Defeating Samsung KNOX with zero privilege

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whoami

- Di Shen a.k.a. Retme (@returnsme)
- Member of Keen Lab
- Android Kernel vulnerability hunting and exploitation since 2014
- Aim: to make out universal rooting exploit for Android
- Trophy:
  - CVE-2016-6787 & CVE-2017-0403 (kernel/events/core.c)
    - Credit to discoveries and exploits
  - CVE-2015-1805 (fs/pipe.c)
    - First working exploit
  - CVE-2015-4421,4422
    - Kernel LPE and TrustZone code execution for Huawei Mate 7
  - Exploiting Wireless Extension for all common Wi-Fi chipsets (BHEU 16')
  - And more To Be Announced in the future

Agenda

- Overview of KNOX 2.6
  - KASLR (Samsung’s implementation)
  - Real-time kernel protection (RKP)
  - Data Flow Integrity (DFI)
- Bypassing techniques
  - KASLR bypassing
  - DFI bypassing
  - SELinux bypassing
  - Gain root

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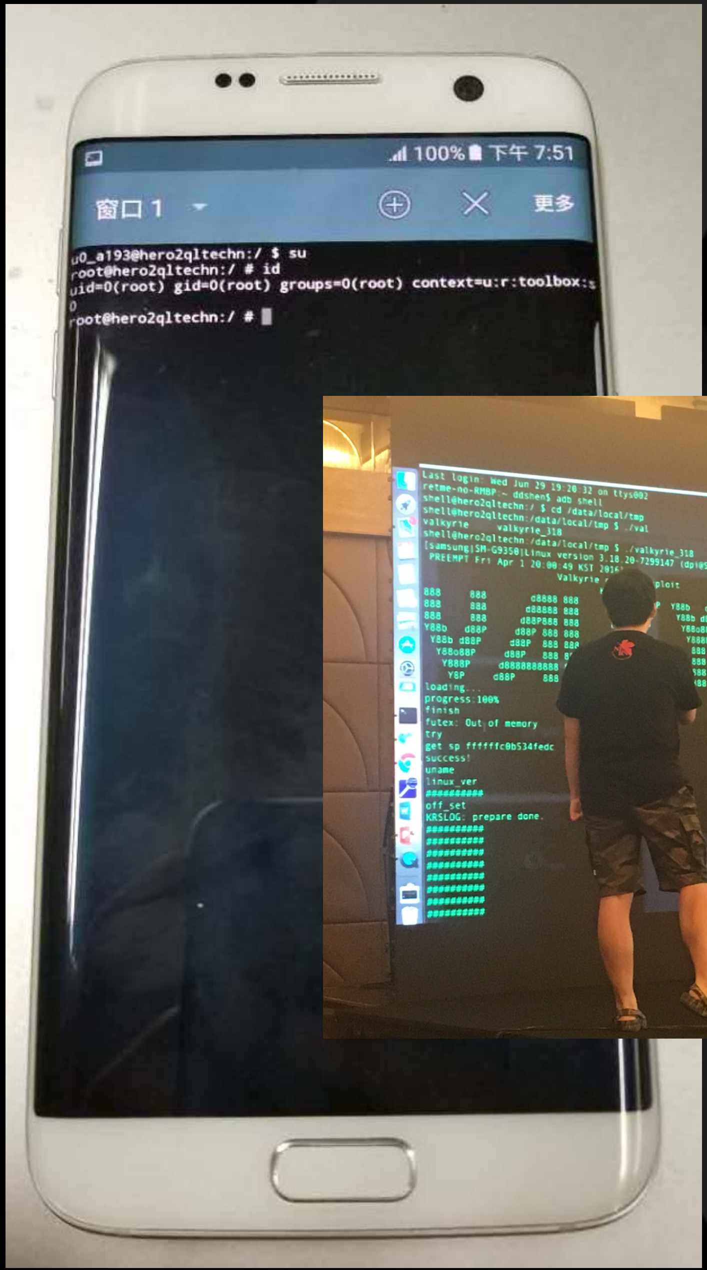
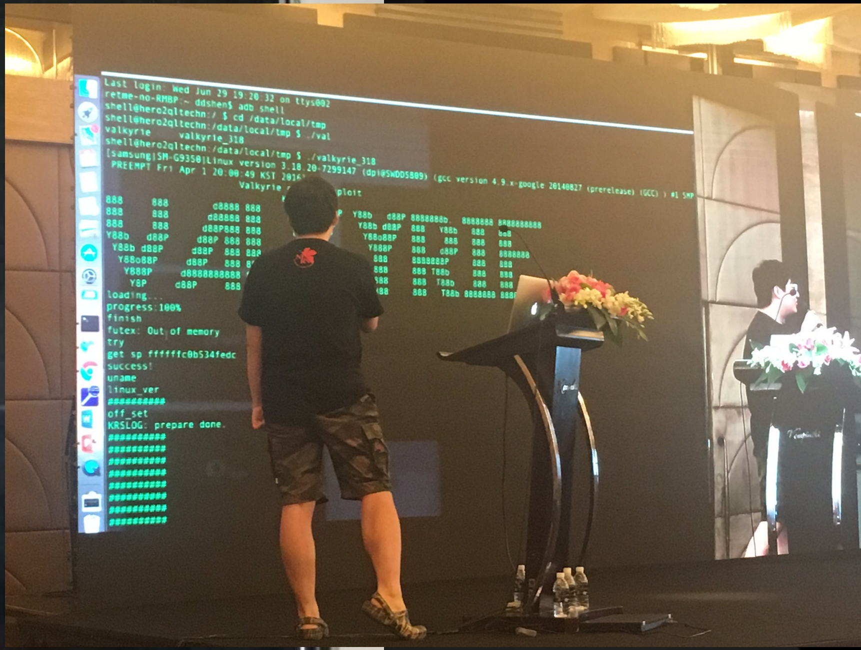
Target device

- Samsung Galaxy S7 edge
  - SM-G9350 (Hong Kong ver.)
  - Qualcomm-based
  - KNOX 2.6
- Exploit chain was finished in June 2016
- Demonstrated in July 1st 2016 at Shanghai





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Common LPE flow on Android

Arbitrary kernel memory overwriting → Overwrite ptmx_fops → Overwrite address_limit → Overwrite uid, security id,and selinux_enforcing

LPE flow on Glaxy S7 edge

Bypass KASLR → Arbitrary kernel memory overwriting → Overwrite ptmx_fops → Overwrite address_limit → Bypass DFI → Bypass SELinux for Samsung → Gain root privilege

KASLR for Linux 3.18 - Initialization

- CONFIG_RELOCATABLE_KERNEL by Samsung
- The Random size is passed to kernel by loader
- X1,X2 are set upon kernel start up
  - X1: phycal offset X2: vitual text offset
  - Store to __boot_kernel_offset
  - __boot_kernel_offset[0] : physical address of kernel
  - __boot_kernel_offset[1] : the actual load address
  - __boot_kernel_offset[2] : TEXT_OFFSET 0x8000

```
ENTRY(stext)
#ifdef CONFIG_RKP_CFP_ROPP
    /* Must intialize RRK to zero before any RET/BL
    mov RRK, #0
#endif
#ifdef CONFIG_RKP_CFP_JOPP
    /* We need RRS to be loaded before we take our 
    load_function_entry_magic_number_before_reloc h
#endif
#ifdef CONFIG_RELOCATABLE_KERNEL
    mov x22, x1                 // x1=PHYS_OFFSET
    mov x19, x2                 // x2=real TEXT_OFFSET
    adr x21, __boot_kernel_offset
    stp x1, x2, [x21]
#endif
```

KASLR for Linux 3.18 - relocating

- __relocate_kernel() handles kernel relocating
  - Similar to a aarch64 linker in user space

```
#ifdef CONFIG_RELOCATABLE_KERNEL

#define R_AARCH64_RELATIVE  0x403
#define R_AARCH64_ABS64     0x101

__relocate_kernel:
    sub x23, x19, #TEXT_OFFSET
    adrp    x8, __dynsym_start
    add x8, x8, :lo12:__dynsym_start    //x8: start of symbol table
    adrp    x9, __reloc_start
    add     x9, x9, :lo12:__reloc_start //x9: start of relocation table
    adrp    x10, __reloc_end
    add x10, x10, :lo12:__reloc_end     //x10: end of relocation table
```

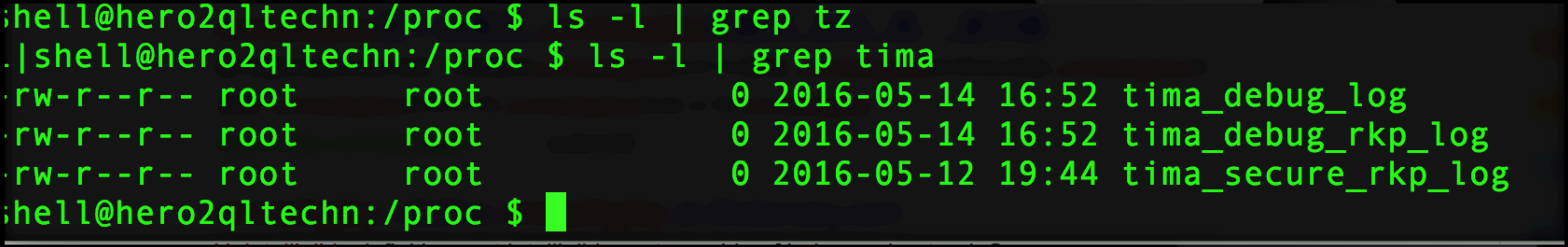
KASLR for Linux 3.18 - .rela section

- __relocate_kernel handles kernel relocating
  - Similar to a aarch64 linker in user space
  - Relocation section '.rela' at offset 0x1446600 contains 233903 entries:

Offset	Info	Type	Sym. Value	Sym. Name + Addend	
ffffffc000081698	000000000403	R_AARCH64_RELATIV		-3ffff7e968	
ffffffc0000816a0	000000000403	R_AARCH64_RELATIV		-3ffe5d1e20	
ffffffc000081798	000000000403	R_AARCH64_RELATIV		-3ffff7e868	
…					
ffffffc00008e000	000000000403	R_AARCH64_RELATIV		-3ffff546b8	# Begin of sys_call_table
…					
ffffffc000f6f800	000600000101	R_AARCH64_ABS64	ffffffc000080000	_text + 0	# Begin of kallsyms_addresses
…					
ffffffc0013b1468	000000000403	R_AARCH64_RELATIV		-3ffec1afdd	

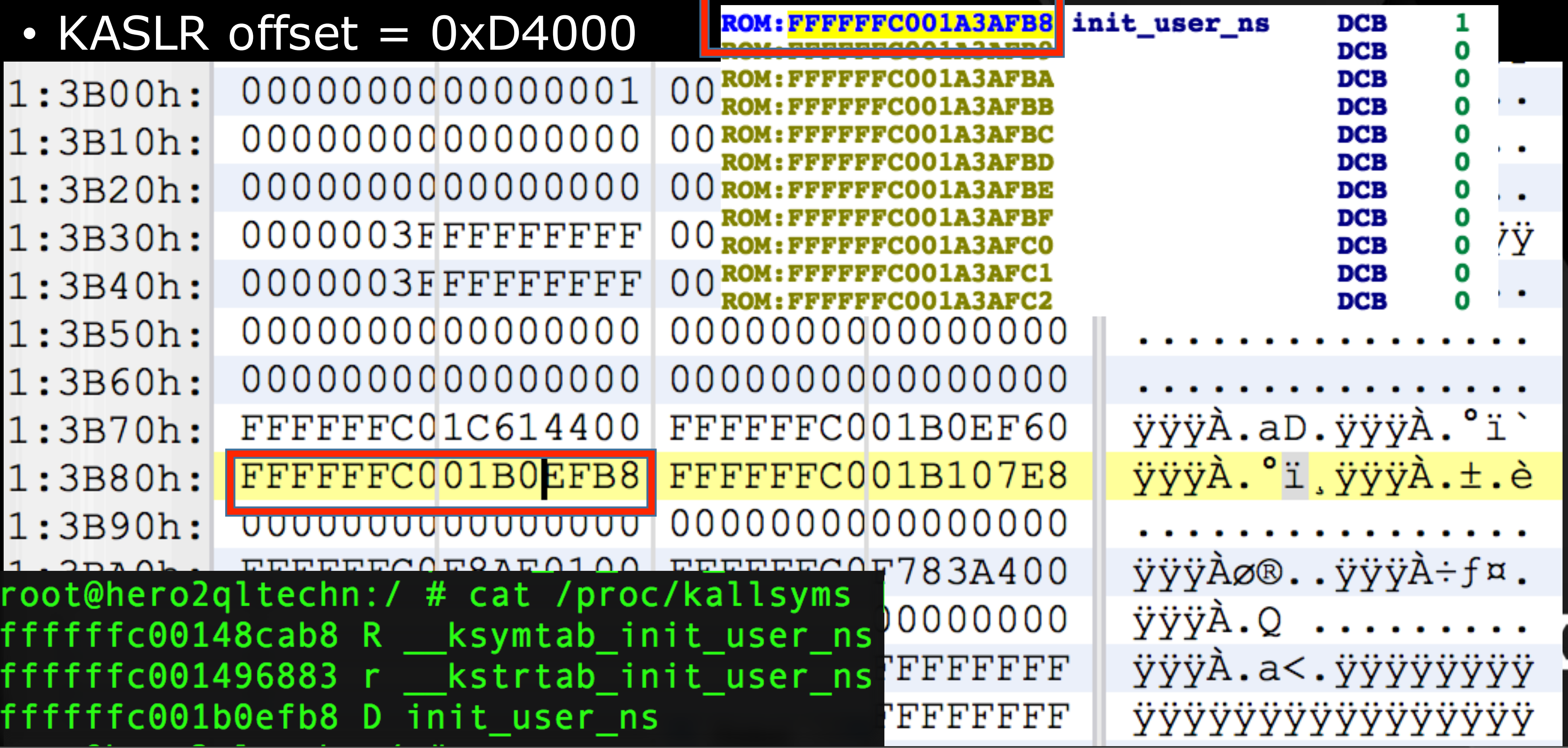
Bypassing KASLR

- Readable TIMA logs



Kernel information leaking

- Kernel pointer leaked in /proc/tima_secure_rkp_log
- At 0x13B80 -> *init_user_ns*
- Real:0xFFFFFFC001B0EFB8 Static:0xFFFFFFC01A3AFB8
- KASLR offset = 0xD4000



Achieve arbitrary kernel mem overwriting

- By exploiting CVE-2016-6787
- Use-after-free due to race condition in perf subsystem
  - Moving group in sys_perf_event_open() is not locked by mutex correctly
- Spray struct perf_event_context{}
  - Control code flow by refill ctx->pmu->pmu_disable(X0)
- Another long story ☺

```
+	/*
+	 * Take the group_leader's group_leader_mutex before observing
+	 * anything in the group leader that leads to changes in ctx,
+	 * many of which may be changing on another thread.
+	 * In particular, we want to take this lock before deciding
+	 * whether we need to move_group.
+	 */
+	if (group_leader)
+		mutex_lock(&group_leader->group_leader_mutex);
+
	if (pid != -1 && !(flags & PERF_FLAG_PID_CGROUP)) {
		task = find_lively_task_by_vpid(pid);
		if (IS_ERR(task)) {
@@ -7686,6 +7697,8 @@
		put_ctx(gctx);
	}
	mutex_unlock(&ctx->mutex);
+	if (group_leader)
+		mutex_unlock(&group_leader->group_leader_mutex);
```

Real-time Kernel Protection

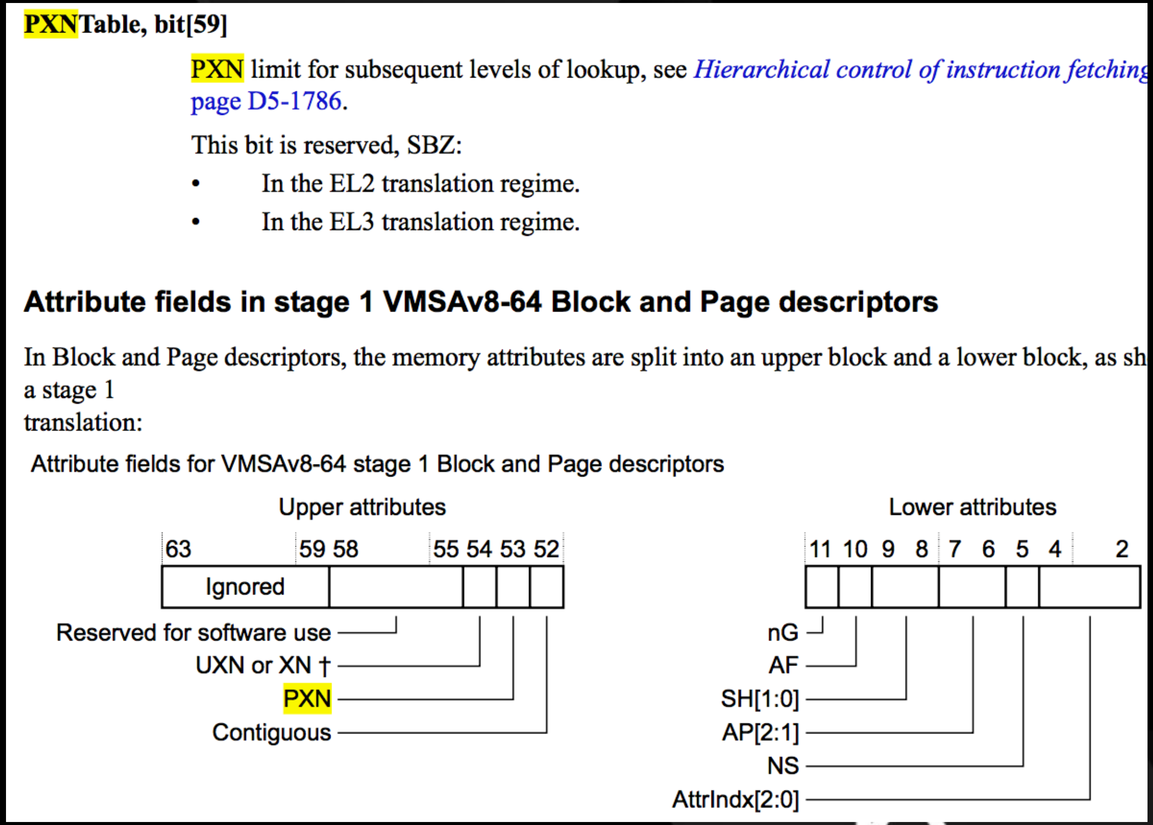
- Implemented in TrustZone or hypervisor
  - Depends on device model, for S7 edge (SM-G9350), it’s TrustZone
- CONFIG_TIMA_RKP , CONFIG_RKP_KDP
- Targeted features via samsungknox.com:
  - “completely prevents running unauthorized privileged code”
  - “prevents kernel data from being directly accessed by user processes”
  - “monitors some critical kernel data structures to verify that they are not exploited by attacks”

rkp_call()

- RKP call entry
  - Called by many critical kernel functions
    - SLAB allocation and de-allocation
    - Page Table operations
    - Copy/Override/Commit creds

Kernel code protection

- Not exclusive features for KNOX 2.6
  - “config KERNEL_TEXT_RDONLY”
  - Data section not executable
  - Privileged eXecute Never (PXN)
    - Kill ret2user and other ancient tricks
- New in KNOX 2.8?
  - Control flow protection



PXNTable, bit[59]

PXN limit for subsequent levels of lookup, see *Hierarchical control of instruction fetching* page D5-1786.

This bit is reserved, SBZ:

- In the EL2 translation regime.
- In the EL3 translation regime.

Attribute fields in stage 1 VMSAv8-64 Block and Page descriptors

In Block and Page descriptors, the memory attributes are split into an upper block and a lower block, as sh
a stage 1
translation:

Attribute fields for VMSAv8-64 stage 1 Block and Page descriptors

Kernel page and page table protection

- rkp_call() handles :
  - allocations, de-allocations of page table
  - manipulations of page entries
- Neither kernel or user space can change attributes of protected pages unauthorizedly
- Related functions
  - pdg_alloc/free()
  - set_pte/pmd/pud()

```
static inline void set_pte(pte_t *ptep, pte_t pte)
{
#ifdef CONFIG_TIMA_RKP
	if (pte && rkp_is_pg_dbl_mapped((u64)(pte))){
		panic("TIMA RKP : Double mapping Detected pte =
			return;
		}
	if (rkp_is_pte_protected((u64)ptep)) {
		rkp_flush_cache((u64)ptep);
		rkp_call(RKP_PTE_SET, (unsigned long)ptep, pte_v
		rkp_flush_cache((u64)ptep);
	} else {
		asm volatile(
			"mov x1, %0\n"
			"mov x2, %1\n"
			"str x2, [x1]\n"
			:
			: "r" (ptep), "r" (pte)
			: "x1", "x2", "memory" );
	}
#else
	*ptep = pte;
#endif /* CONFIG_TIMA_RKP */
```

Kernel data protection

- Based on read only pages
- Read-only global variables
  - RO after initialization
- RKP_RO_AREA located in page __rkp_ro_start[]
  - struct cred init_cred
  - struct task_secrity_struct init_sec
  - struct security_oprations security_ops

```
#define RKP_RO_AREA   __attribute__((section (".rkp.prot.page")))
extern int rkp_cred_enable;
extern char __rkp_ro_start[], __rkp_ro_end[];

extern struct cred init_cred;
```

Kernel object protection

- Allocated in Read-only pages
  - Writable for hypervisor or TrustZone
- Protected Object type (name of its kmem_cache):
  - cred_jar_ro : credential of processes
  - tsec_jar: security context
  - vfsmnt_cache: struct vfsmount
- Allocation, deallocation and overwriting routines will
  - call rpk_call() to operate read-only objects
- Prevent kernel/user mode manipulating credentials, security context and mount namespace

History: bypassing trick on S6

- Kernel Object protection had been applied on S6
- Could be bypassed by calling rkp_override_creds()
  - able to override current process's credentials via rkp_call() in secure world
- Not working on S7
  - S7 add more checking in secure world

- On S6, attacker can call this function to bypass previous kernel object protection

Case study: rkp_override_creds( )

```
#ifdef CONFIG_RKP_KDP
const struct cred *rkp_override_creds(struct cred **cnew)
#else
const struct cred *override_creds(const struct cred *new)
#endif  /* CONFIG_RKP_KDP */
{
    const struct cred *old = current->cred;
#ifdef CONFIG_RKP_KDP
    struct cred *new = *cnew;
    struct cred *new_ro;
    volatile unsigned int rkp_use_count = rkp_get_usecount(new);
    void *use_cnt_ptr = NULL;
    void *tsec = NULL;
#endif  /* CONFIG_RKP_KDP */

    kdebug("override_creds(%p{%d,%d})", new,
           atomic_read(&new->usage),
           read_cred_subscribers(new));

    validate_creds(old);
    validate_creds(new);
#ifdef CONFIG_RKP_KDP
    if(rkp_cred_enable) {
        cred_param_t cred_param;
        new_ro = kmem_cache_alloc(cred_jar_ro, GFP_KERNEL);
        if (!new_ro)
            panic("override_creds(): kmem_cache_alloc() failed");

        use_cnt_ptr = kmem_cache_alloc(usecnt_jar,GFP_KERNEL);
        if(!use_cnt_ptr)
            panic("override_creds() : Unable to allocate usage pointer\n");

        tsec = kmem_cache_alloc(tsec_jar, GFP_KERNEL);
        if(!tsec)
            panic("override_creds() : Unable to allocate security pointer\n");

        rkp_cred_fill_params(new,new_ro,use_cnt_ptr,tsec,RKP_CMD_OVRD_CREDS,rkp_use_count);
        rkp_call(RKP_CMDID(0x46),(unsigned long long)&cred_param,0,0,0,0);

        rocred_uc_set(new_ro,2);
        rcu_assign_pointer(current->cred, new_ro);
```

- To override process's credentials
- Allocate new cred from RO kmem_cache
- Ask RKP to update current cred and security context

Further cred verifying in secure world

- rpk_override_creds()
  - -> rkp_call(RPK_CMD(0x41)) -> rkp_assign_creds()
- rkp_assign_creds()
  - Real implementation of override_cred() in secure world
  - Additional verifying in KNOX 2.6

```
if ( !v1 )
  return rkp_printk("NULL pData", 0LL, 0LL, 0LL);
__memcpy((__int64)&v11, v1, 0x30u);
result = intergrity_chk();
if ( result )
{
  v3 = get_caller_thread_info();
  pcb = get_physical_addr(v3);
  old_cred = get_physical_addr(*(_QWORD *)(pcb + 8 * hardcode_table[17]));
  new_cred = get_physical_addr(v11);
  v7 = get_physical_addr(v12);
  new_cred_copy = v7;
  if ( new_cred && v7 && !sub_85803838(v7) )
  {
    if ( (unsigned int)check_there_is_adbd_zygote(pcb, old_cred) && (unsigned int)uid_checking(new_cred, old_cred) )
    {
      rkp_printk(
        "Priv Escalation!",
        new_cred,
        *(_QWORD *)(new_cred + 8LL * HIDWORD(hardcode_table[19])),
        *(_QWORD *)(old_cred + 8LL * HIDWORD(hardcode_table[19])));
      result = priv_escalation_abort(new_cred, old_cred, 1LL);
    }
```

- Part of Data flow integrity
- UID checking

uid_checking( )

- Check if adbd and zygote has started up
  - If not, allow the override
  - If true, the Android initialize has been finished, start UID checking
- Unprivileged process(uid>1000) cannot override the credential with high privilege(uid 0~1000)
- But still can change its kernel capabilities (very important!)

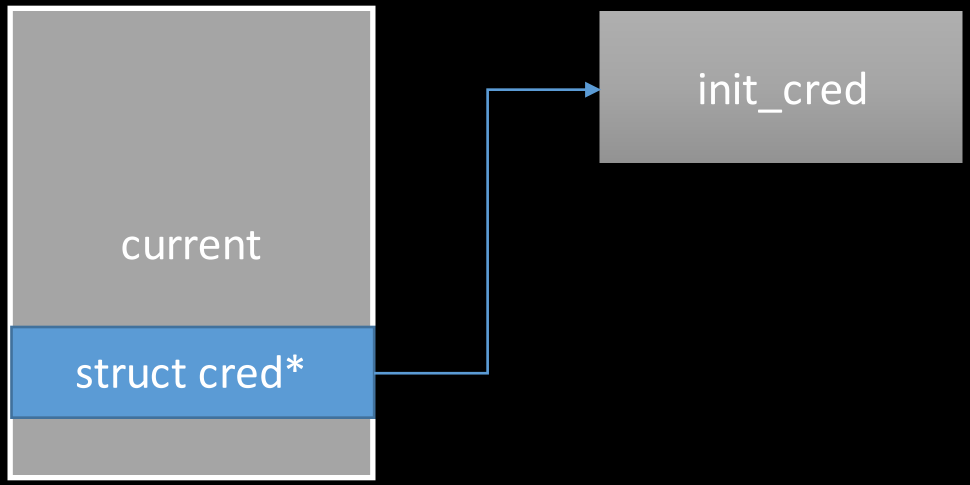
```
__int64 __fastcall sub_8580438C(unsigned int new_uid, unsigned int origin_uid)
{
  return (origin_uid > 1000) & (unsigned __int8)(new_uid <= 1000);
}
```

integrity_checking( )

- Do similar checking with security_integrity_current() in Linux Kernel
- Will analyze security_integrity_current() later

Another old trick to change credential

- For now we know credentials are READ-ONLY
- What if we reuse init's credential?



- Not working on S7,because of Data Flow Integrity

Data Flow Integrity

- New in KNOX 2.6
- Implemented in both Linux kernel and Secure world
  - security_integrity_current()   (kernel)
  - Integrity_checking()
- Additional members in struct cred{}

```
#endif
    struct user_struct *user;     /
    struct user_namespace *user_n
    struct group_info *group_info
    struct rcu_head rcu;          /
#ifdef CONFIG_RKP_KDP
    atomic_t *use_cnt;
    struct task_struct *bp_task;
    void *bp_pgd;
    unsigned long long type;
#endif /*CONFIG_RKP_KDP*/
};
#ifdef CONFIG_RKP_KDP
```

- use_cnt: pointer to refcount of cred
- bp_task: pointer to this cred's owner
- bp_pgd: pointer to process's PGD
- type: not used in DFI

Data Flow Integrity

- New in KNOX 2.6
- Implemented in both Linux kernel and Secure world
  - security_integrity_current()   (kernel)
  - Integrity_checking()
- Additional members in struct task_security_struct{}

```
struct task_security_struct {
    u32 osid;        /* SID prior to last exe
    u32 sid;         /* current SID */
    u32 exec_sid;        /* exec SID */
    u32 create_sid;      /* fscreate SID */
    u32 keycreate_sid;   /* keycreate SID */
    u32 sockcreate_sid;  /* fscreate SID */
#ifdef CONFIG_RKP_KDP
    void *bp_cred;
#endif
};
```

- bp_cred: pointer to this context's owner cred

security_integrity_current( )

- Hard-coded hooking in every SELinux routines
  - Verify process's credential in real-time
  - To check if
    - current *struct cred{}* and *struct task_security_struct{}* are allocated in RO page
    - cred->bp_task is current process's
    - task_security->bp_cred is current cred
    - current mount namespace is malformed

```
}
/* Main function to verify cred security context of a process */
int security_integrity_current(void)
{
    if ( rkp_cred_enable &&
        (rkp_is_valid_cred_sp((u64)current_cred(),(u64)current_cred()->secu
        cmp_sec_integrity(current_cred(),current->mm)||
        cmp_ns_integrity())) {
        rkp_print_debug();
        panic("RKP CRED PROTECTION VIOLATION\n");
    }
    return 0;
}
unsigned int rkp_get_task_sec_size(void)
```

References

Name

- security_integrity_current
  - security_integrity_current
  - selinux_set_mnt_opts
  - selinux_cmp_sb_context
  - selinux_sb_clone_mnt_opts
  - selinux_parse_opts_str
  - selinux_sb_show_options
  - selinux_binder_set_context_mgr
  - selinux_binder_transaction
  - selinux_binder_transfer_binder
  - selinux_binder_transfer_file
  - selinux_ptrace_access_check
  - selinux_ptrace_traceme
  - selinux_capget
  - selinux_capset
  - selinux_capable
  - selinux_quotactl
  - selinux_quota_on
  - selinux_syslog
  - selinux_vm_enough_memory
  - selinux_bprm_set_creds
  - selinux_bprm_secureexec
  - selinux_bprm_committing_creds
  - selinux_bprm_committed_creds
  - selinux_sb_alloc_security
  - selinux_sb_free_security
  - selinux_sb_copy_data
  - selinux_sb_remount
  - selinux_sb_kern_mount
  - selinux_sb_statfs
  - selinux_mount
  - selinux_umount
  - selinux_inode_alloc_security
  - selinux_inode_free_security
  - selinux_dentry_init_security

Summary of RKP and DFI

- Even we achieved arbitrary kernel memory overwriting, we cannot:
  - Manipulate credentials and security context in kernel mode
  - Point current credential to init_cred
  - Call rkp_override_creds() to ask secure world to help us override credential with uid 0~1000
- But we still can:
  - Call kernel function from user mode
    - Hijacking *ptmx_fops->check_flags(int flag)*
    - The number of parameters is limited
    - Only low 32bit of X0 is controllable
  - Override credential with full kernel capabilities (cred->cap_**)
  - Overwrite unprotected data in kernel

Bypassing RKP and DFI

- Main idea: ask kernel to create a privileged process for me
- Creating a root process
- I can't call *call_usermodehelper(path,argv,envp,wait)* via *ptmx_fops->check_flags(flag)*
- Call orderly_poweroff() instead

orderly_poweroff()

```
/**
 * orderly_poweroff - Trigger an orderly system poweroff
 * @force: force poweroff if command execution fails
 *
 * This may be called from any context to trigger a system shutdown.
 * If the orderly shutdown fails, it will force an immediate shutdowr
 */
int orderly_poweroff(bool force)
{
    if (force) /* do not override the pending "true" */
        poweroff_force = true;
    schedule_work(&poweroff_work);
    return 0;
}
EXPORT_SYMBOL_GPL(orderly_poweroff);
```

- Call __oderly_poweroff() in worker thread

```
char poweroff_cmd[POWEROFF_CMD_PATH_LEN] = "/sbin/poweroff";

static int __orderly_poweroff(bool force)
{
    char **argv;
    static char *envp[] = {
        "HOME=/",
        "PATH=/sbin:/bin:/usr/sbin:/usr/bin",
        NULL
    };
    int ret;

    argv = argv_split(GFP_KERNEL, poweroff_cmd, NULL);
    if (argv) {
        ret = call_usermodehelper(argv[0], argv, envp, UMH_WAIT_EXEC);
        argv_free(argv);
    } else {
```

- Worker create a new root process, cmd is *poweroff_cmd*
- *poweroff_cmd* is writeable

Bypassing steps

- Call rpk_override_creds() via ptmx_fops->check_flags()
  - Override own cred to gain full kernel capabilities
  - But don’t change uid
- Overwrite *poweroff_cmd* with “/data/data/***/ss7kiler”
- Call orderly_poweroff() via ptmx_fops->check_flags()
- Modify ss7killer’s thread_info->address limit
- ss7killer: call rpk_override_creds() to change its sid from *u:r:kernel:s0* to *u:r:init:s0*

Result: privileged ss7killer

- root
- u:r:init:s0

```
shell@hero2qltechn:/ $ ps -Z | grep init
u:r:init:s0                    root      1     0     /init
u:r:init:s0                    root      20592 1     /data/local/tmp/ss7killer
u:r:init:s0                    root      20608 20592 su
u:r:init:s0                    root      20611 1     daemonsu:mount:master
u:r:init:s0                    root      20614 1     daemonsu:master
u:r:init:s0                    root      20797 20614 daemonsu:0
u:r:init:s0                    root      21161 20614 daemonsu:10193
u:r:init:s0                    root      21163 21161 daemonsu:10193:21157
```

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u:r:init:s0

- Not good enough
- Still be limited by SELinux
- Almost can do nothing…
- Disabling/Bypassing SELinux is necessary

SELinux enhancement

- Disabled CONFIG_SECURITY_SELINUX_DEVELOP long time ago
  - Cannot disable SELinux by overwrite selinux_enforcing
  - Statically enforcing all the time
- init process cannot reload SELinux policy after system initialized
- Permissive domain is not allowed

Permissive domain

- Officially used by Google before Lollipop
  - For policy developing purpose
- All domains are non-permissive since Lollipop
- Domains still can be switched to permissive mode by policy reloading (/sys/fs/selinux/load)

AndroidXRef KitKat 4.4.4_r1

xref: /external/sepolicy/init.te

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```
# init switches to init domain (via init.rc).
type init, domain;
permissive init;
# init is unconfined.
unconfined_domain(init)
```

Permissive domain – kernel support

- A permissive domain's access vector decision(AVD) will be set AVD_FLAGS_PERMISSIVE
- All operations are permitted

```c
static noinline int avc_denied(u32 ssid, u32 tsid,
                u16 tclass, u32 requested,
                u8 driver, u8 xperm, unsigned flags,
                struct av_decision *avd)
{
    if (flags & AVC_STRICT)
        return -EACCES;

    if (selinux_enforcing && !(avd->flags & AVD_FLAGS_PERMISSIVE))
        return -EACCES;

    avc_update_node(AVC_CALLBACK_GRANT, requested, driver, xperm, ssid,
                tsid, tclass, avd->seqno, NULL, flags);
    return 0;
}
```

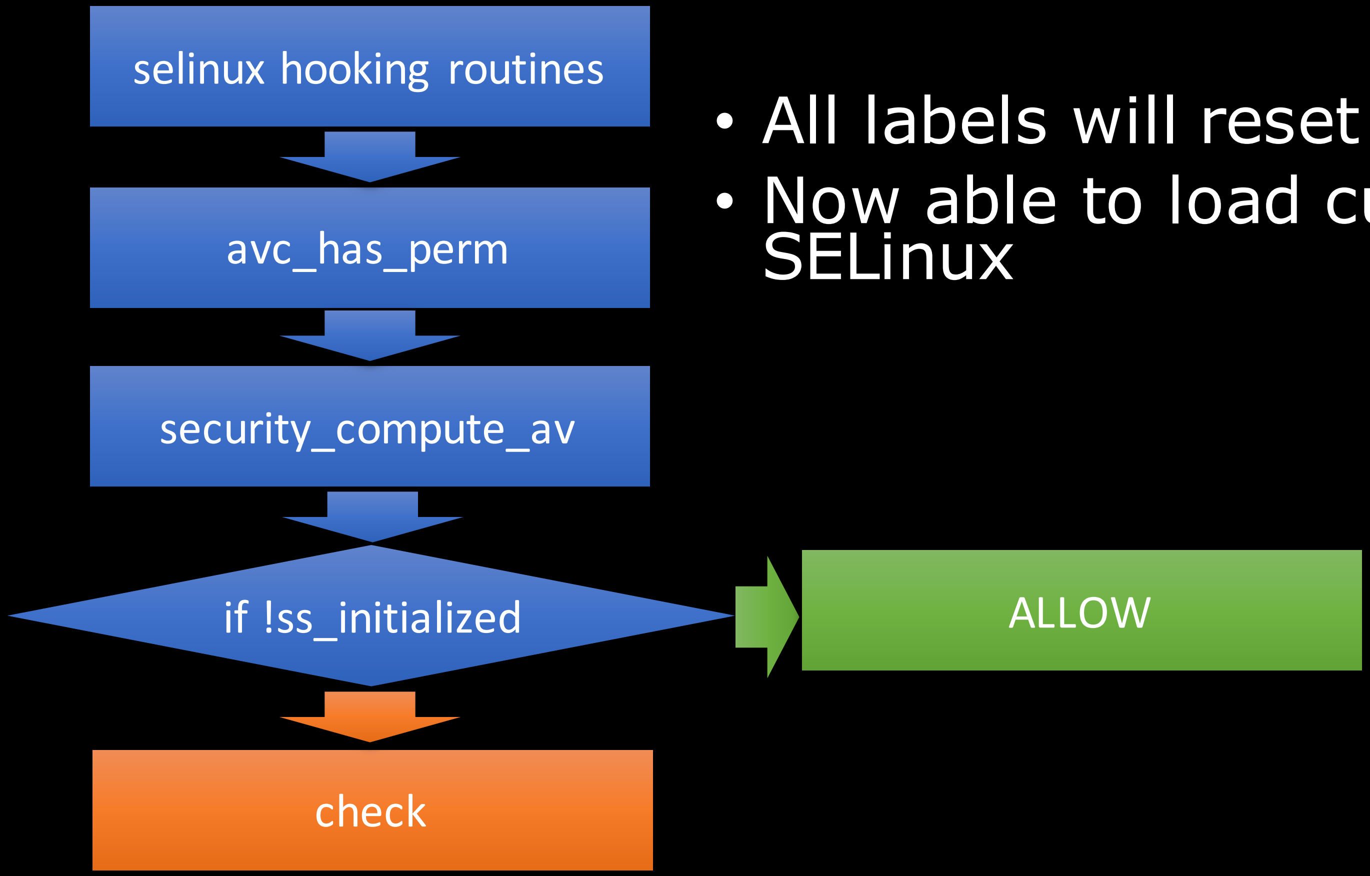
S7 removed AVD_FLAGS_PERMISSIVE

- avc_denied always simply return –EACCES

```
avc_denied.isra.0
MOV                     W0, #0xFFFFFFF3
RET
; End of function avc_denied.isra.0
```

Bypass SELinux on S7

- Cheating kernel that SELinux is not initialized yet
  - Depends on global variable ss_initialized (writable)



- All labels will reset to none except kernel domain
- Now able to load customized policy and reinitialize SELinux

After setting ss_initialized = 0

- All labels missed except kernel
  - SELinux must be re-enabled ASAP, or Apps may corrupt files’ label permanently
- Load customized policy and reinitialize SELinux

```
kernel                          root      900   2     dhd_watchdog_th
kernel                          root      901   2     dhd_rpm_state_t
-                               system    903   1     /system/bin/factory.adsp
-                               net_admin 910   1     /system/bin/ipacm
-                               radio     914   1     /system/vendor/bin/qti
-                               radio     922   1     /system/bin/netmgrd
-                               radio     947   1     /system/bin/rild
-                               jack      950   694   androidshmservice
kernel                          root      1157  2     irq/140-arm-smm
kernel                          root      1160  2     irq/141-arm-smm
-                               system    1161  1     /system/bin/mcDriverDaemon
kernel                          root      1209  2     tee_scheduler
kernel                          root      1218  2     irq/162-arm-smm
kernel                          root      1219  2     irq/167-arm-smm
kernel                          root      1221  2     irq/163-arm-smm
kernel                          root      1223  2     irq/168-arm-smm
-                               system    1250  728   system_server
```

Policy customizations

- Policy database locate at /sys/fs/selinux/policy
- Modify the database with libsepol API
  - Load policy DB to the user memory
  - Add rules into database
    - Allow untrusted_app, init, toolbox domain to do everything
  - Ask kernel to reload the database
- Set ss_initialized to 1

Gain Root

- Leaking kernel information √
- Bypassing KASLR √
- Overwriting arbitrary memory √
- Bypassing RKP & DFI √
- Bypassing enforced SELinux √

ddshen — adb shell — 91×29

```
Last login: Wed Jun 29 19:23:54 on ttys000
retme-no-RMBP:~ ddshen$ adb shell
shell@hero2qltechn:/ $ ps -Z | grep s7kill
u:r:init:s0                    root      14453 1907  /data/local/tmp/s7killer
shell@hero2qltechn:/ $ ps -Z | grep daemonsu
u:r:init:s0                    root      14593 1     daemonsu:mount:master
u:r:init:s0                    root      14596 1     daemonsu:master
u:r:init:s0                    root      14620 14596 daemonsu:0
shell@hero2qltechn:/ $ su
root@hero2qltechn:/ # id
uid=0(root) gid=0(root) groups=0(root) context=u:r:toolbox:s0
root@hero2qltechn:/ # getenforce
Enforcing
root@hero2qltechn:/ #
```

Tencent

KEEN
security
lab