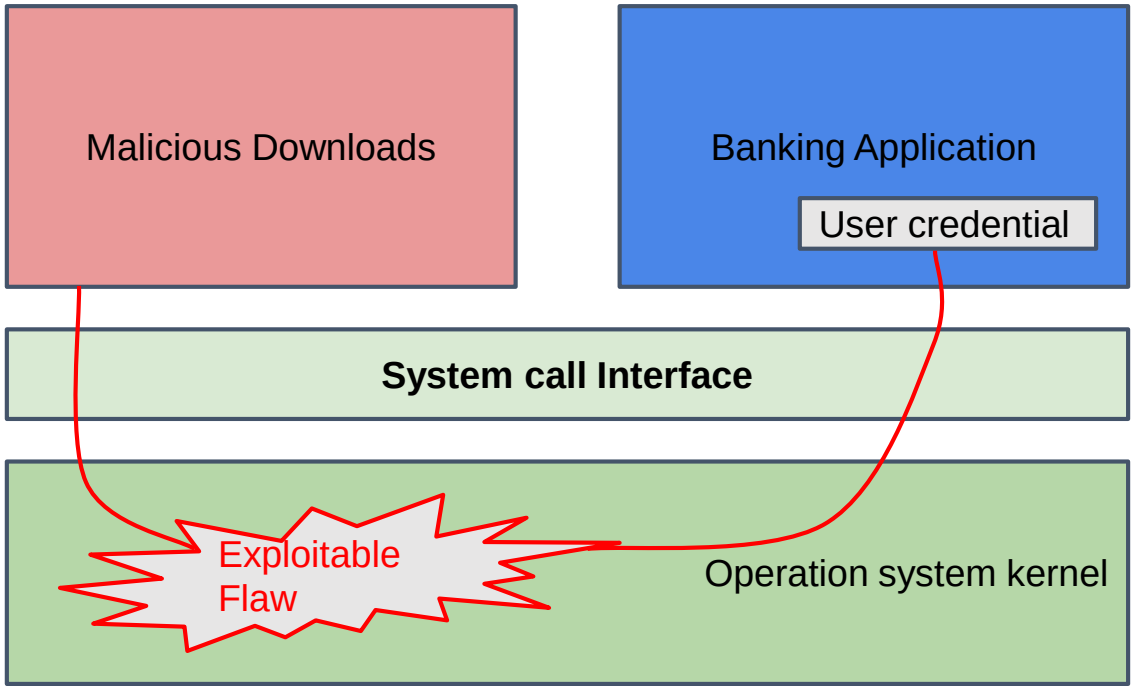
Trusted Execution Environment 2

Jinsoo Jang

ARM TrustZone

Need for Security

- Valuable data, such as banking credentials
- Downloading arbitrary third-party apps.

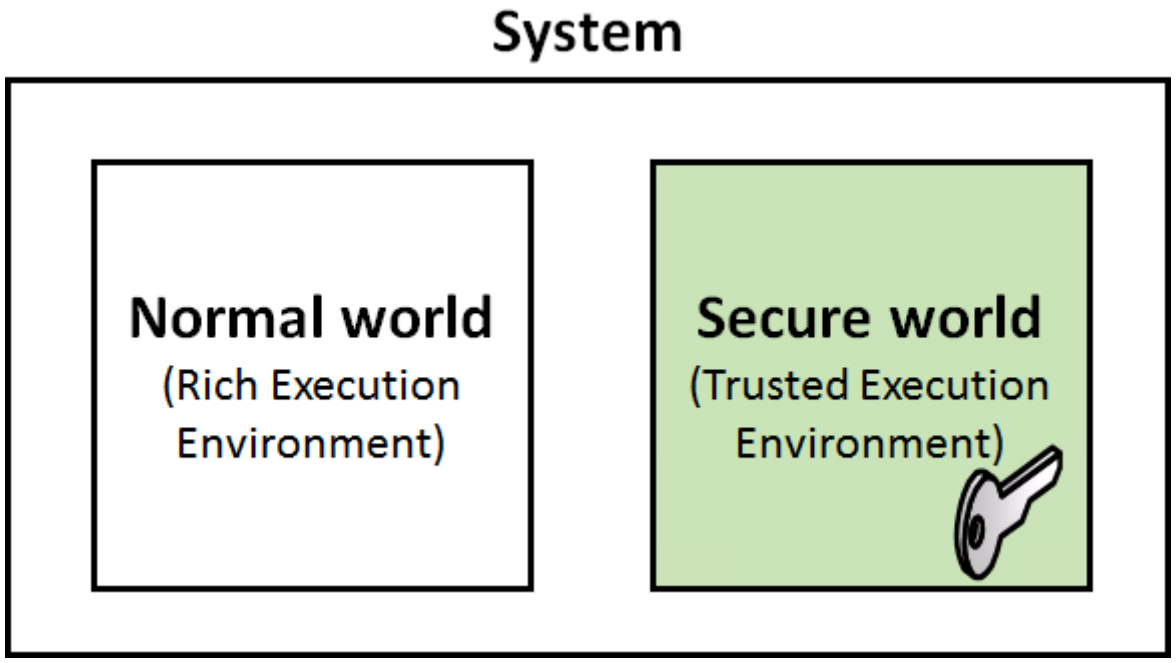


How are Devices Attacked?

- Hack attack
  - Software level attack
    - Malwares
- Shack attack
  - Low-budget hardware attack
    - e.g. Using a JTAG debugger
- Lab attack
  - Laboratory equipments
    - Electron microscopes
    - Transitor-level reversing
    - Power usage analysis

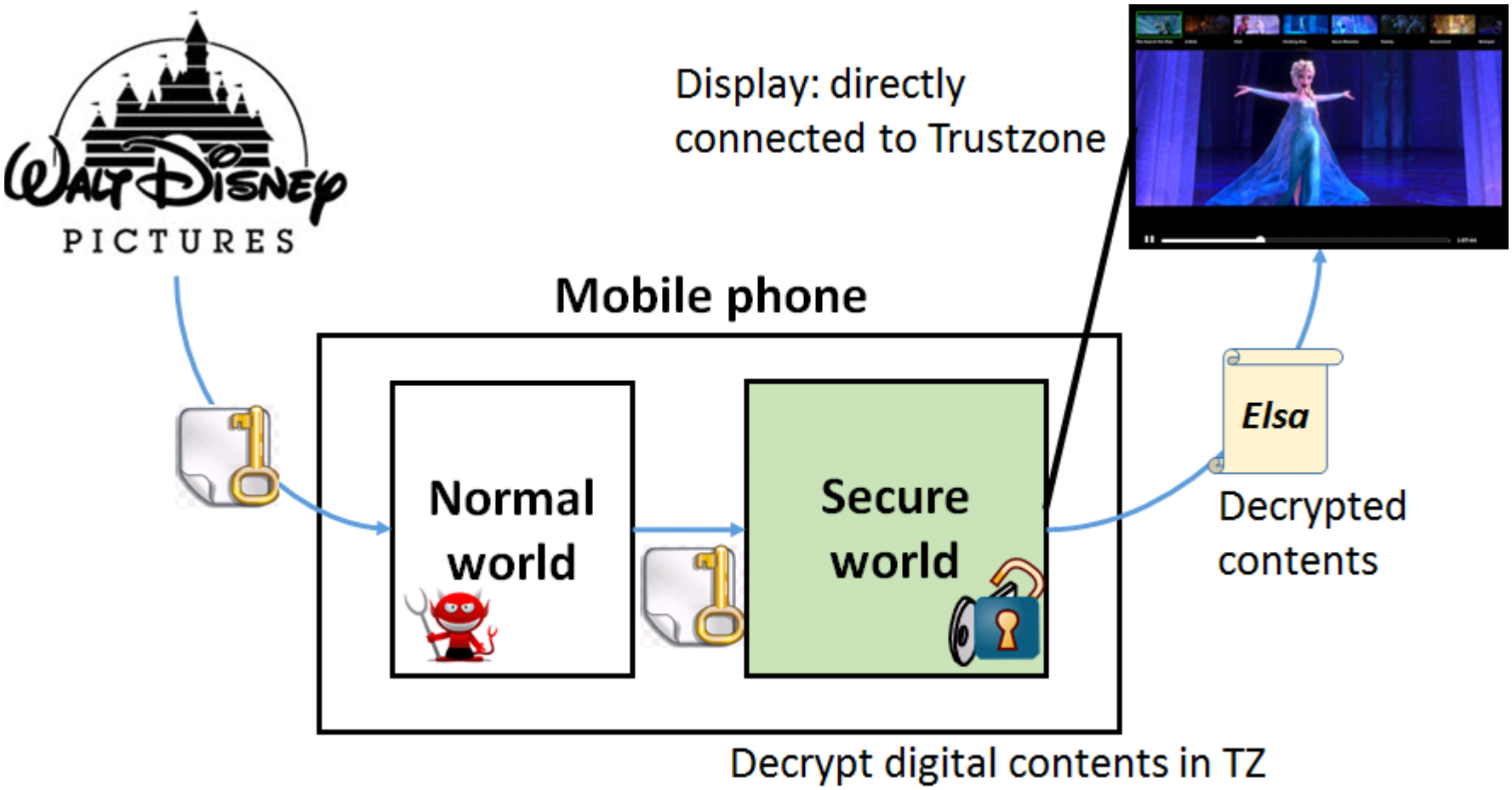
ARM TrustZone (Overview)

- Extension to the processors
- Hardware security
- Countermeasure for may of hack & shack attacks

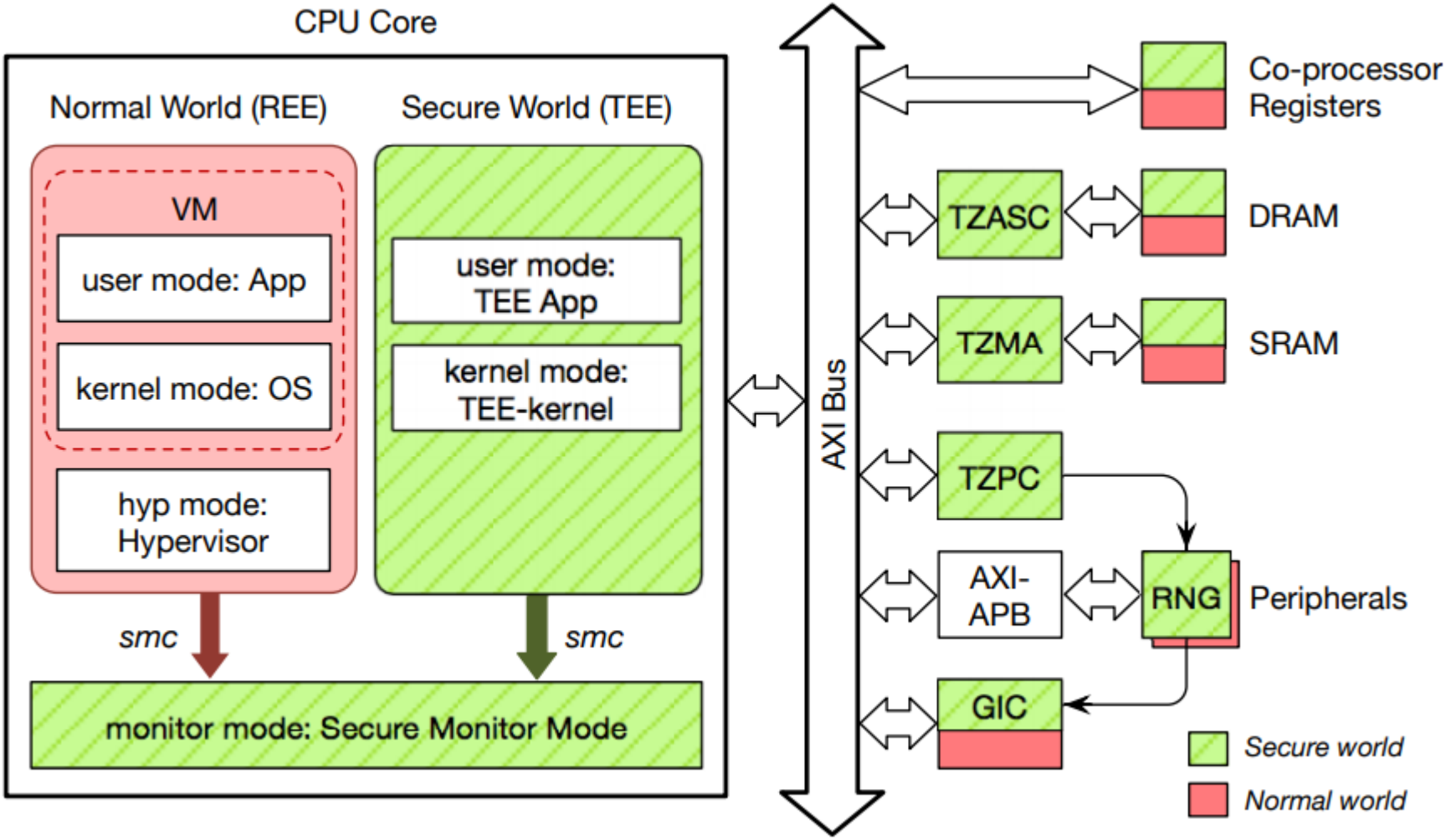


Example Use Case

- DRM (Digital Right Management) in TZ



TrustZone Hardware Architecture

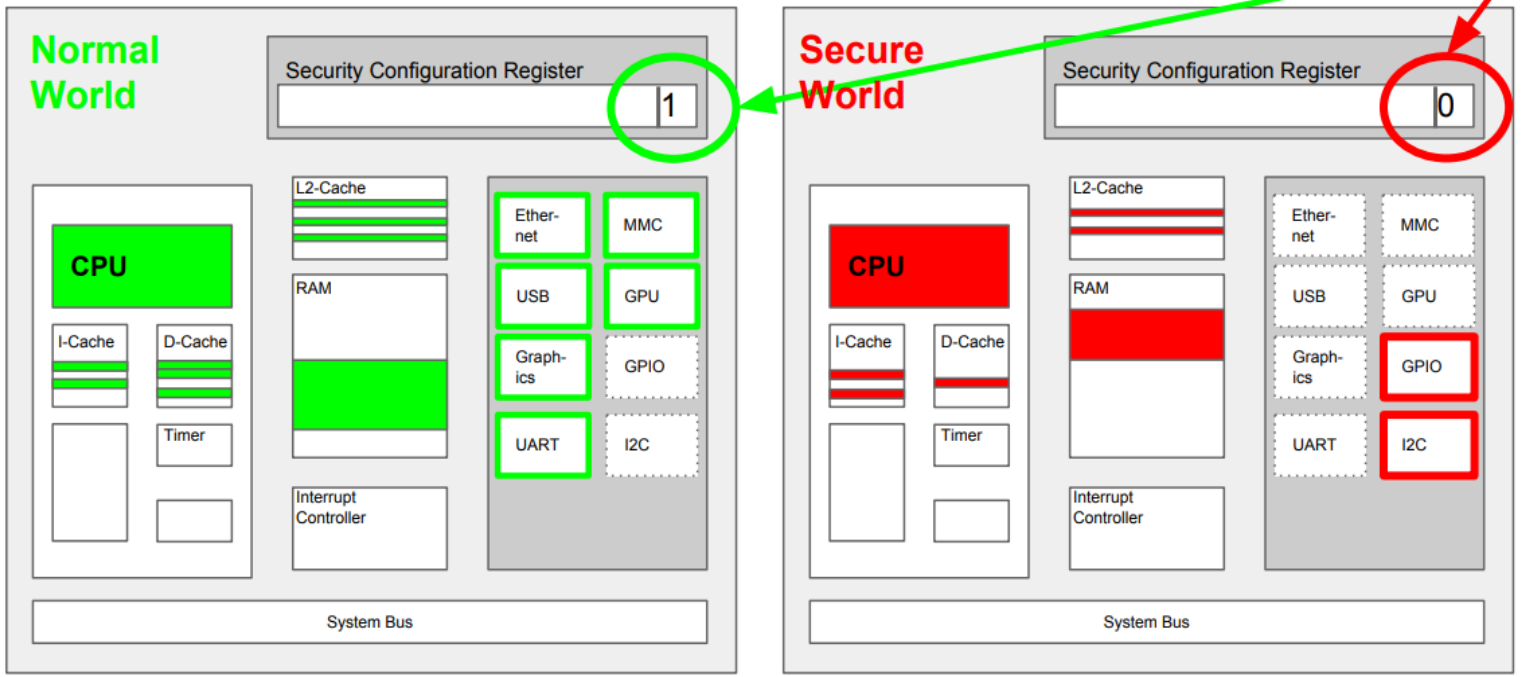


Partions SoC into Normal and Secure

ARM TrustZone®

Partitions SoC into Normal World and Secure World

Non-Secure (NS) bit (bit 0) in the Secure Configuration Register in CP15



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TrustZone to TEE in 3 Steps

1. Define secure hardware architecture
   - Two seperate domains: normal and secure
   - Extends across system
     - processor, display, keypad, memory, clock, radios
2. Implement in silicon system on chip (SoC)
   - Enforcing secure/normal separation physically
3. Combine SoC with Trusted SW
   - Seperate but connected to main OS

Result:

A **T**rusted **E**xecution **E**nvironment (TEE)

1. Ready to develop and run trusted services

Development env. & SierraTEE Example

Open source TZ software

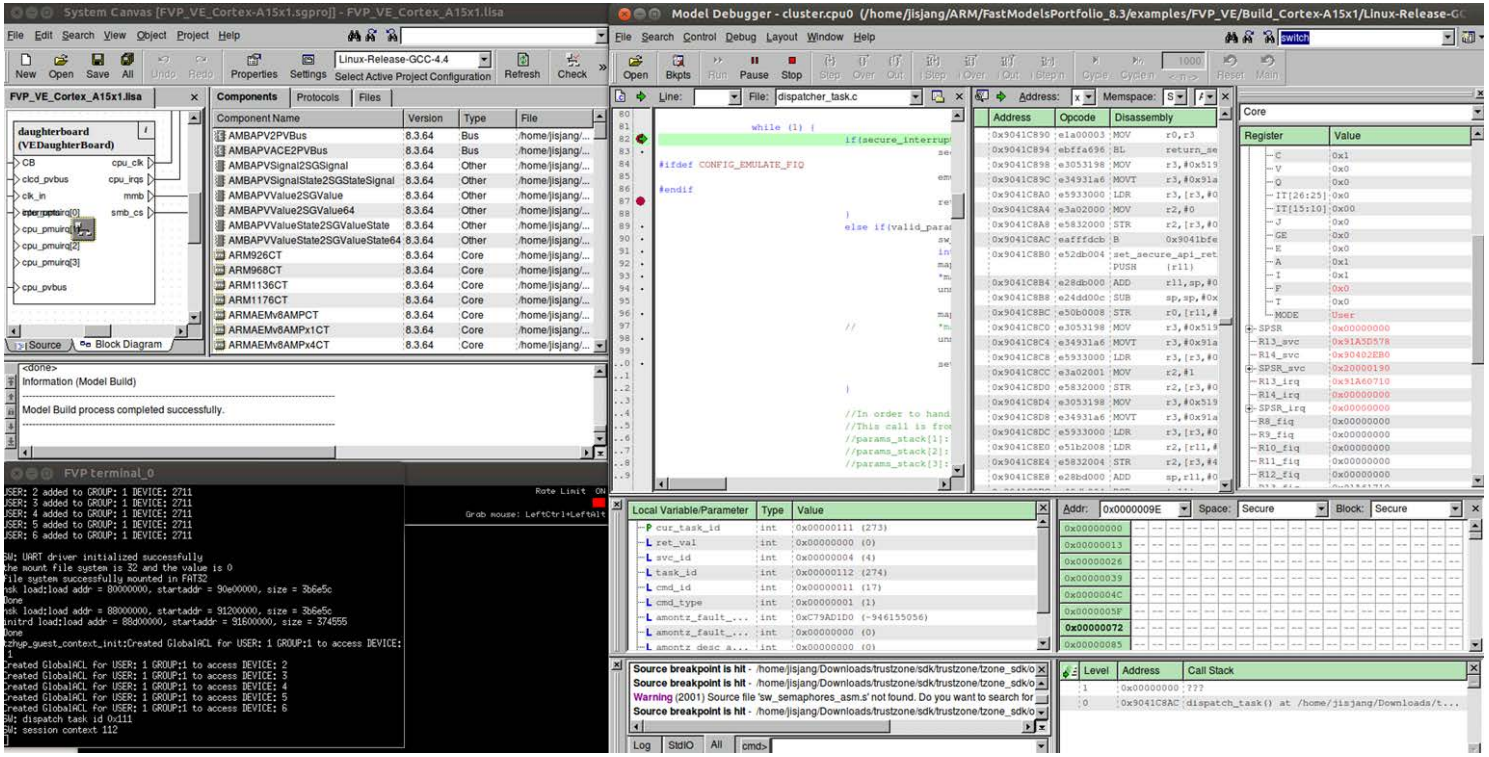
- Open Virtualization
  - Provides TrustZone OS and toolchains
  - Download:
    - http://www.openvirtualization.org/download.html

SierraTEE and SierraVisor Source Code	
License:	GPLv2
Requirements:	Linux 2.6 (or above) development platform, JDK 6.0
Open Virtualization SDK:	SDK_Sep25_2014_TEE.tar.gz
Toolchain:	toolchain_sep_25_2014.tar.bz2 (99.9 MB)
Date of SDK Release:	September 25, 2014
64-bit Rootfs	rootfs.bz2
Documentation:	Open Virtualization Developer's Guide, Build Instructions, and Porting Guide

SierraVisor and SierraTEE Binary for Xilinx(R) Zynq-7000 AP SOC	
License:	Free
ZC702 Binary:	xilinx_zc702_Jan02_2013.tar.bz2 (35.4 MB)
Date of Binary Release:	January 2, 2013
Documentation:	Xilinx Boot Guide

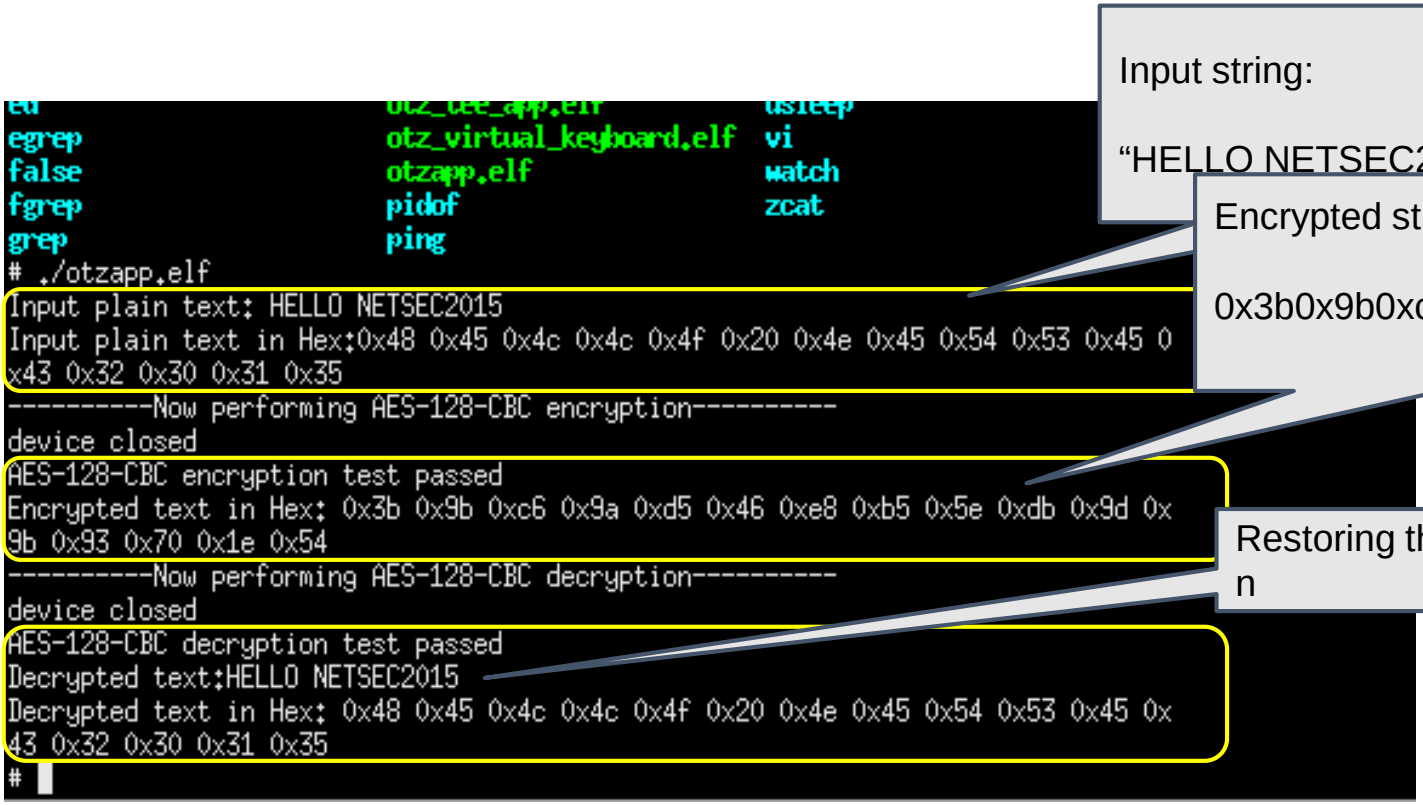
ARM Development Tools

- Fast Models
  - ARM instruction set simulator
  - Provides a debugging environment
  - Download: www.arm.com



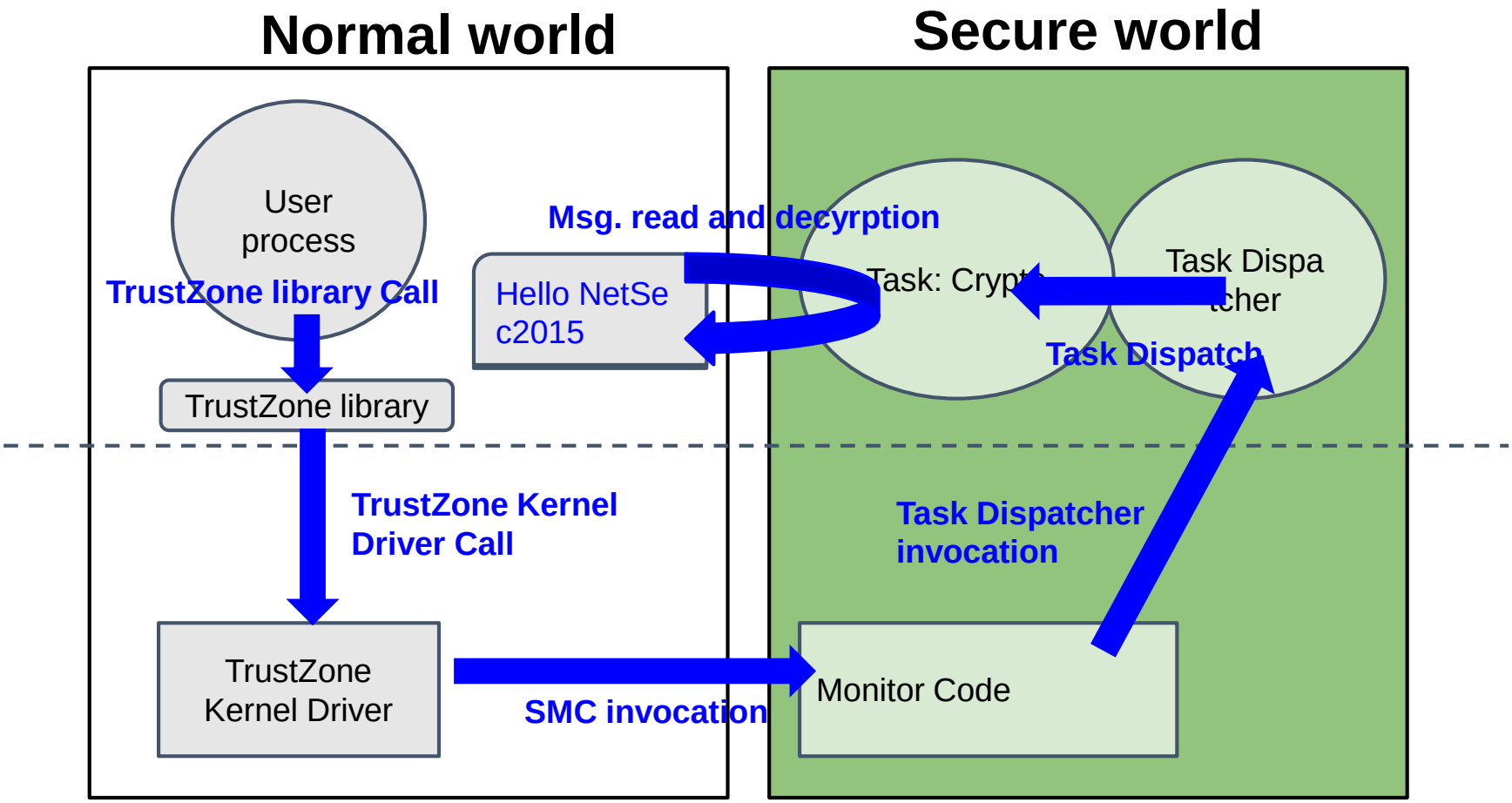
Sample TrustZone Application

- Running a sample crypto program
  - **Encrypts & decrypts a input Sting by using TrustZone**



How It Works? (Overview)

- Data decryption example



How It Works? (Source Code)

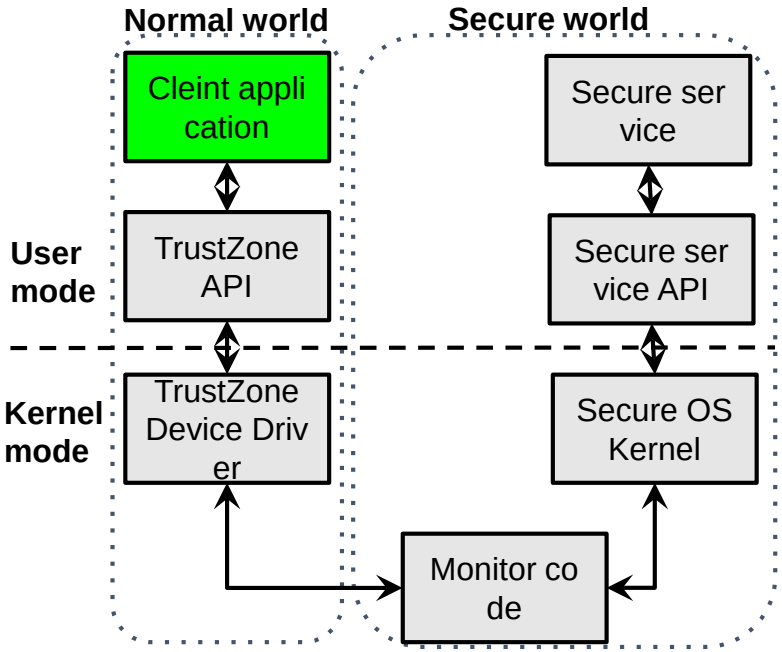
- Client application (User mode in Normal world)
  - requests crypto service to TrustZone

Open TrustZone kernel driver

```
perform_crypto(unsigned char *input_buf,int input_buf_len,
                unsigned char *init_vector,int init_vector_len,
                    unsigned char *key_buf,int key_len,int cmd_type,
                        unsigned char *output_buf, int *output_buf_len,
                                                unsigned char cipher_action)

    crypto_data_t crypt_data;
    uint8_t  *out_data,in_data[1];
    otz_device_t device_otz;
    otz_session_t session_otz;
    otz_operation_t operation_otz;
    otz_return_t ret=0, service_ret;

    device_otz.ui_state = OTZ_STATE_UNDEFINED;
    ret = otz_device_open("/dev/otz_client", (void*)O_RDWR, &device_otz);
    if (ret != OTZ_SUCCESS){
        perror("device open failed\n");
        return 0;
```

Invoke TrustZone API

```
    on_otz.ui_state = OTZ_STATE_UNDEFINED;
    tion_otz.ui_state = OTZ_STATE_UNDEFINED;
    et = otz_operation_prepare_open(&device_otz,OTZ_SVC_CRYPT, NULL, NULL,
                                    &session_otz, &operation_otz);
    if(ret != OTZ_SUCCESS) {
        goto end_func;
    }
    /* Call otz_operation_perform to open session */
    ret = otz_operation_perform(&operation_otz ,&service_ret);
    if(ret != OTZ_SUCCESS){
        if(ret == OTZ_ERROR_SERVICE)
            printf("%s \n",otz_strerror(ret));
        else
            perror("session open  failed\n");
        session_otz.ui_state = OTZ_STATE_UNDEFINED;
    }
```



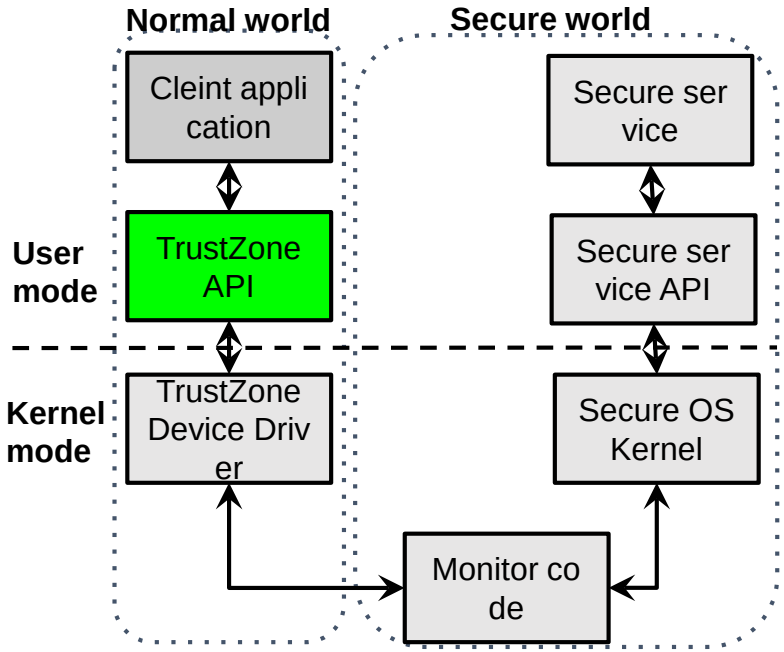
How It Works? (Source Code)

- TrustZone API (User mode in Normal world)
  - Invokes TrustZone kernel driver via ioctl

```
otz_return_t otz_operation_perform(otz_operation_t* ps_operation,
                                   otz_return_t* pui_service_return )
{
    int ret = 0;
    struct ser_ses_id ses_close;
    struct ser_ses_id ses_open;
    struct otz_client_encode_cmd enc;
```

Invoke TrustZone device driver

```
  if(ps_operation->type == OTZ_OPERATION_OPEN)
  {
      ses_open.service_id = ps_operation->session->service_id;

      ret = ioctl(ps_operation->session->device->fd,
                  OTZ_CLIENT_IOCTL_SES_OPEN_REQ, &ses_open);
          if(ret < 0){
               /* Error is detected before reaching the service */
              *pui_service_return = OTZ_ERROR_GENERIC;
              ps_operation->ui_state = OTZ_STATE_INVALID;
              ps_operation->s_errno = errno;
              /*return  Error actually occurred */
              /*Decoder functions cannot be used on the operation */
```

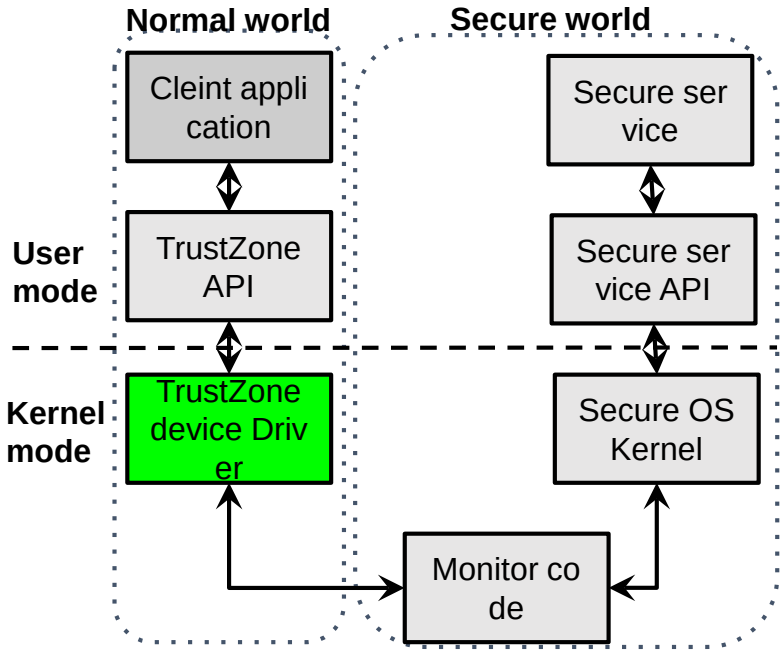


How It Works? (Source Code)

- TrustZone device driver (Kernel in Normal world)
  - Sets params for secure services
  - Invokes SMC instruction to switch to monitor mode

```
static u32 _otz_smc(u32 cmd_addr)
{
    register u32 r0 asm("r0") = CALL_TRUSTZONE_API;
    register u32 r1 asm("r1") = cmd_addr;
    register u32 r2 asm("r2") = OTZ_CMD_TYPE_NS_TO_SECURE;
    do {
        asm volatile(
            __asmeq("%0", "r0")
            __asmeq("%1", "r0")
            __asmeq("%2", "r1")
            __asmeq("%3", "r2")
            "smc    #0  @ switch to secure world\n"
            : "=r" (r0)
            : "r" (r0), "r" (r1), "r" (r2));
    } while (0);

    return r0;
}
```

Invoke SMC to switch the mode



How It Works? (Source Code)

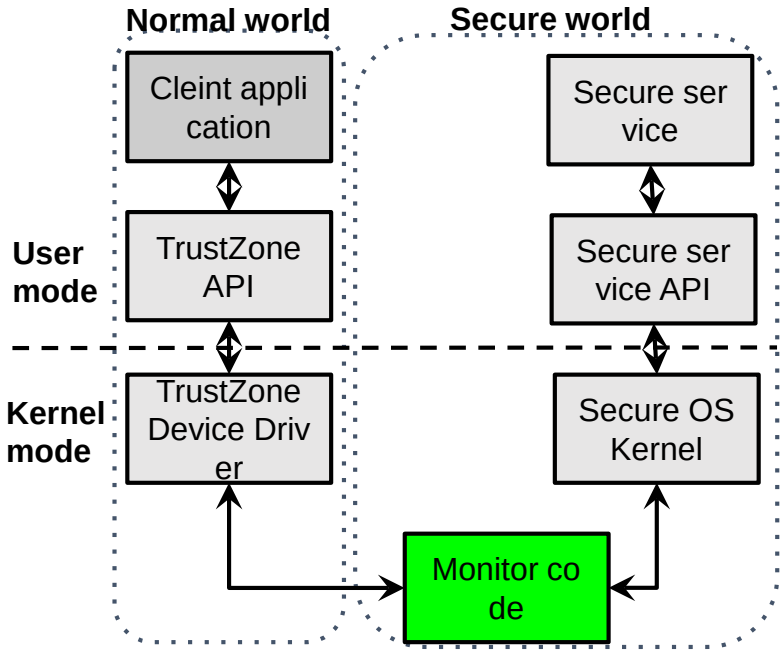
- Monitor code (Monitor mode in Secure world)

```
.align 12
.global monitor
monitor:
@ Monitor's
monitor_reset:
b   monitor_reset       @ Reset       - not used by Monitor
monitor_undef:
b   monitor_undef       @ Undef       - not used by Monitor
b   smc_handler         @ SMC_Handler
monitor_pref:
b   monitor_pref        @ Prefetch    - can by used by Monitor
monitor_abort:
b   monitor_abort       @ Data abo                  onitor
monitor_reserv:
b   monitor_reserv      @ RESERVE
b   monitor_irq         @ IRQ                       y Monitor
b  monitor_fiq_handler        @ Monitor FIQ Handler
```

Exception vectors in monitor mode

Exception handler for SMC

```
smc_handler:
cmn     r0, #0
blt     board_smc
CMP r0, # CALL_TRUSTZONE_API
beq     tz_api
CMP r0, #CALL_FROM_AMONTZ_STUB
beq     tz_api
```

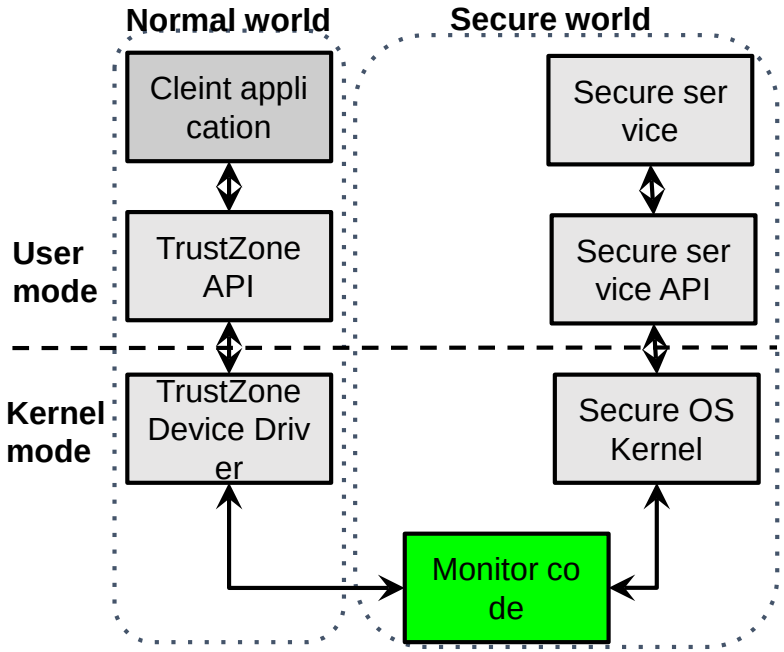


How It Works? (Source Code)

- Monitor code (Monitor mode in Secure world)
  - Branches to switch the context to secure world's

```
        tz_api:
#ifdef CONFIG_SW_MULTICORE
        push    {r0}
        GET_CPU_ID  r0
        cmp     r0, #0
        pop     {r0}
        beq     1f
        b       smc_error
#endif

#ifndef CONFIG_SW_DEDICATED_TEE
        1:  push    {r4, lr}  /* the corresponding pops happens from
                                 save_context */
        push    {r0 - r3}

        /* Copy args to params stack */
        ldr     r4, =params_stack
        stmia   r4, {r0-r3}

        ldr r1, =valid_params_flag
        mov r2, #0x1
        str r2, [r1]

        b mon_switchto_sworld
```

Switch the context to secure world's



How It Works? (Source Code)

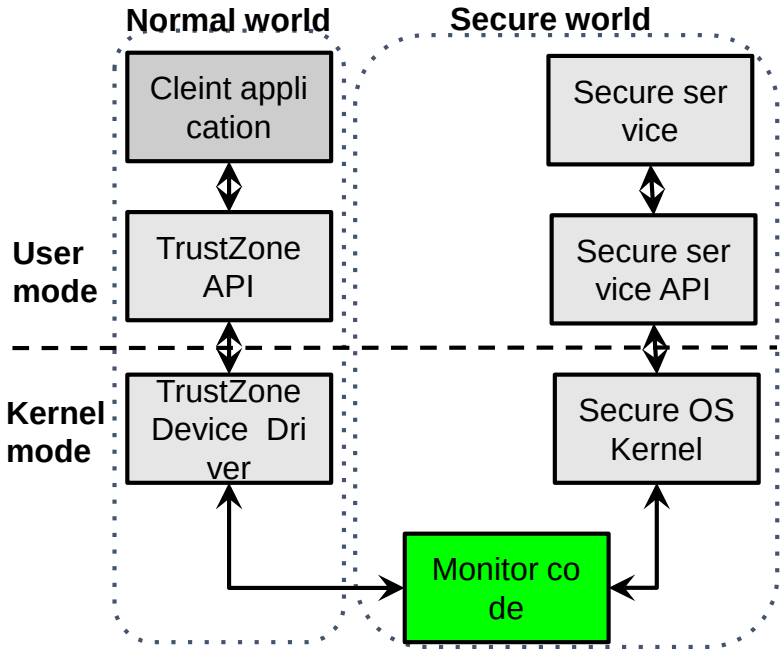
- Monitor code (Monitor mode in Secure world)
  - Clear NS-bit and save the context of normal world

```
        .func  mon_switchto_sworld
        mon_switchto_sworld:

        @Move to Secure
        scr_nsbit_clear r0

        GET_CORE_CONTEXT ns_sys_current
        bl     save_context
        GET_CORE_CONTEXT s_sys_current
        bl     restore_context
        @ Clear local monitor
        @ -------------------
        clrex

        movs     pc, lr
        .endfunc
```

Exception vectors i n monitor mode

```
.func save_context
.global save_context
save_context:
@ Save general purpose registers SPSR
@ ------------------------------------
mov     r4, r0
pop     {r0 - r3}                @ Retrieve from stack
stmia   r4!, {r0 - r3}           @ r0 - r3
mov     r0, r4
```

Save the normal wo rld's context

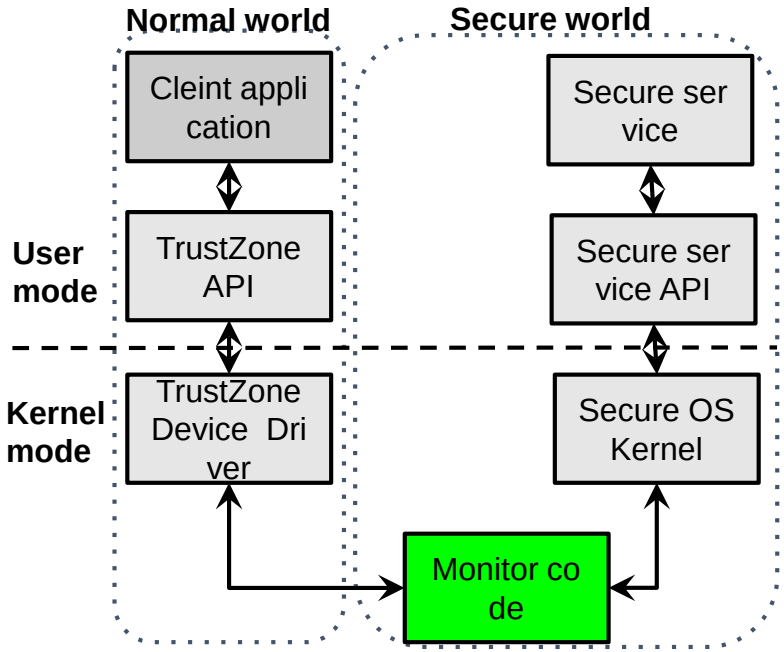


How It Works? (Source Code)

- Monitor code (Monitor mode in Secure world)
  - Restore the context of secure world
  - General registers, SPSR, LR, PC ...

```
.func restore_context
.global restore_context
restore_context:
@ Restore other world's registers, SPSR and LR
@ ----------------------------------------
push    {lr}

mov r4, r0
ldmia r4!, {r0 - r3}

push {r0, r1}
mov r0, r4

ldmia r0!, {r4 - r12}           @r4 - r12

ldmia r0!, {r1, lr}             @spsr, lr
msr spsr_cxsf, r1

@Restore banked registers
cps #Mode_SVC
ldmia   r0!, {r1, r13, lr}
msr spsr_cxsf, r1
```

Restore the secure world's context



How It Works? (Source Code)

- Dispatcher service (User mode in Secure world)
  - Parses requests and dispatches secure tasks

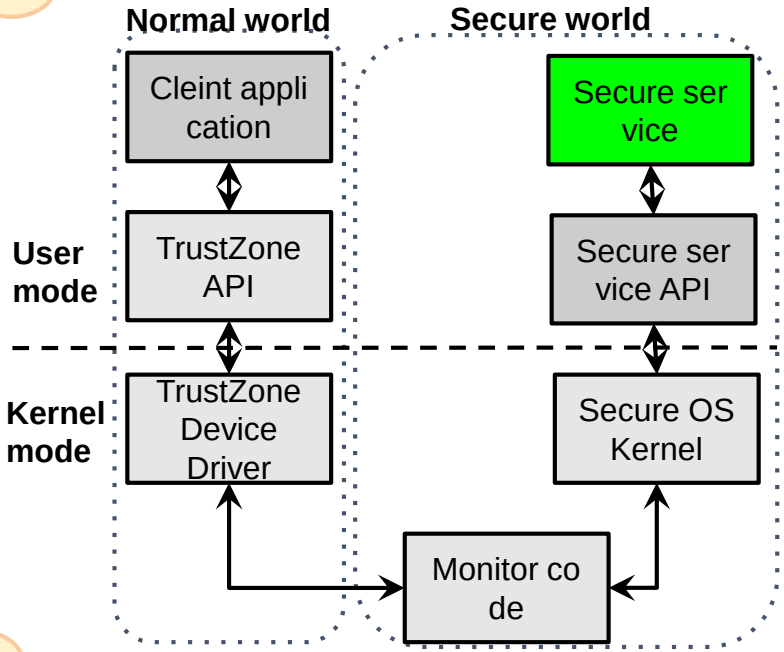
```
void dispatch_task(int cur_task_id)
{
        int ret_val;
        int svc_id, task_id, cmd_id, cmd_type;
```

-Parses a request
-Create a task

```
        (cmd_id == OTZ_GLOBAL_CMD_ID_OPEN_SESSION)) {
 if(cmd_type == OTZ_CMD_TYPE_NS_TO_SECURE) {
         /*                      sw_buddy_print_state(); */
         ret_val = open_session_from_ns((void*)params_stack[1]);
         if(ret_val == OTZ_ENOMEM)
                 set_secure_api_ret(SMC_ENOMEM);
```

```
         else if(svc_id != OTZ_SVC_INVALID  &&
                         task_id != 0 &&
                         cmd_id != OTZ_GLOBAL_CMD_ID_INVALID) {
                 start_task(task_id, params_stack);
         }
         else {
                 sw_printf("SW: Invalid service id %x\n", svc_id);
                 set_secure_api_ret(0);
         }
 }
 schedule();
```

Start a secure task to handel the request



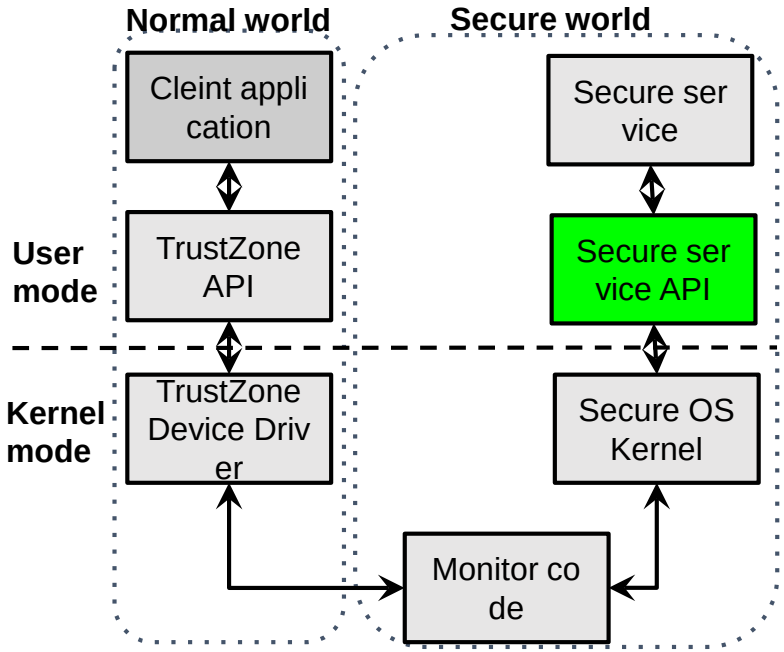
How It Works? (Source Code)

- Secure service API (User mode in Secure world)
  - Invokes system calls (memory maps, scheduling…)

```
int open_session_from_ns(void *param)
{

    int ret_val;
    int *svc_id = NULL;
    sa_config_t sa_config;
    pa_t cmd_phy;
    struct otz_smc_cmd *cmd = NULL;
    void *session_context = NULL;

    cmd_phy = (pa_t) param;


    if(map_to_ns(cmd_phy, (va_t*) &cmd)) {
        ret_val = OTZ_ENOMEM;
        goto ret_func;
    }
void schedule(void)
{
#ifdef CONFIG_EMULATE_FIQ
    emulate_timer_irq();
#else
    asm volatile("swi #0xbbbb");
#endif
}
```

System calls for ker nel services

System calls for ker nel services



How It Works? (Source Code)

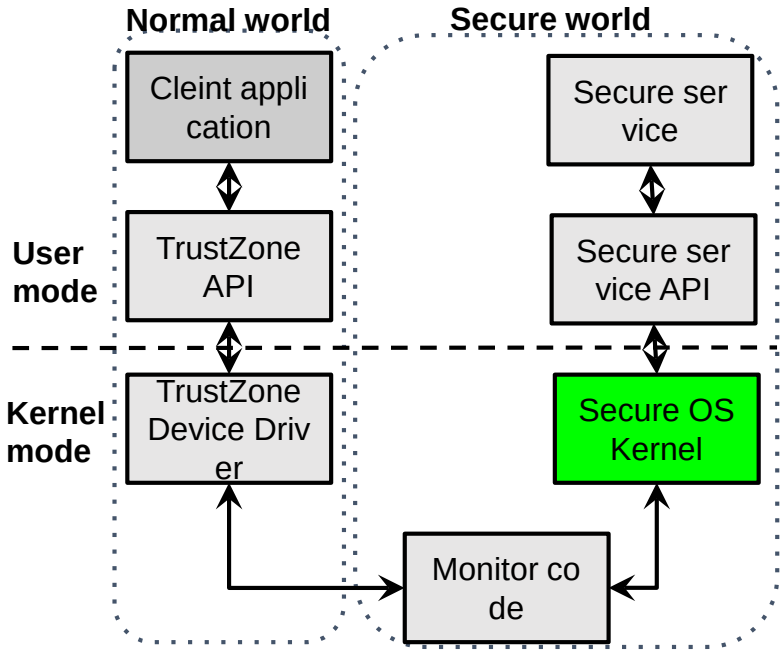
- Secure OS (Kernel mode in Secure world)

```
.global secure_exception_vectors
secure_exception_vectors:
/*
Vector table
*/
    B       _reset_handler
    B       _undefined_handler
    B       _swi_handler
    B       _prefetch_handler
    B       _abort_handler
    b       _reserved_vector
    B       _irq_handler
    B       _fiq_handler
```

Exception vector for kernel mode in Secure world

```
.global _swi_handler
.func   _swi_handler
_swi_handler:
    stmfd   sp!, {r0-r12, lr}
    ldr     r0,  [lr, #-4]
    bic     r0, r0, #0xff000000
    mrs     r2, spsr
    stmfd   sp!, {r2}
    mov   r1, sp
    bl      swi_handler
    ldmfd   sp!, {r2}
    msr     spsr, r2
    push    {r0}
    mov     r0, #0
    dsb
    pop     {r0}
    ldmfd   sp!, {r0-r12, pc}^
.endfunc
```

System-call exception handler

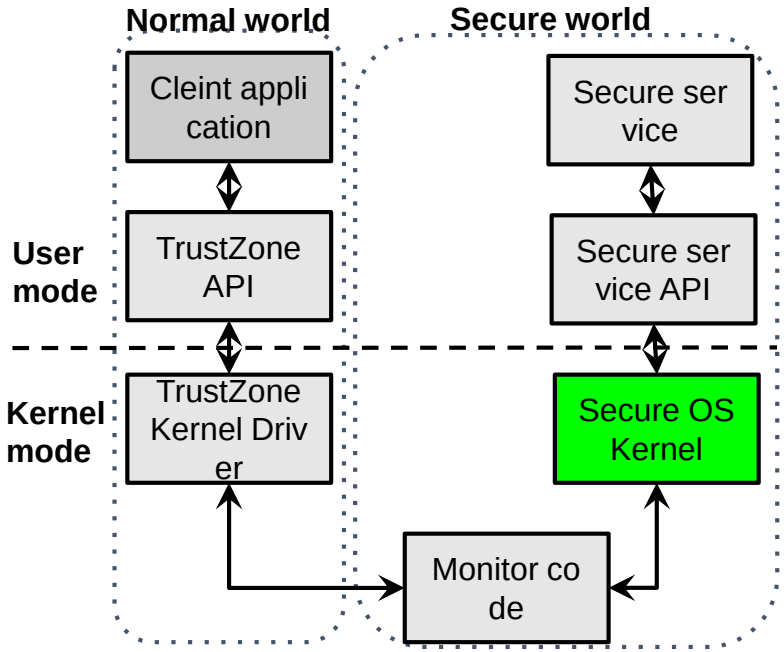


How It Works? (Source Code)

- Secure OS (Kernel mode in Secure world)
  - System call handler (triggers a scheduler)

```
void swi_handler(int swi_id, struct swi_temp_regs *regs)
{
    /*    int i = 0; */

#ifdef CONFIG_KSPACE_PROTECTION
    int ret=0;
    struct list *l1;
    struct sw_file_operations *dev_info;
#endif

    switch(swi_id) {
        case 0xbbbb:
        case 0xcccc:
            /*
               for(i = 0; i < 14; i++)
               tz_printf("swi temp regs[%x] = 0x%x\n", i, regs[i]);
             */
            temp_swi_regs = regs;
            scheduler();
            break;
```

Triggers a Secure world's scheduler

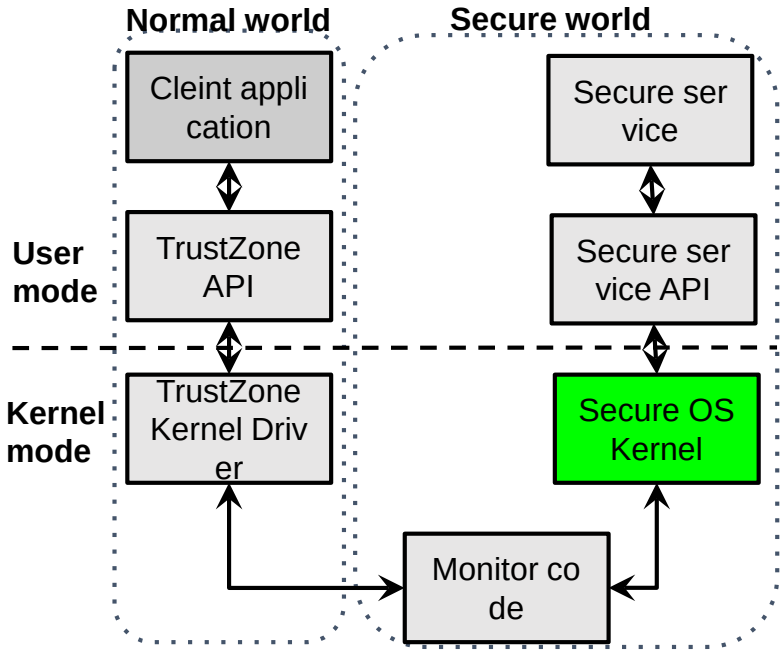


How It Works? (Source Code)

- Secure OS (Kernel mode in Secure world)
  - Scheduler: new task scheduling

```
void scheduler(void)
{
    struct sw_task *next_task;
    struct sw_task *current_task;

    current_task = get_current_task();
    next_task = get_next_task();

    if(current_task != next_task) {
        if(next_task) {
            next_task->state = TASK_STATE_RUNNING;
            update_current_task(next_task);
        }
        task_context_switch(next_task, current_task);

    }

    if(!next_task)
        disable_timer();
}
```

Context swi tch for a ne w task



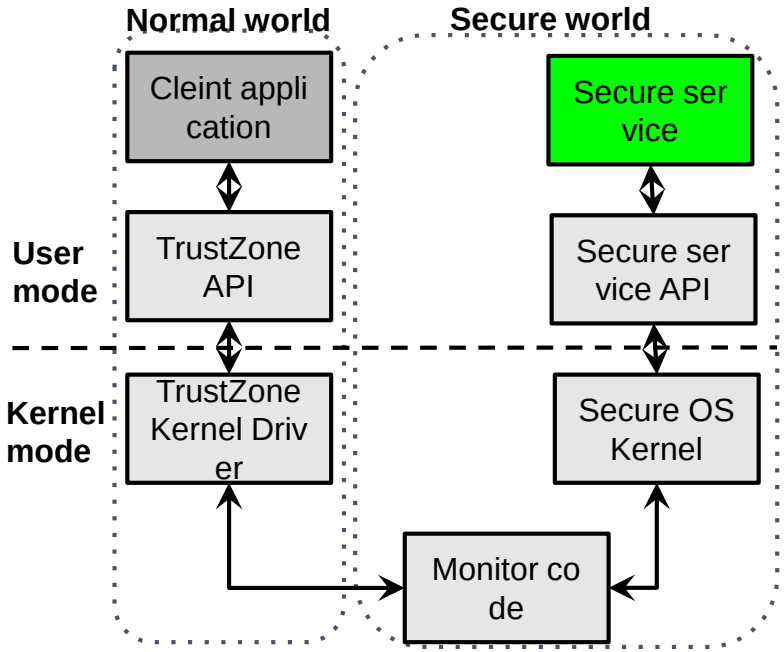
How It Works? (Source Code)

- Crypto service (User mode in Secure world)
  - Handle the actual request (message decryption)

```
void crypto_task(int task_id, sw_tls* tls)
{
    tls->ret_val = process_otzapi(task_id, tls);
    handle_task_return(task_id, tls);
    while(1);
}
```

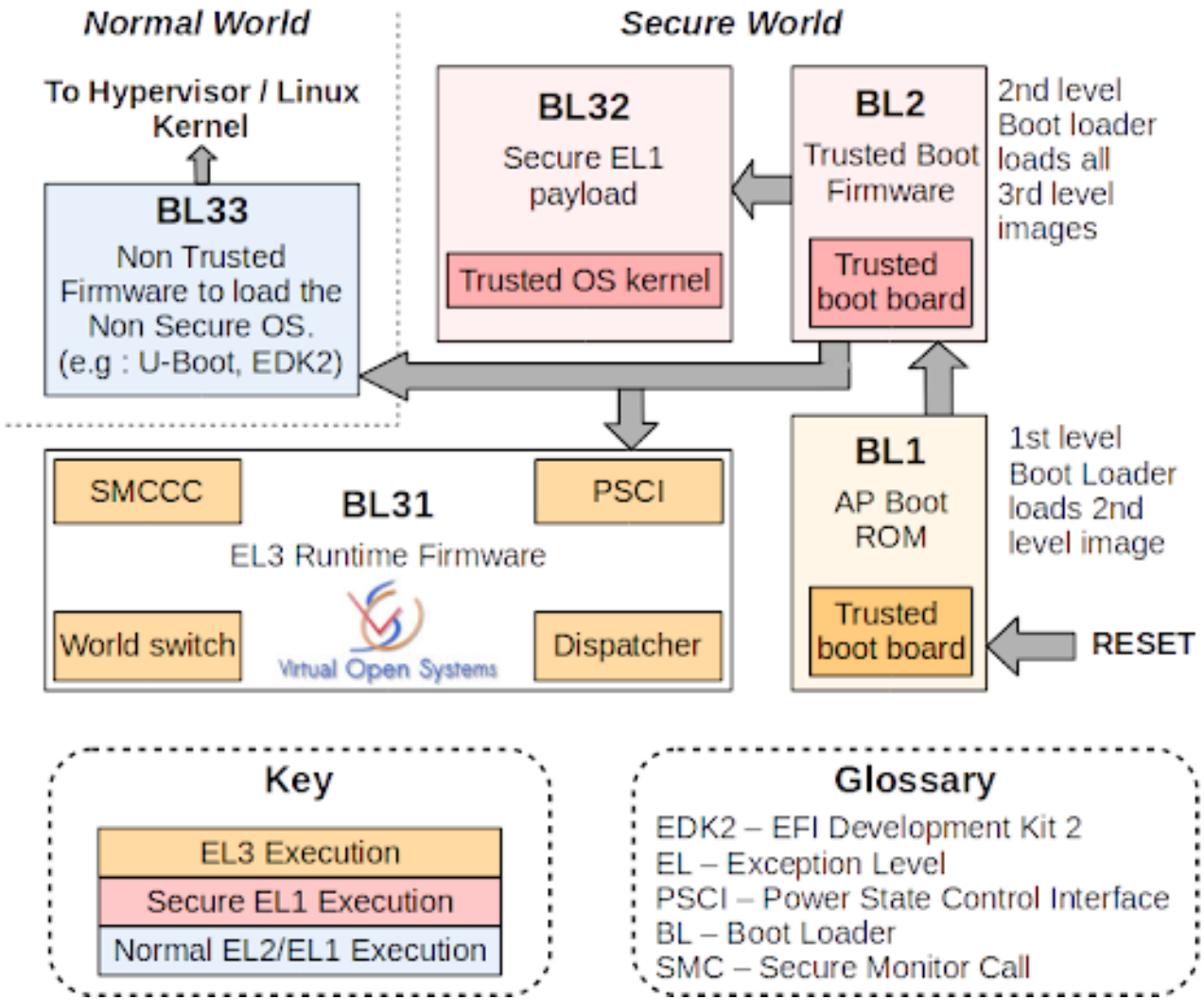
```
case OTZ_CRYPT_CMD_ID_CIPHER_AES_128_CBC:
case OTZ_CRYPT_CMD_ID_CIPHER_AES_128_ECB:
case OTZ_CRYPT_CMD_ID_CIPHER_AES_128_CTR:
case OTZ_CRYPT_CMD_ID_CIPHER_AES_128_XTS:
case OTZ_CRYPT_CMD_ID_CIPHER_DES_ECB:
case OTZ_CRYPT_CMD_ID_CIPHER_DES_CBC:
case OTZ_CRYPT_CMD_ID_CIPHER_DES3_ECB:
case OTZ_CRYPT_CMD_ID_CIPHER_DES3_CBC:
    ret_val = process_otz_crypto_cipher_cmd(req_buf,req_buf_len,
            resp_buf,res_buf_len,meta_data,
            ret_res_buf_len,svc_cmd_id);
    break;
default:
    ret_val = SMC_EOPNOTSUPP;
    break;
```

Decrypt the message from Normal world

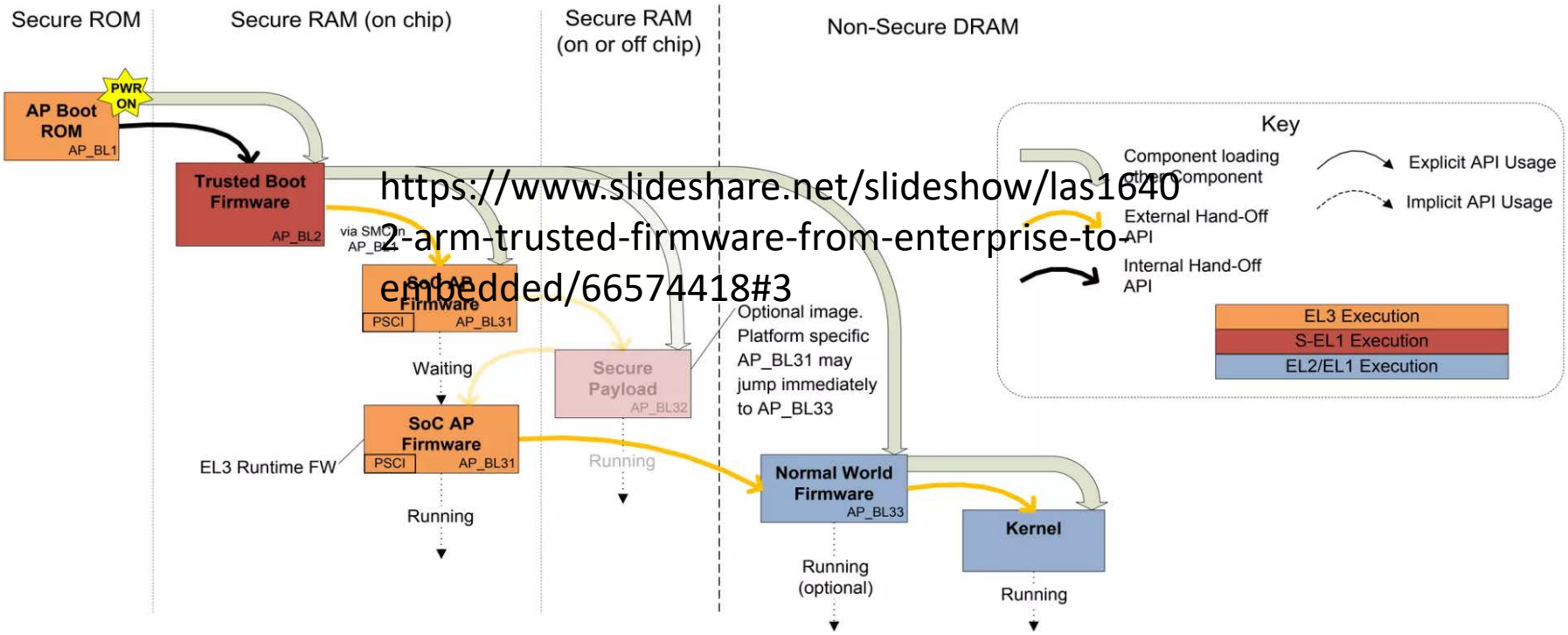


ARM Trusted Firmware

ARM Trusted Firmware



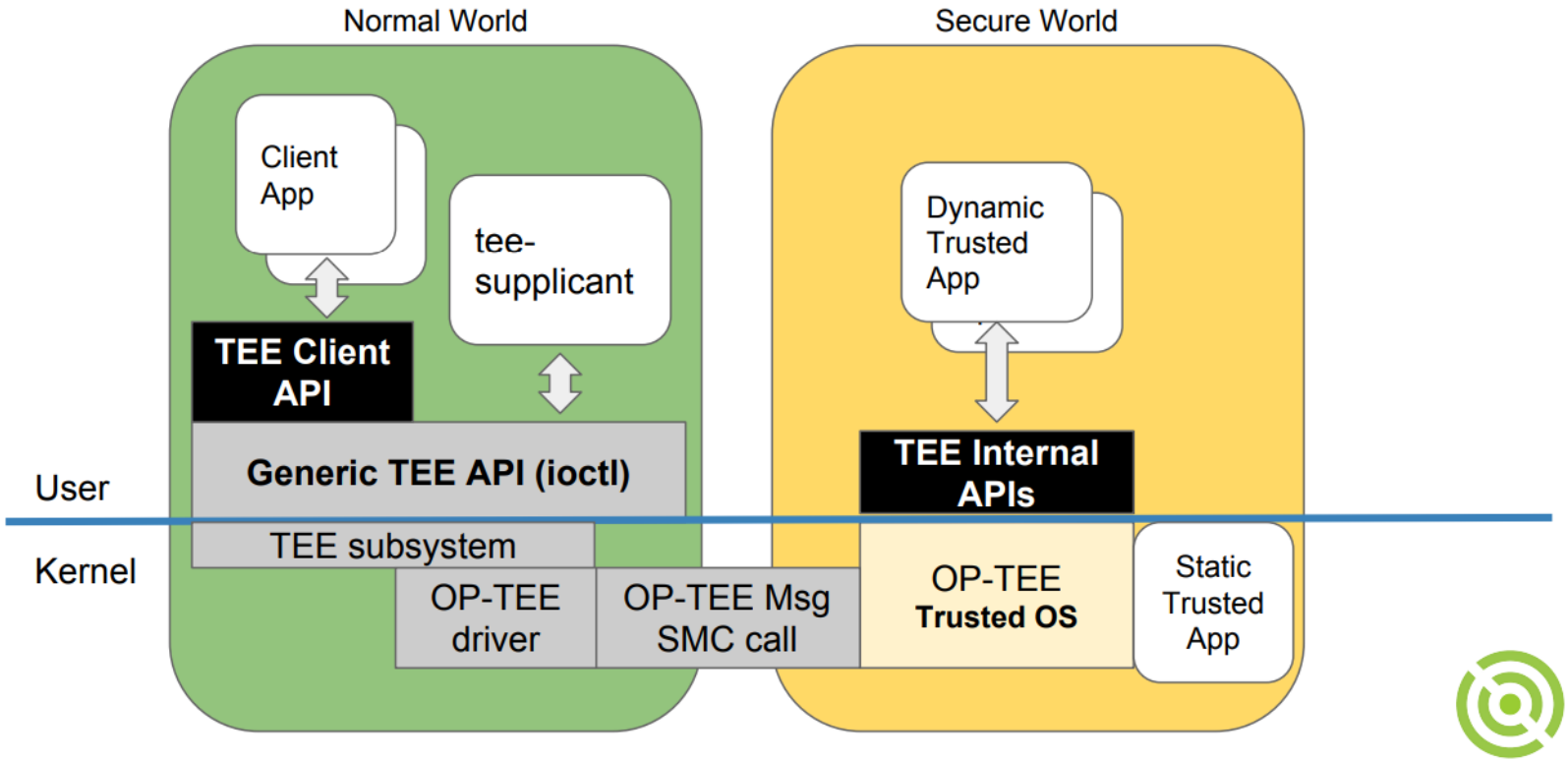
Booting Process on AArch64



https://www.slideshare.net/slideshow/las16402-arm-trusted-firmware-from-enterprise-to-embedded/66574418#3

OP-TEE

OP-TEE Architecture



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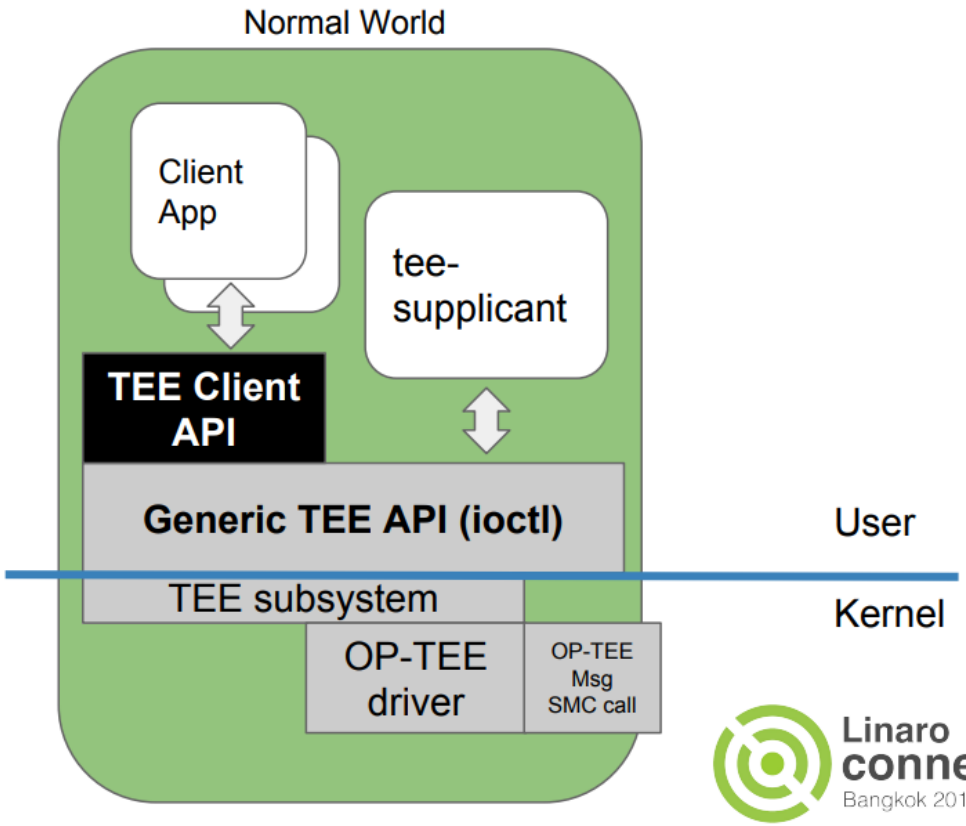
OP-TEE: Linux Kernel Subsystem

- TEE subsystem:
  - Manages Shared Memory,
  - Provides generic API as ioctl.
- tee-supplicant:
  - Helper process for TEE.
- OP-TEE driver:
  - Forwards command from the Clients to OP-TEE,
  - Manages RPC requests from OP-TEE to the supplicant.

For more details, please read optee_design.md at GitHub.



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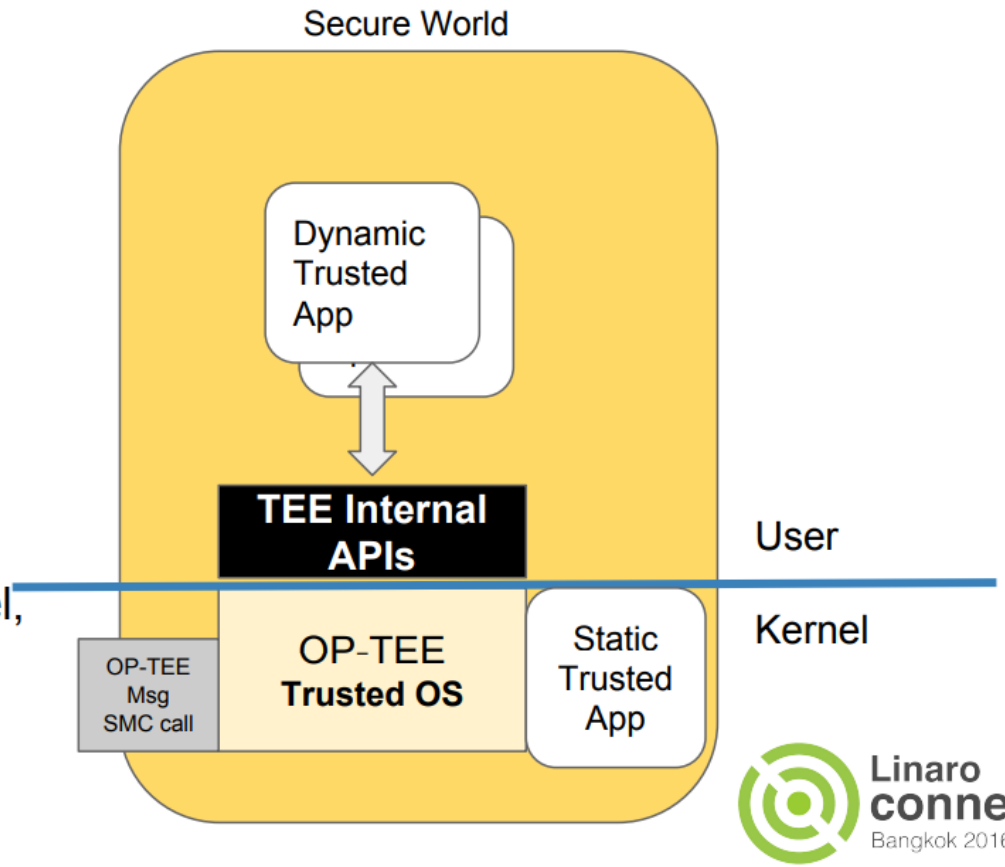
OP-TEE: Managing Trusted Apps

- Trusted Apps:
  - **Static**: run in kernel mode,
  - **Dynamic**: run in user mode:
    - Stored in File System,
    - Loaded by OP-TEE
      - Using tee_supplicant.

- MMU L1 Translation tables:
  - Large: 4GiB for OP-TEE kernel,
  - Small tables: 32MiB:
    - TA Virtual Memory,
    - One per thread.



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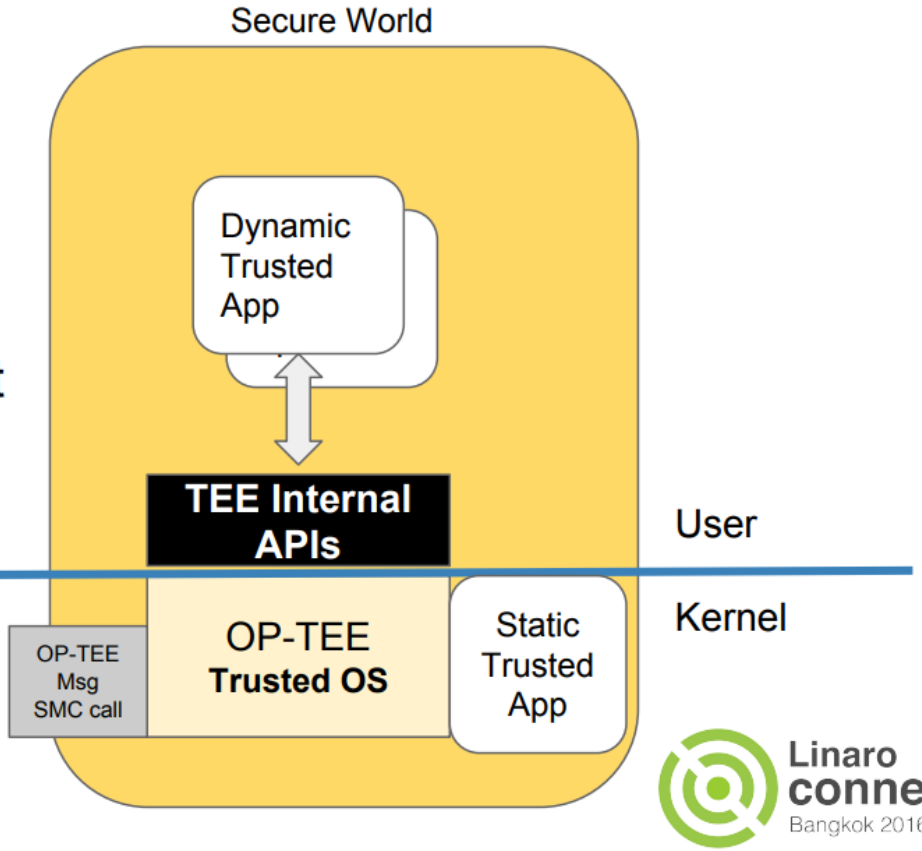
OP-TEE: Comm. & Sechduling

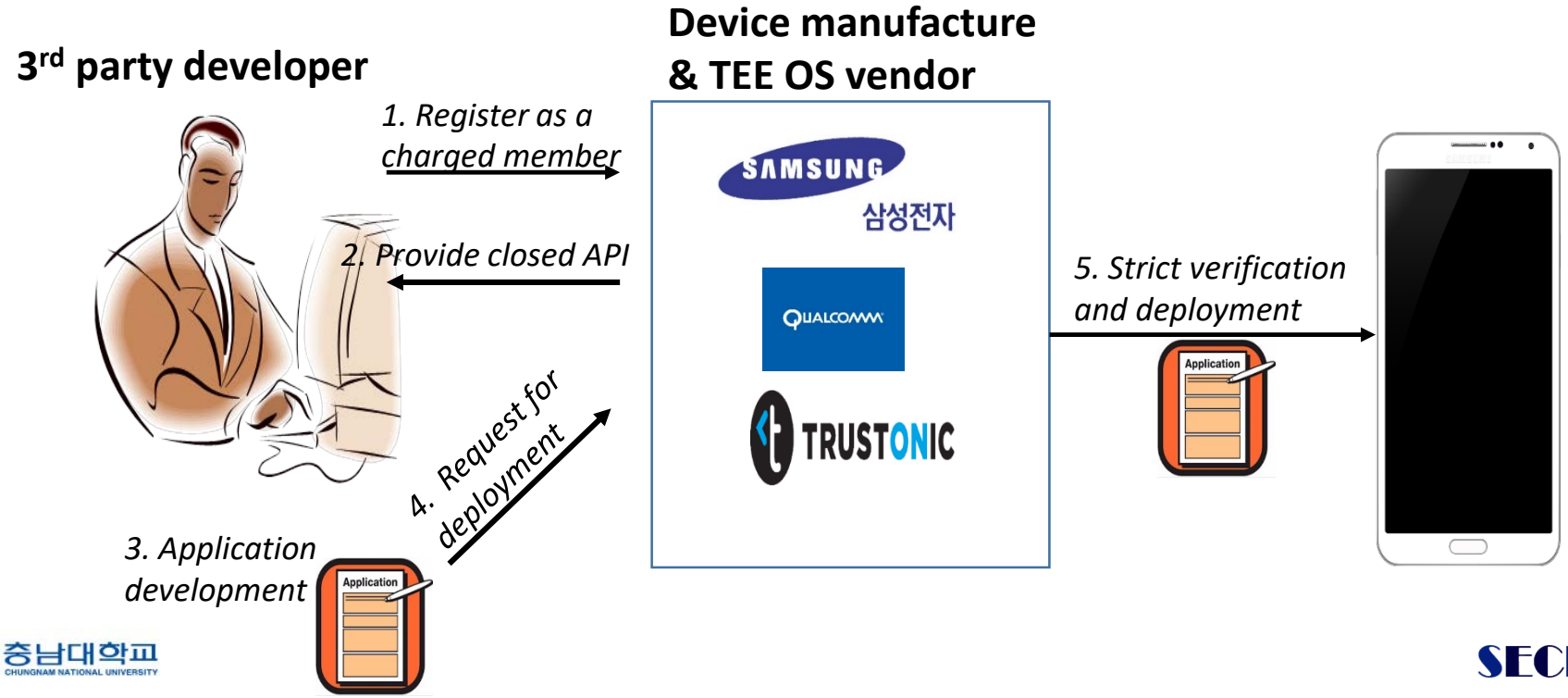
- Entry into secure world from SMC (or FIQ arriving).
- Command arriving → Allocated to thread (if available), TA context set up and called;
  - If supplicant needed, RPC is started and thread suspended.
- Return to normal world on task completion, RPC (or IRQ arriving).



Use cases

Closed Development Model

- Charged service, sometimes expensive
- TEE is maintained by TEE service providers
  - Device manufacturer: Samsung, Qualcomm
  - TEE OS provider: Trustonic



Open Source TEE

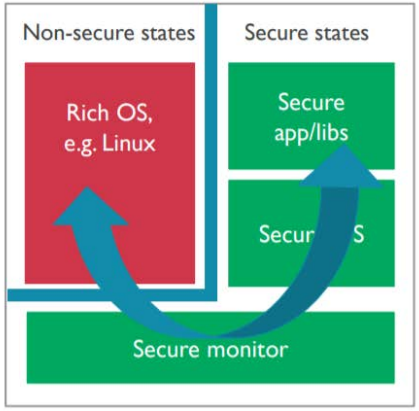
- Google Trusty
  - https://source.android.com/security/trusty/
  - Consist of TEE OS, TrustZone driver and APIs
- Linaro OP-TEE
  - https://wiki.linaro.org/WorkingGroups/Security/OP-TEE
  - Support various platforms

Platform	Composite PLATFORM flag	Publicly available?
Allwinner A80 Board	`PLATFORM=sunxi`	No
ARM Juno Board	`PLATFORM=vexpress-juno`	Yes
FSL ls1021a	`PLATFORM=ls-ls1021atwr`	Yes
FSL i.MX6 Quad SABRE Lite Board	`PLATFORM=imx-mx6qsabrelite`	Yes
FSL i.MX6 Quad SABRE SD Board	`PLATFORM=imx-mx6qsabresd`	Yes
FSL i.MX6 UltraLite EVK Board	`PLATFORM=imx-mx6ulevk`	Yes
NXP i.MX7Dual SabreSD Board	`PLATFORM=imx-mx7dsabresd`	Yes
ARM Foundation FVP	`PLATFORM=vexpress-fvp`	Yes
HiSilicon D02	`PLATFORM=d02`	No
HiKey Board (HiSilicon Kirin 620)	`PLATFORM=hikey` or `PLATFORM=hikey-hikey`	Yes
HiKey960 Board (HiSilicon Kirin 960)	`PLATFORM=hikey-hikey960`	Yes
MediaTek MT8173 EVB Board	`PLATFORM=mediatek-mt8173`	No
QEMU	`PLATFORM=vexpress-qemu_virt`	Yes
QEMUv8	`PLATFORM=vexpress-qemu_armv8a`	Yes
Raspberry Pi 3	`PLATFORM=rpi3`	Yes
Renesas RCAR	`PLATFORM=rcar`	No

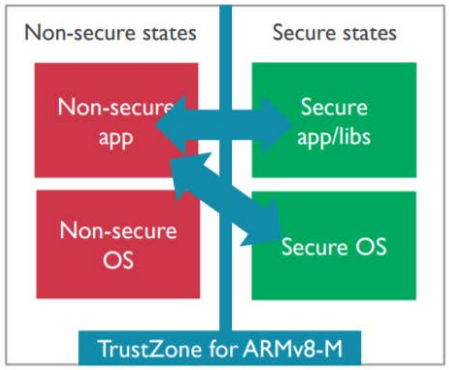
TrustZone with Different Arch.

- ARMv7
  - 32-bit architecture
- ARMv8
  - Both 32-bit and 64-bit architectures
  - ARMv8-A,R: for high-end devices (e.g., mobile phone)
  - ARMv8-M: for microcontrollers

TrustZone for ARMv8-A



TrustZone for ARMv8-M



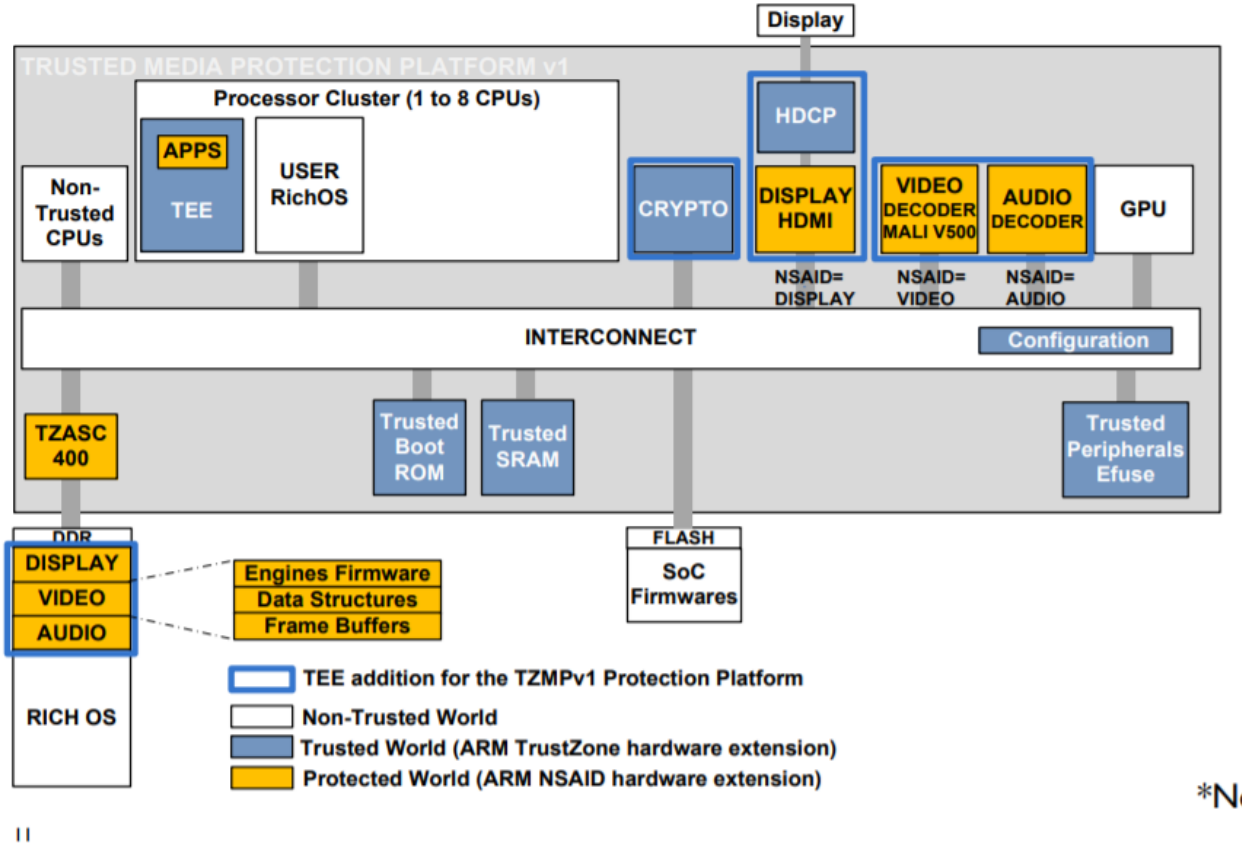
Secure transitions handled by the processor to maintain embedded class latency

Figure retrieved from: http://www2.keil.com/docs/default-source/default-document-library/using_trustzone_on_arm_cortex-m23_and_cortex-m33.pdf?sfvrsn=2

TrustZone in Industry

- Samsung
  - KNOX: security platform
  - Samsung pay: TEE service
- Qualcomm
  - QSEE : Qualcomm TEE
- TrustTonic
  - Trustonic Secured Platforms (TSP)
- Google
  - Trusty: open sourced TEE
- ARM
  - Mbed

Content Protection



DRM & Keys protected by TEE
Hardware isolated video path

*Non-Secure Access ID

ARM

Figure retrieved from: http://www.armtechforum.com.cn/2014/sz/A-8_FIDOandTEE-SimplerStrongerAuthentication.pdf

MDM & Enterprise

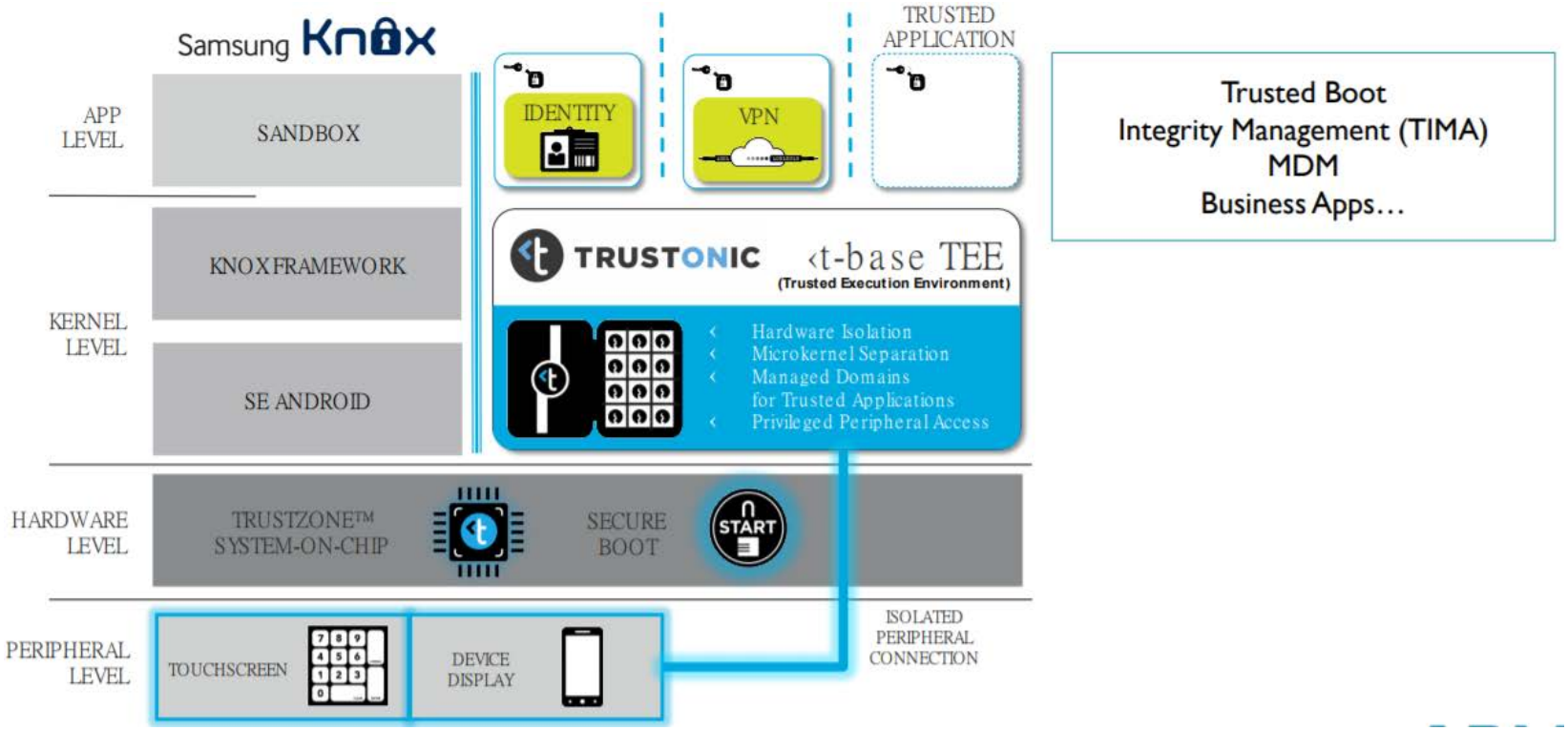


Figure retrieved from: http://www.armtechforum.com.cn/2014/sz/A-8_FIDOandTEE-SimplerStrongerAuthentication.pdf

Secure Payment

Figure retrieved from: http://www.armtechforum.com.cn/2014/sz/A-8_FIDOandTEE-SimplerStrongerAuthentication.pdf

Privacy-preserving Contact Tracing

Tracing without violating privacy

Figure from: Towards Confidential Computing with Trusted Execution Environment

Medical Data Sharing

Data sharing without violating privacy

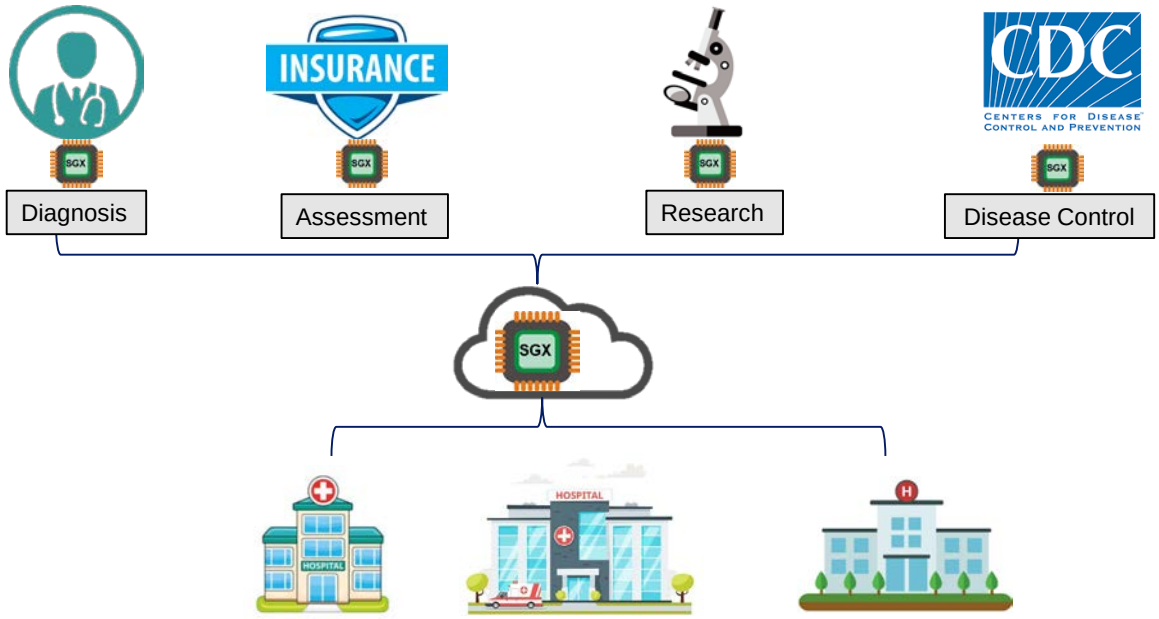
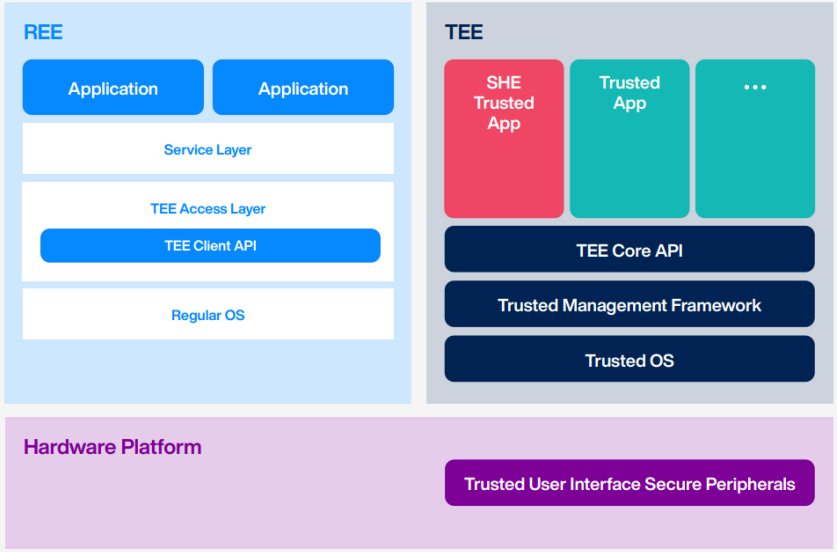


Figure from: Towards Confidential Computing with Trusted Execution Environment

Automotive Systems Security

4.3.1 Trusted Execution Environment Architecture

Figure 16:
GlobalPlatform Trusted Execution Environment Architecture



Drone Security

SiMa.ai

SiMa.ai

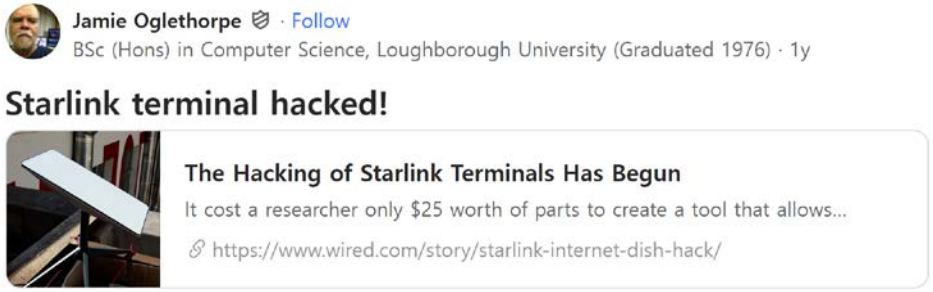
APPLICATIONS

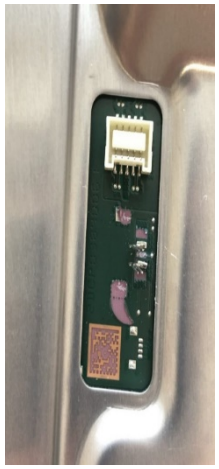
High-end consumer
Professional enterprise
Logistics
Construction and public safety
Agriculture and mining
Utilities and building inspection

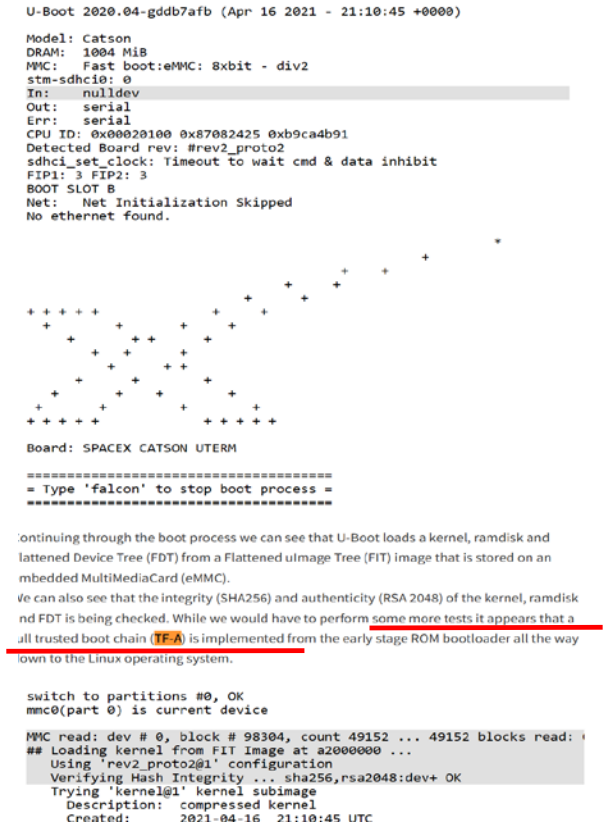
+ Authentication and encryption capabilities enable you to protect your sensitive data and IP.

+ Integrated secure boot, Arm TrustZone, secure communication, and data security.

Satellite Security

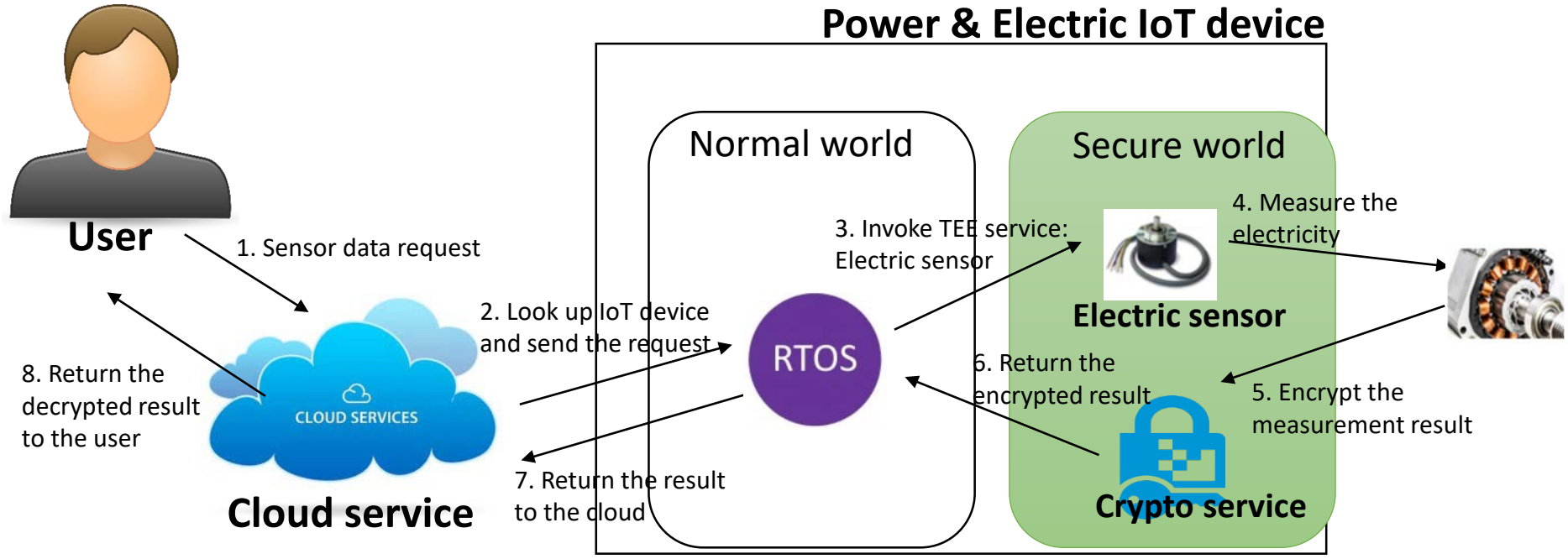






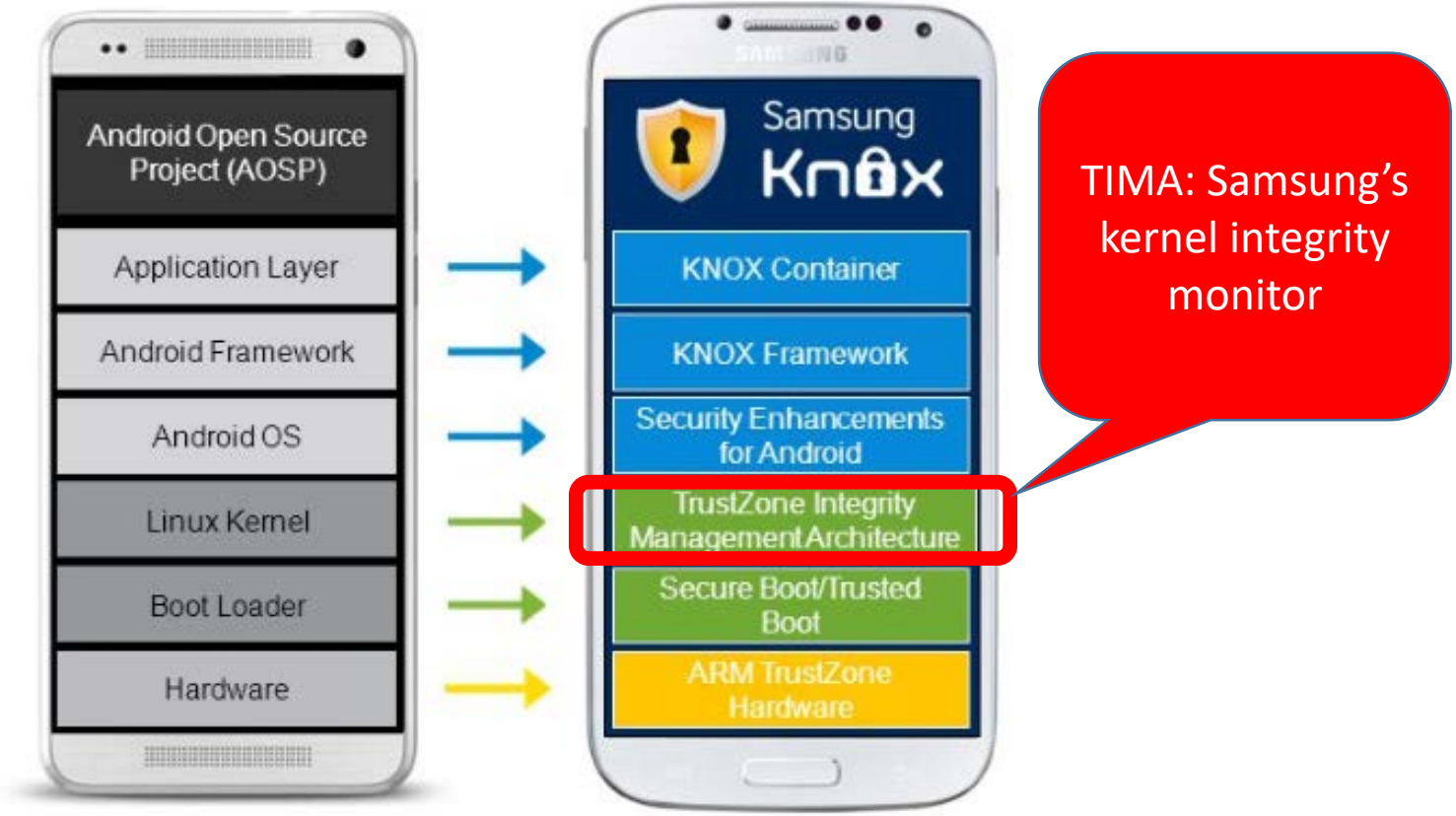
Electric IoT devices

- Define the critical resources and isolate them in the TEE
  - Example: Network components (non-critical), Electric sensor and crypto logic (critical)



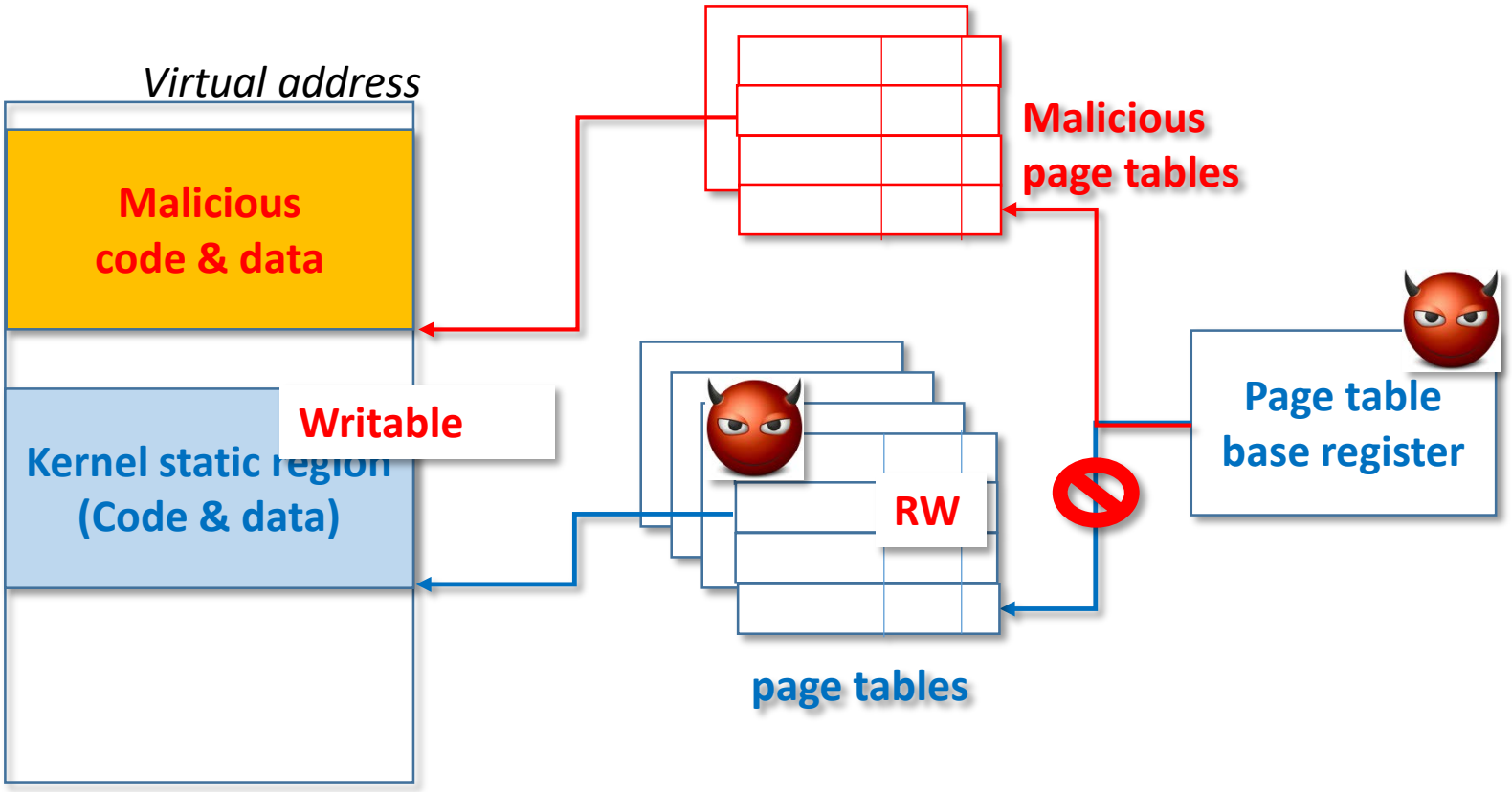
Samsung Mobile Security

❖ Samsung Knox



Case Study: SAMSUNG TIMA

Security critical components.

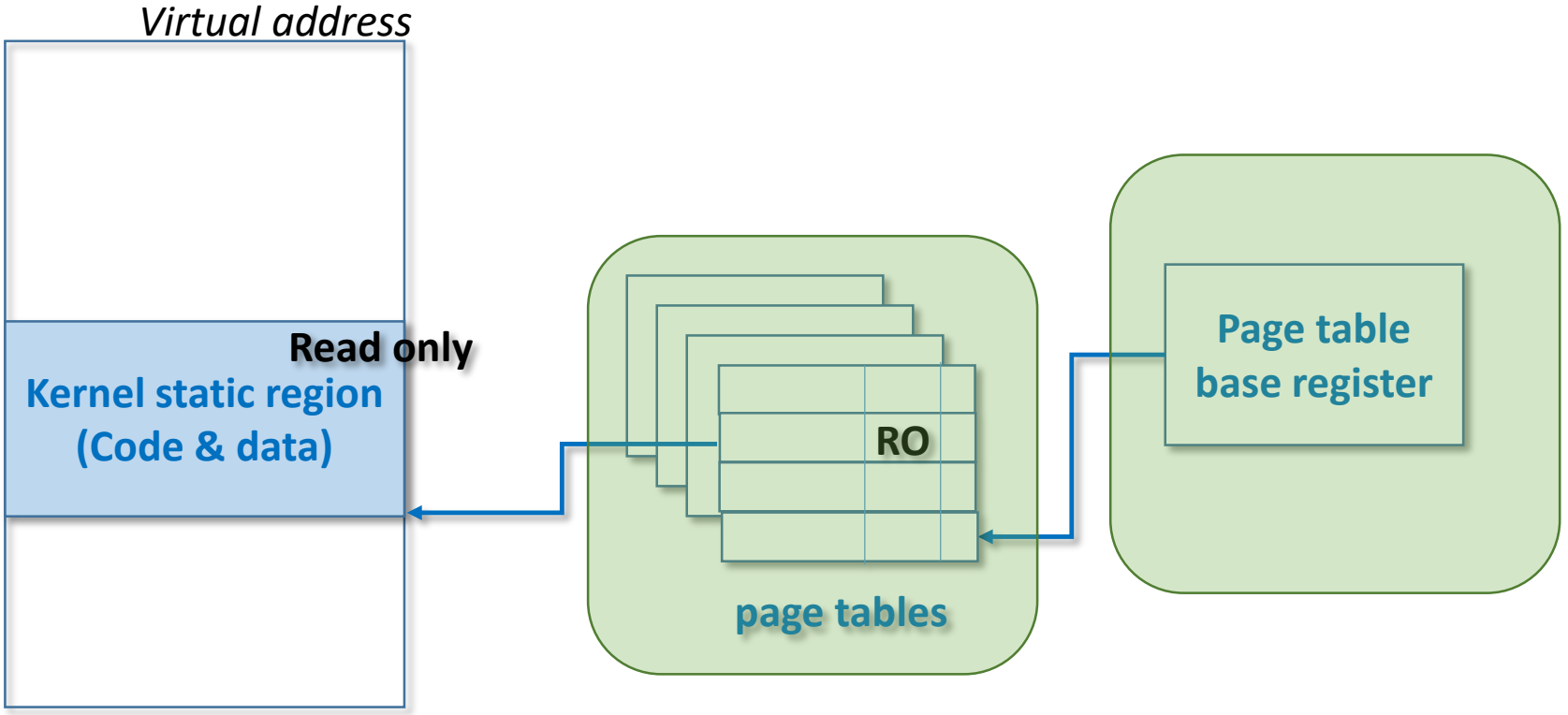


Case Study: SAMSUNG TIMA

Security critical components.

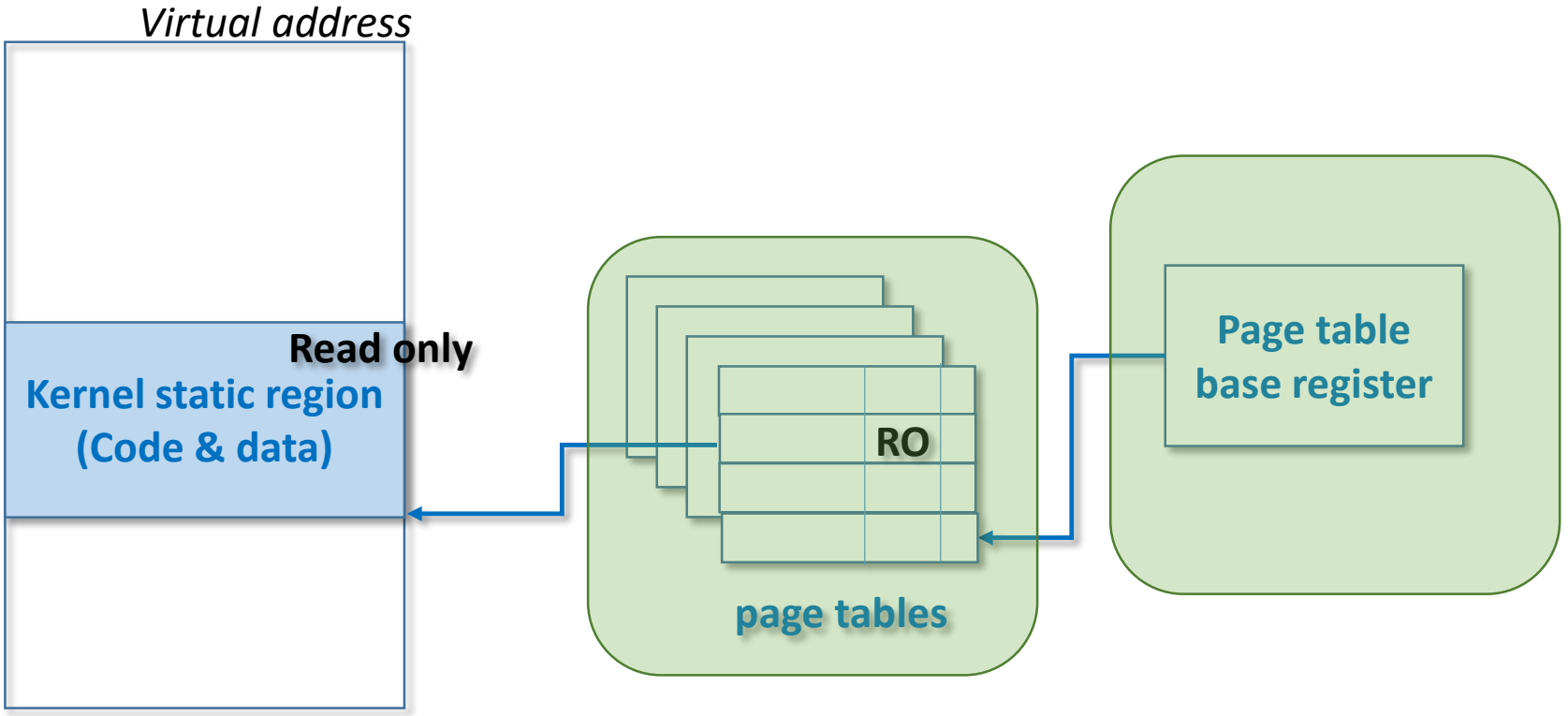
→ Page tables

→ System registers (e.g., page table base register)



Case Study: SAMSUNG TIMA

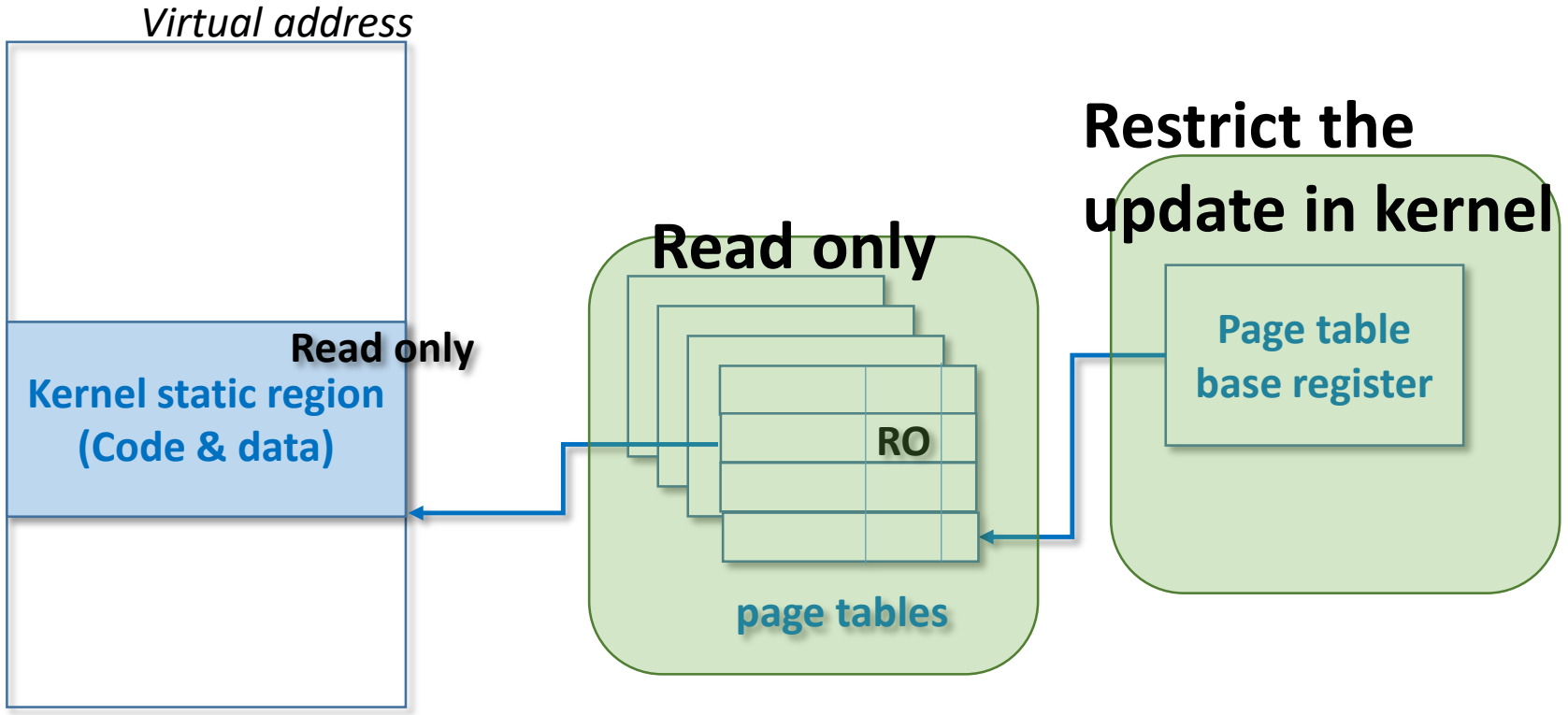
How can we protect them?



Case Study: SAMSUNG TIMA

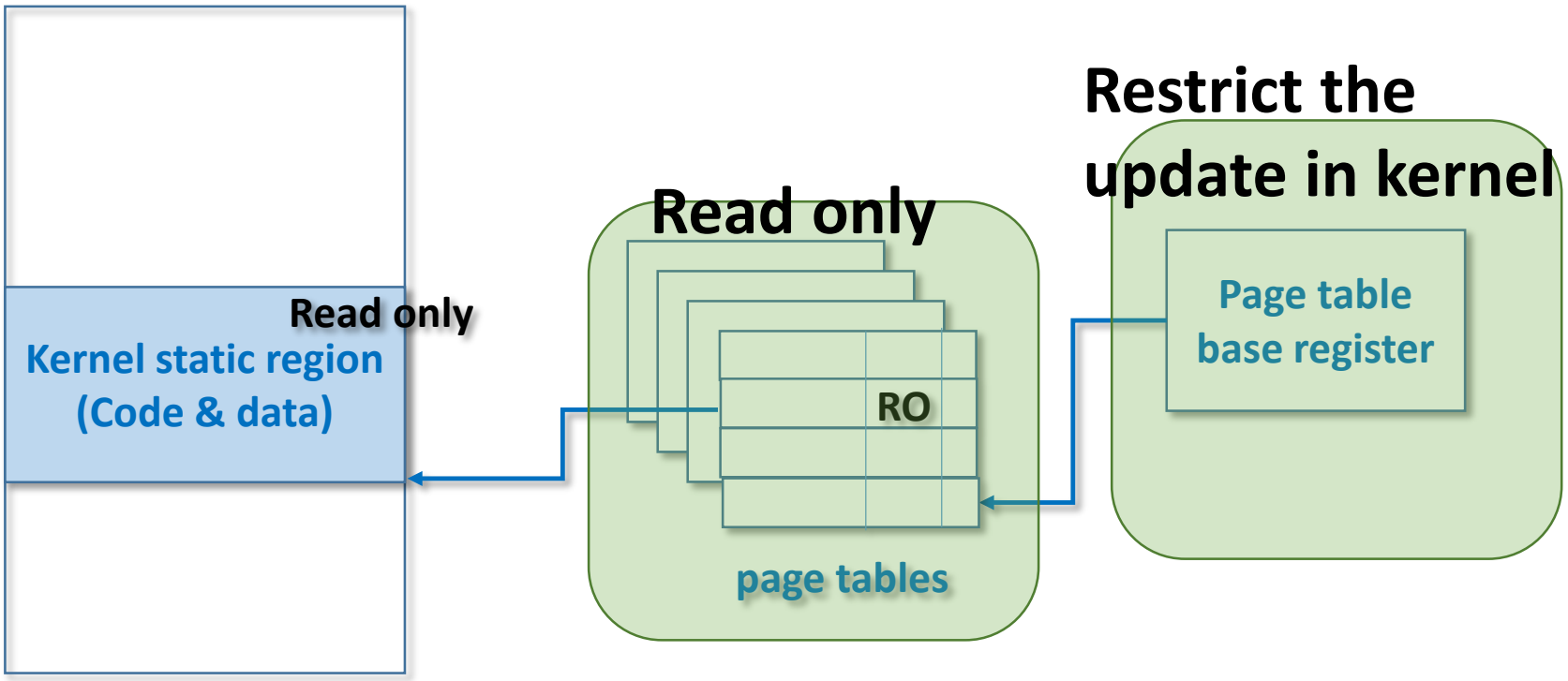
How can we protect them?

→ De-privileging the kernel



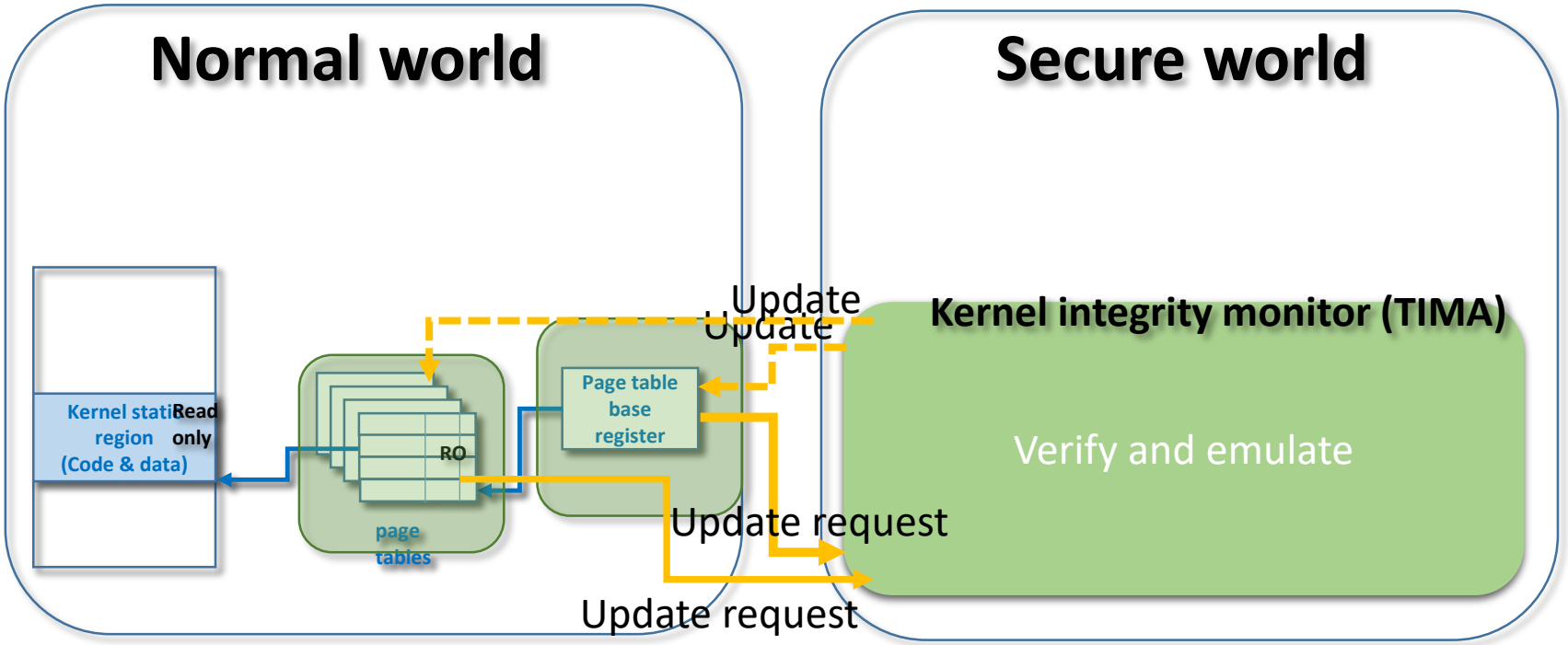
Case Study: SAMSUNG TIMA

How can we support original operations? → Adopt TrustZone



Case Study: SAMSUNG TIMA

TIMA verifies and emulates the security critical operations!



Q & A

Thank you!