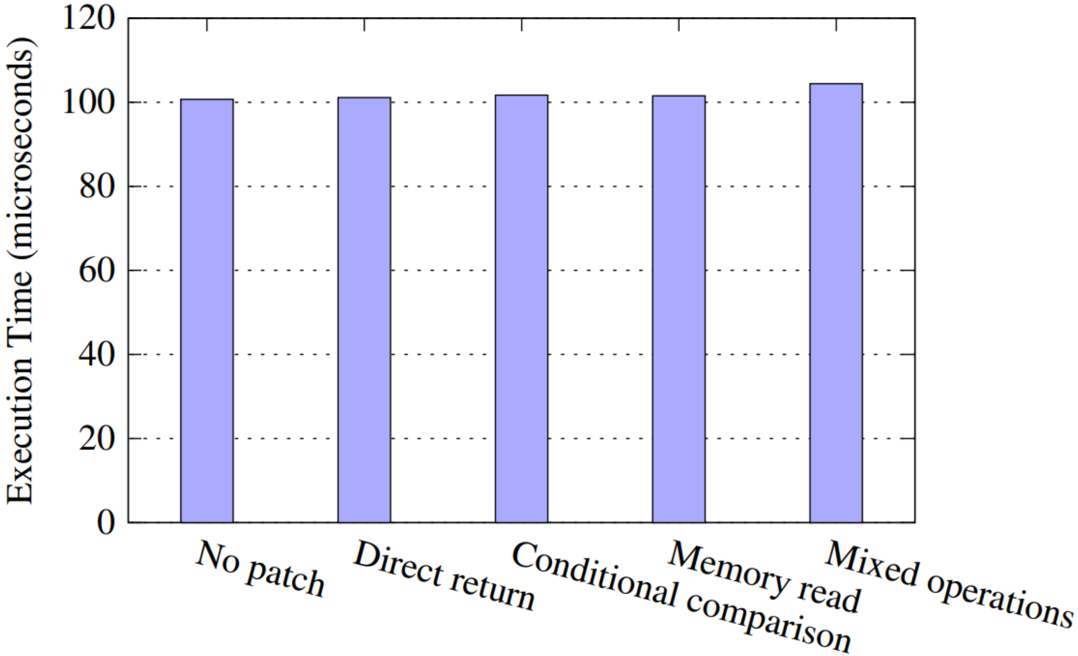
KARMA’s semantic matching

Evaluation: Performance



CF-Bench results with different patches

Evaluation: Performance



Execution time of chmod with different patches

Future Work

- User-space vulnerability protection
  - Project Treble → only partially solve the problem
- Lua engine in the kernel (11*K* SLOC)
  - Alternative execution engines, like BPF or sandboxed binary patches
- Error handling code could be vulnerable
  - Error injection to detect vulnerable error-handling code
- Improve semantic matching

Q & A

Adaptive Android Kernel Live Patching

www.YueChen.me

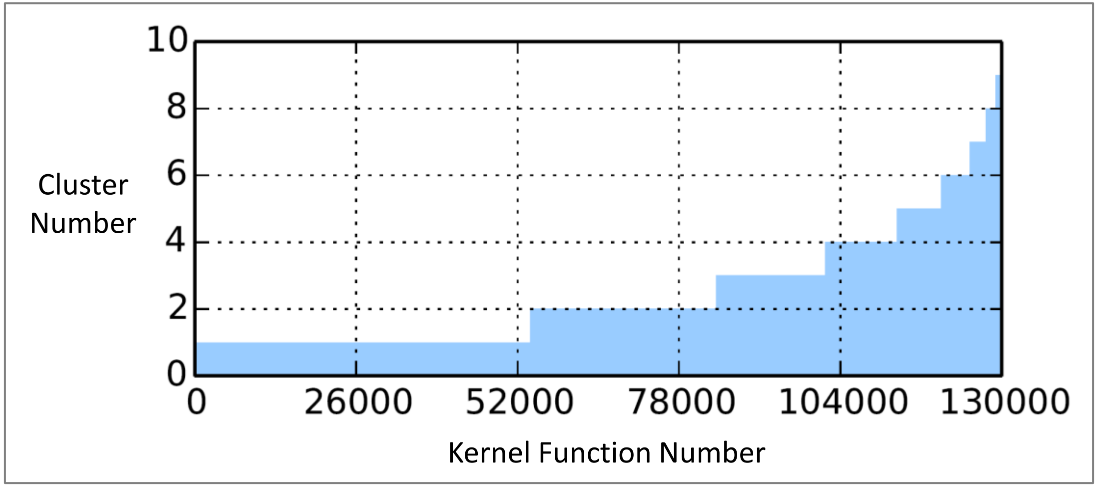
Backup Slides

Attack TrustZone from Kernel

- Example:
  - Downgrade Attack on TrustZone (see its references)

Observations

- Most kernel functions are **stable** across devices and Android releases.

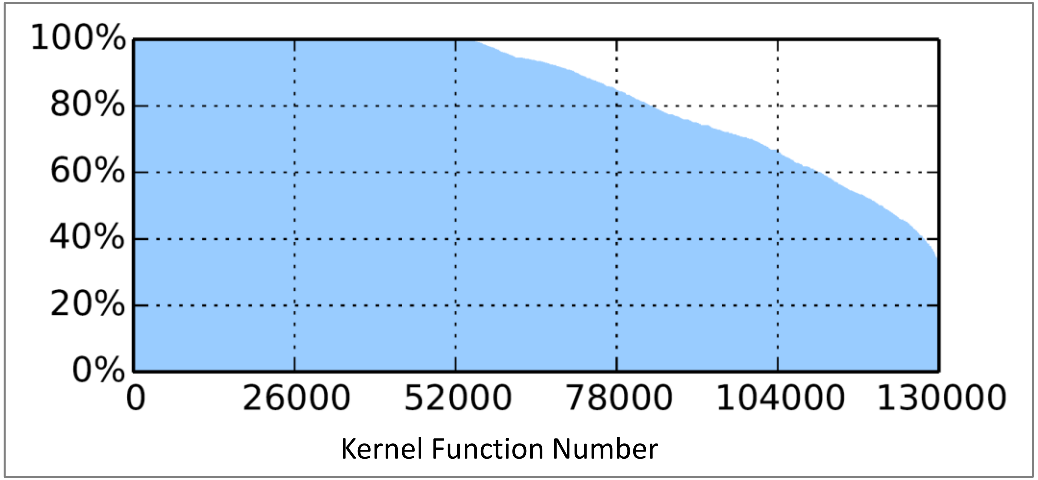


Number of syntax clusters for each function

About 40% of the shared functions have only one cluster, and about 80% of them have 4 clusters or less.

Observations

- Most kernel functions are **stable** across devices and Android releases.



Percentage of kernels in the largest cluster for each function

For about 60% of shared functions, the largest cluster contains more than 80% of all the kernels that have this function.

Symbolic Execution

- Challenges
  - Avoid path explosion
  - Impact to the environment
- Practical Solution
  - Non-local memory writes
  - Function calls (and their arguments)
  - Function return values
- Adaptation (e.g., mutate constants or offsets)
  - foo(symbol_A + 4, 36) → foo(symbol_A + 8, 36)

Evaluation: Overall Performance

- *Complex* patch for *most frequent* syscall (gettimeofday) during web browsing
- Overall system performance overhead in this *extreme* situation: 0.9%

Example: CVE-2013-6123

```
static long msm_ioctl_server(struct file *
     file, void *fh, bool valid_prio, int cmd,
      void *arg)
{
     ...
     if (copy_from_user(&u_isp_event,
          (void __user *)ioctl_ptr->ioctl_ptr,
          sizeof(struct msm_isp_event_ctrl))) {
          ...
     }
     ...
+    if(u_isp_event.isp_data.ctrl.queue_idx<0
+    || u_isp_event.isp_data.ctrl.queue_idx >=
+         MAX_NUM_ACTIVE_CAMERA) {
+         pr_err("%s: Invalid index %d\n",
+              __func__, u_isp_event.isp_data.
      ctrl.queue_idx);
+         rc = -EINVAL;
+         return rc;
+    }
     ...
}
```

Example: CVE-2013-6123

```
static long msm_ioctl_server(struct file *
        file, void *fh, bool valid_prio, int cmd,
        void *arg)
{
        ...
        if (copy_from_user(&u_isp_event,
                (void __user *)ioctl_ptr->ioctl_ptr,
                sizeof(struct msm_isp_event_ctrl))) {
                ...
        }
        ...
+       if(u_isp_event.isp_data.ctrl.queue_idx <0
+       || u_isp_event.isp_data.ctrl.queue_idx >=
+               MAX_NUM_ACTIVE_CAMERA) {
+               pr_err("%s: Invalid index %d\n",
+                       __func__, u_isp_event.isp_data.
        ctrl.queue_idx);
+               rc = -EINVAL;
+               return rc;
+       }
        ...
}
```

Example: CVE-2013-6123

```
static long msm_ioctl_server(struct file *
      file, void *fh, bool valid_prio, int cmd,
       void *arg)
{
    ...
    if (copy_from_user(&u_isp_event,
        (void __user *)ioctl_ptr->ioctl_ptr,
        sizeof(struct msm_isp_event_ctrl))) {
        ...
    }
    ...
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