Demystifying the Secure Enclave Processor

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Introduction

- iPhone 5S was a technological milestone
  - First 64-bit phone
- Introduced several technological advancements
  - Touch ID
  - M7 motion coprocessor
  - Security coprocessor (SEP)
- Enabled sensitive data to be stored securely
  - Fingerprint data, cryptographic keys, etc.

Secure Enclave Processor

- Security circuit designed to perform secure services for the rest of the SOC
  - Prevents main processor from gaining direct access to sensitive data
- Used to support a number of different services
  - Most notably Touch ID
- Runs its own operating system (SEPOS)
  - Includes its own kernel, drivers, services, and applications

Secure (?) Enclave Processor

- Very little public information exists on the SEP
  - Only information provided by Apple
- SEP patent only provides a high level overview
  - Doesn't describe actual implementation details
- Several open questions remain
  - What services are exposed by the SEP?
  - How are these services accessed?
  - What privileges are needed?
  - How resilient is SEP against attacks?

Talk Outline

- Part 1: Secure Enclave Processor
  - Hardware Design
  - Boot Process
- Part 2: Communication
  - Mailbox Mechanism
  - Kernel-to-SEP Interfaces
- Part 3: SEPOS
  - Architecture / Internals
- Part 4: Security Analysis
  - Attack Surface and Robustness

Hardware Design

Demystifying the Secure Enclave Processor

SEP's ARM Core: Kingfisher

- Dedicated ARMv7a "Kingfisher" core
  - Even EL3 on AP's core won't doesn't give you access to SEP
- Appears to be running at 300-400mhz~
- One of multiple kingfisher cores in the SoC
  - 2-4 Other KF cores - used for NAND/SmartIO/etc
  - Other cores provide a wealth of arch knowledge
- Changes between platforms (A7/A8/A9)
  - Appears like anti-tamper on newer chips

Dedicated Hardware Peripherals

- SEP has its own set of peripherals accessible by memory-mapped IO
  - Built into hardware that AP cannot access
    - Crypto Engine & Random Number Generator
    - Security Fuses
    - GID/UID Keys
- Dedicated IO lines -
  - Lines run directly to off-chip peripherals
    - GPIO
    - SPI
    - UART
    - I2C

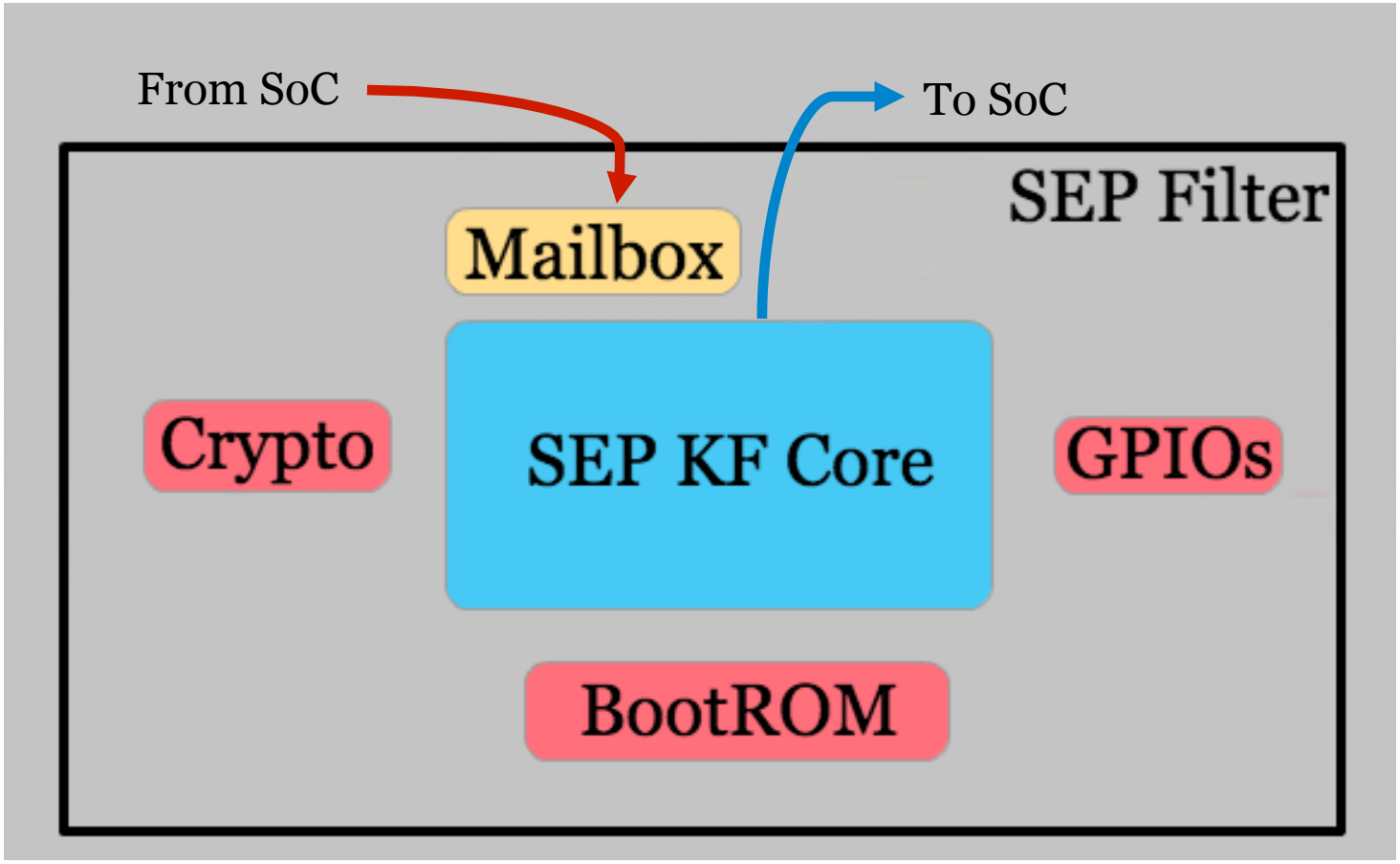
Shared Hardware Peripherals

- SEP and AP share some peripherals
- Power Manager (PMGR)
  - Security fuse settings are located in the PMGR
  - Lots of other interesting items
- Memory Controller
  - Can be poked at via iOS kernel
- Phase-locked loop (PLL) clock generator
  - Nothing to see here move along…
- Secure Mailbox
  - Used to tranfer data between cores
- External Random Access Memory (RAM)

Physical Memory

- Dedicated BootROM (and some SRAM)
  - BootROM physically located at 0x2_0da0_0000
- Uses inline AES to encrypt external RAM
  - Most likely to prevent physical memory attacks against off SoC RAM chips (iPads)
- Hardware “filter” to prevent AP to SEP memory access
  - Only SEP’s KF core has this filter

SEP KF Filter Diagram



Boot Process

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SEP Initialization – First Stage

- AP comes out of reset. AP BootROM releases SEP from reset.
  - This is irreversible. No hardware register to reset or stop SEP accessible by AP.
- Initially uses 4096 bytes of static RAM for stack and variables.
- Uses page tables in ROM.
  - Needs Large Physical Address Extension.
- Starts a message loop.

SEP Initialization – Second Stage

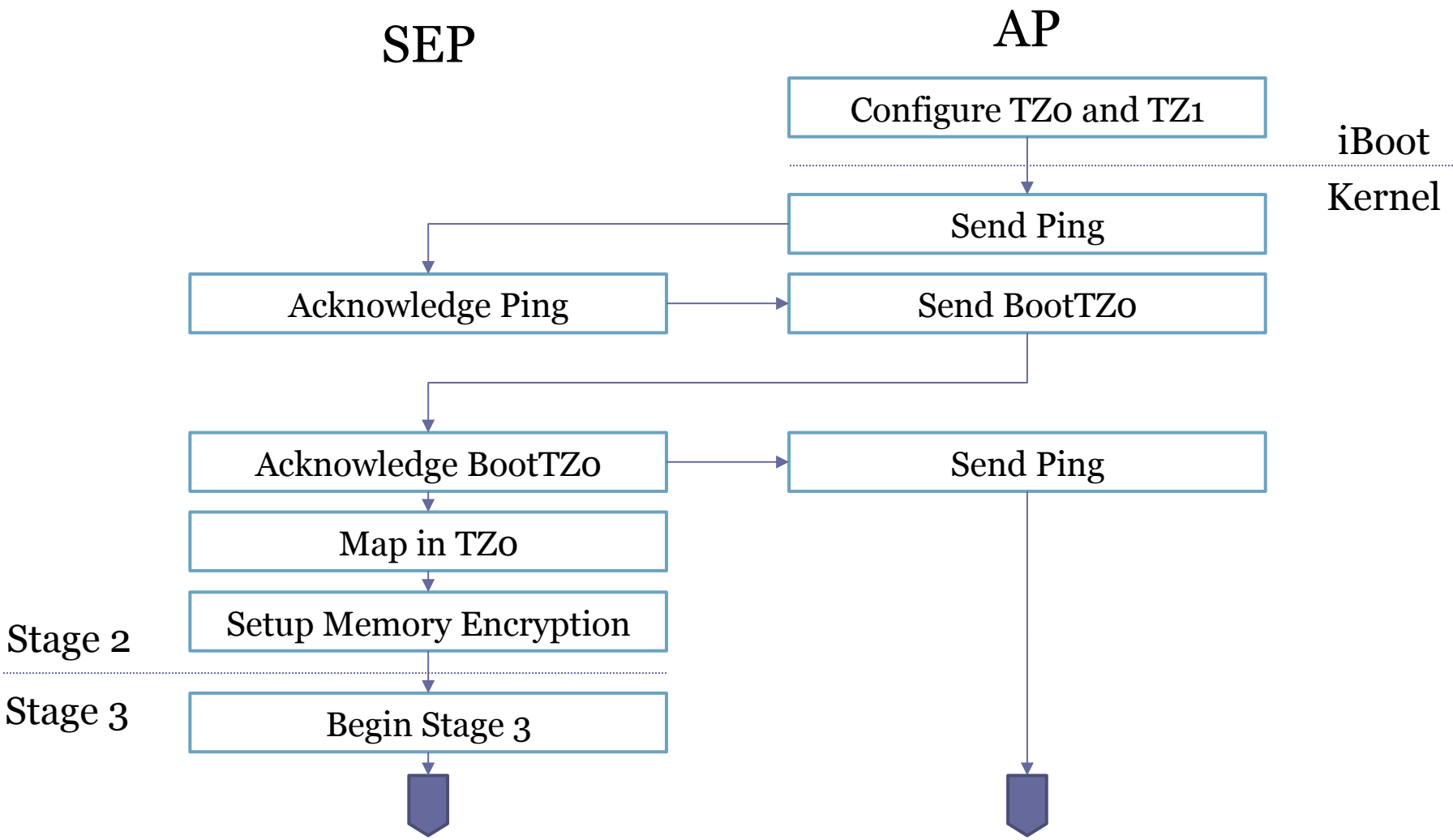
- Listens for messages in the mailbox.
- 8-byte messages that have the same format SEPOS uses.
- All messages use endpoint 255 (EP_BOOTSTRAP)

Opcode	Description
1, 2	“Status check” (Ping)
3	Generate nonce
4	Get nonce word
5	“BootTZo” (Continue boot)

Memory Protections

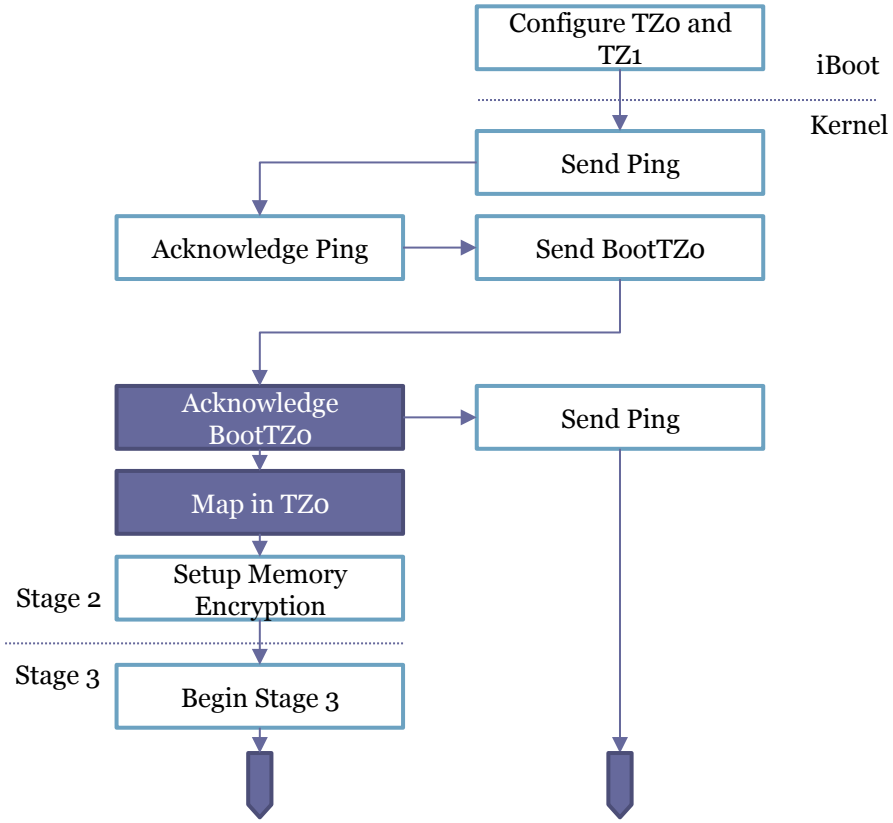
- SEP needs more RAM than 4096 bytes of SRAM, so it needs external RAM.
- RAM used by SEP must be protected against AP tampering.
- Two regions configurable by AP are setup:
  - TZ0 is for the SEP.
  - TZ1 is for the AP's TrustZone (Kernel Patch Protection).
- SEP must wait for AP to setup TZ0 to continue boot.

SEP Boot Flow



SEP Memory Protection Bootstrap

- SEP doesn't take AP's word for it that TZ0 is locked.
  - Checks hardware registers for lock.
  - Then reads size and address of TZ0 from other hardware registers.
- Impossible to change these hardware registers after TZ0 is locked.
- Spin processor on failure.



Memory Encryption Modes

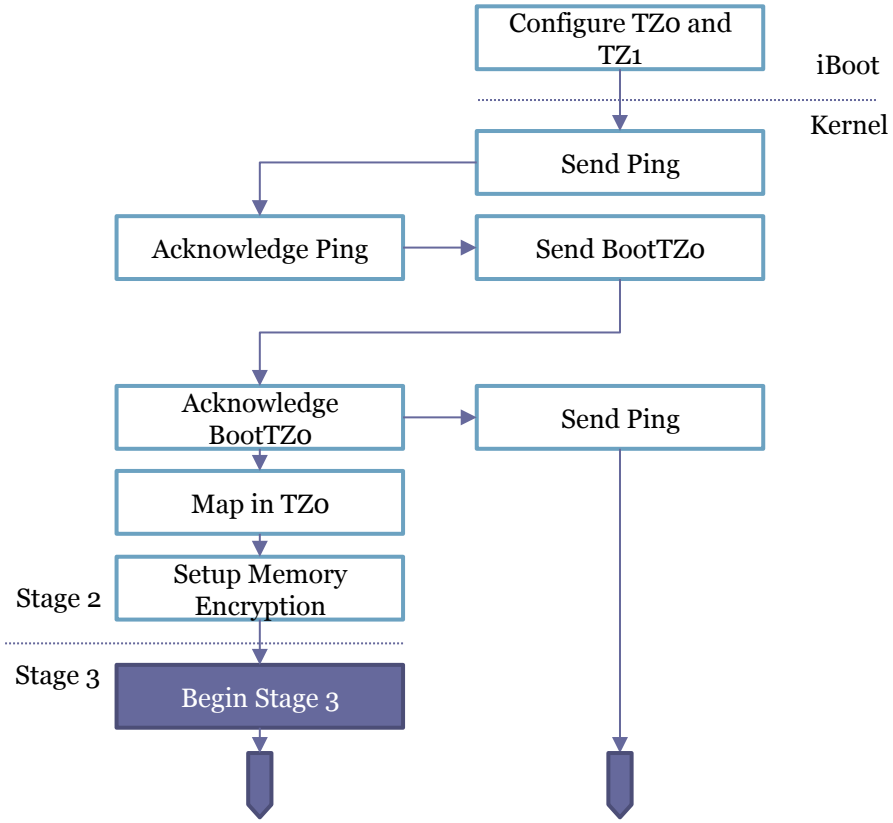
- Appears to support ECB, CBC, and **XEX**.
- Capable of AES-128 or **AES-256**.
- Supports two channels.
  - BootROM uses channel 1.
  - SEPOS uses channel 0.
- All access to certain ranges of physical addresses get encrypted/decrypted transparently.
  - After boot, SEPOS has all page mappings into the encrypted range (except for hardware regs and memory shared with AP).

Key Generation

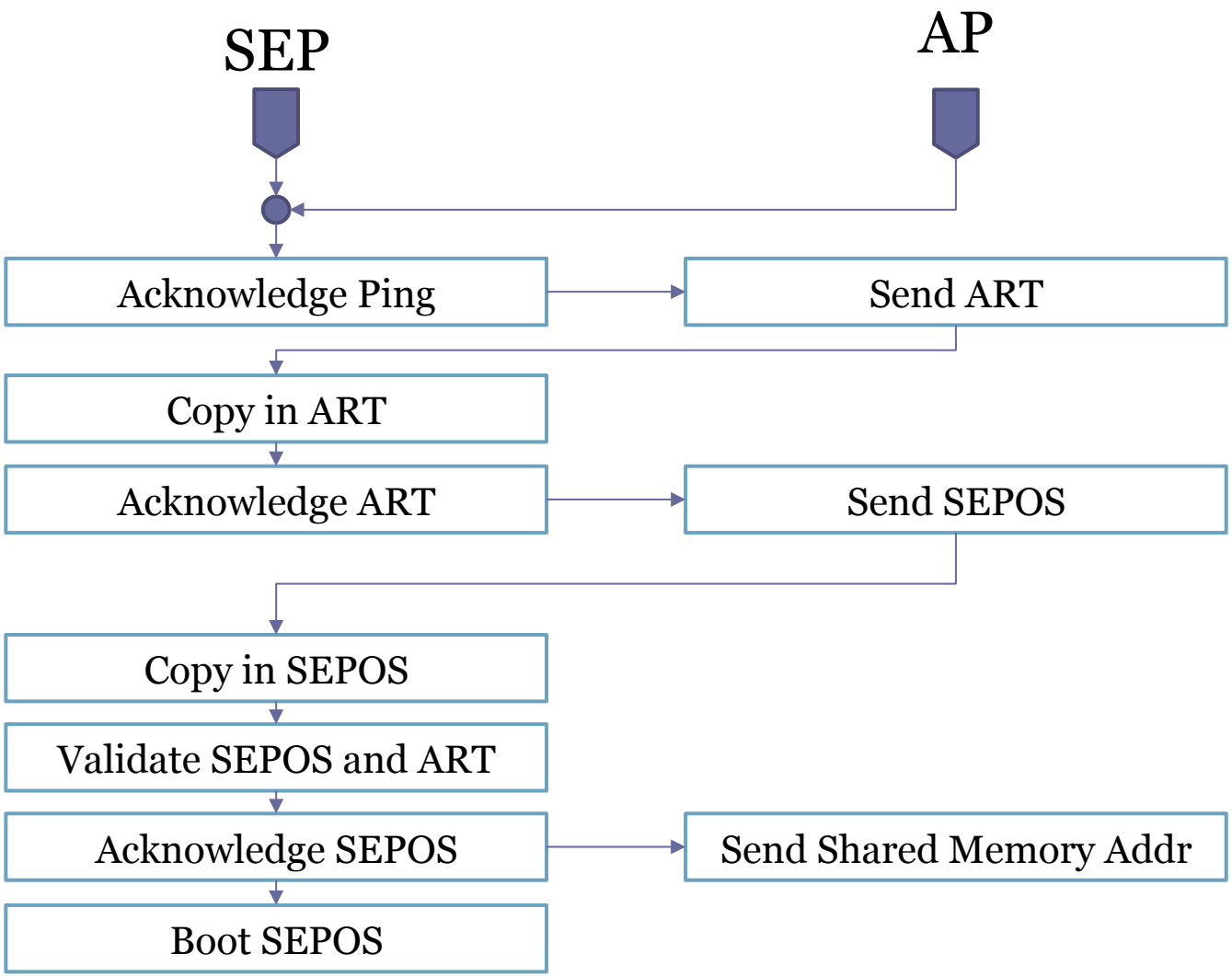
- Keys are generated by “tangling”:
  - True Random Number Generator output
  - Static ”type” value.
- With protected (unreadable) registers:
  - UID, GID, Seed A, Seed B.
    - Seed B tangled with UID == GenID_2B
- Encrypt the following using GenID_2B to generate key:
  - [4 byte magic = 0xFF XK1][4 bytes of 0s][192-bits of randomness]

Beginning Stage 3

- After memory encryption is setup, SEP re-initializes to use encrypted memory:
  - Page tables
  - Stack
  - Data
- Begins a new message loop with no shared code between it and the initial low-capability bootstrap.



SEP Boot Flow: Stage 3



Boot-loading: Img4

- SEP uses the “IMG4” bootloader format which is based on ASN.1 DER encoding
  - Very similar to 64bit iBoot/AP Bootrom
  - Can be parsed with ”openssl -asn1parse”

- Three primary objects used by SEP
  - Payload –
    - Contains the encrypted sep-firmware
  - Restore –
    - Contains basic information when restoring SEP
  - Manifest (aka the AP ticket) -
    - Effectively the Alpha and the Omega of bootROM configuration (and security)

Img4 - Manifest

- The manifest (APTicket) contains almost all the essential information used to authenticate and configure SEP(OS).
- Contains multiple hardware identifier tags
  - ECID
  - ChipID
  - Others
- Is also used to change runtime settings in both software and hardware
  - DPRO – Demote Production
  - DSEC – Demote Security
  - Others…

Reversing SEP's Img4 Parser: Stage 1

- How can you reverse something you cannot see?
  - Look for potential code reuse!
- Other locations that parse IMG4
  - AP BootROM – A bit of a pain to get at
  - iBoot – Dump from phys memory - 0x8700xx000
    - Not many symbols…
    - But sometimes it only takes 1…

```
X8, #aImg4decodecopy@PAGE ; "Img4DecodeCopyManifestHash((const Img4 "...
X8, X8, #aImg4decodecopy@PAGEOFF ; "Img4DecodeCopyManifestHash((const Img4
X8, [SP,#0x3C0+var_3A8]
X8, #0x187
loc_83D8099B4
```

(iBoot from n51)

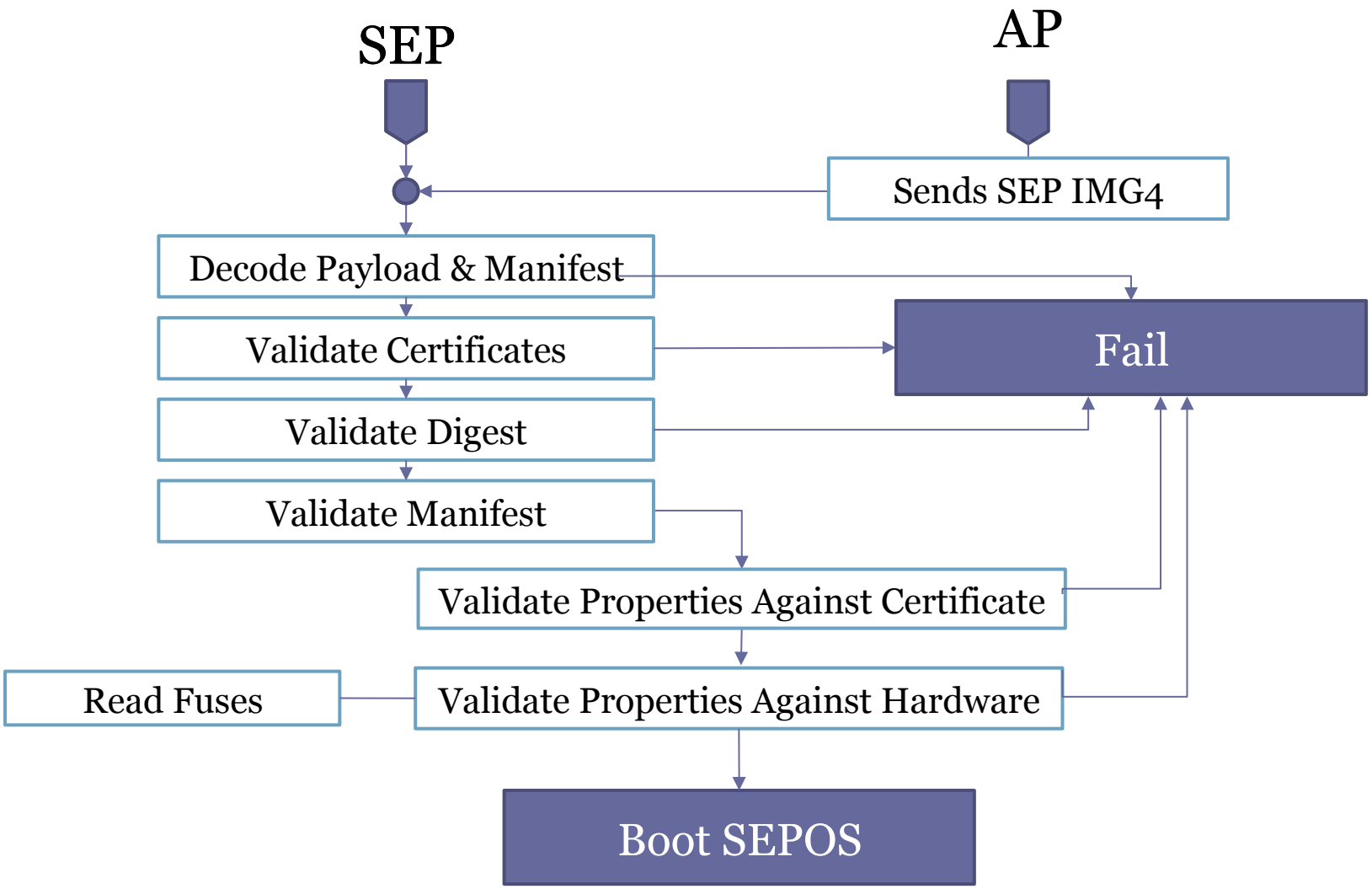
Reversing SEP's Img4 Parser: Stage 2

- Another file also contains the "Img4Decode" symbol
  - /usr/libexec/seputil
- Userland IMG4 parser with many more symbols
  - May not be exact – but bindiff shows it is very close
- From symbols found in seputil we can deduce:
  - The ASN'1 decoder is based on libDER
    - Which Apple so kindly releases as OpenSource.
  - The RSA portion is handled by CoreCrypto
- LibDER + CoreCrypto = SEP's IMG4 Parsing engine
  - We now have a great base to work with

Img4 Parsing Flow

- SEP BootROM copies in the sep-firmware.img4 from AP
- Initializes the DER Decoder
  - Decodes Payload, Manifest, and Restore Info
- Verifies digests and signing certificates
  - Root of trust cert is hardcoded at the end of BootROM
- Verifies all properties in manifest
  - Checks against current hardware fusing
- If all items pass – load and execute the payload

Img4 Parsing Flow



Communication

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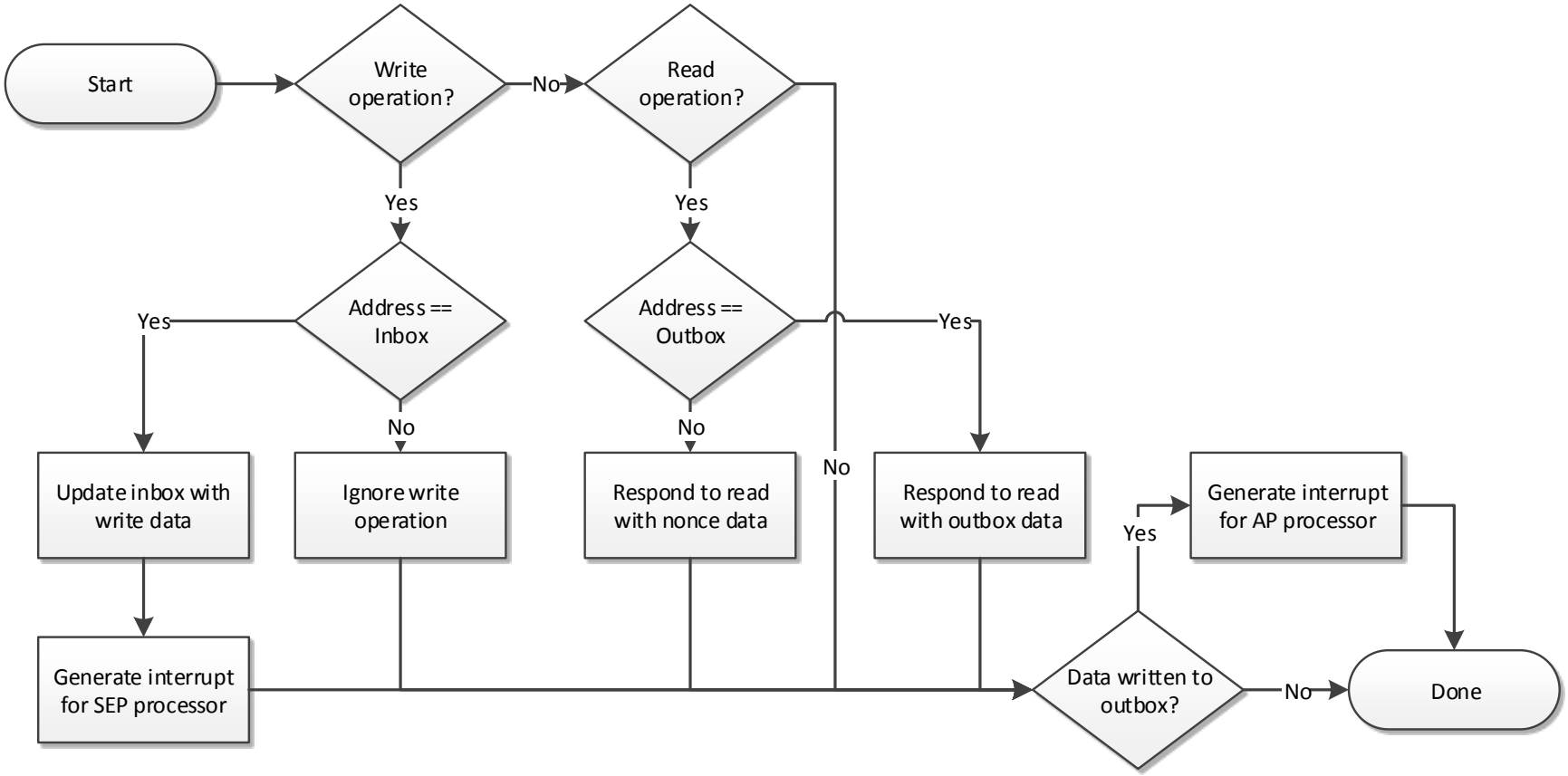
Secure Mailbox

- The secure mailbox allows the AP to communicate with the SEP
  - Features both an inbox (request) and outbox (reply)
- Implemented using the SEP device I/O registers
  - Also known as the SEP configuration space

Interrupt-based Message Passing

- When sending a message, the AP writes to the inbox of the mailbox
- This operation triggers an interrupt in the SEP
  - Informs the SEP that a message has been received
- When a reply is ready, the SEP writes a message back to the outbox
  - Another interrupt is generated in order to let the AP know a message was received

Mailbox Mechanism



Mailbox Message Format

- A single message is 8 bytes in size
- Format depends on the receiving endpoint
- First byte is always the destination endpoint

```
struct {
    uint8_t    endpoint;      // destination endpoint number
    uint8_t    tag;           // message tag
    uint8_t    opcode;        // message type
    uint8_t    param;         // optional parameter
    uint32_t   data;          // message data
} sep_msg;
```

SEP Manager

- Provides a generic framework for drivers to communicate with the SEP
  - Implemented in AppleSEPManager.kext
  - Builds on the functionality provided by the IOP
- Enables drivers to register SEP endpoints
  - Used to talk to a specific SEP app or service
  - Assigned a unique index value
- Also implements several endpoints of its own
  - E.g. the SEP control endpoint

SEP Endpoints (1/2)

Index	Name	Driver
0	AppleSEPControl	AppleSEPManager.kext
1	AppleSEPLogger	AppleSEPManager.kext
2	AppleSEPARTStorage	AppleSEPManager.kext
3	AppleSEPARTRequests	AppleSEPManager.kext
4	AppleSEPTracer	AppleSEPManager.kext
5	AppleSEPDebug	AppleSEPManager.kext
6	<not used>	
7	AppleSEPKeyStore	AppleSEPKeyStore.kext

SEP Endpoints (2/2)

Index	Name	Driver
8	AppleMesaSEPDriver	AppleMesaSEPDriver.kext
9	AppleSPIBiometricSensor	AppleBiometricSensor.kext
10	AppleSEPCredentialManager	AppleSEPCredentialManager.kext
11	AppleSEPPairing	AppleSEPManager.kext
12	AppleSSE	AppleSSE.kext
254	L4Info	
255	Bootrom	SEP Bootrom

Control Endpoint (EP0)

- Handles control requests issued to the SEP
- Used to set up request and reply out-of-line buffers for an endpoint
- Provides interface to generate, read, and invalidate nonces
- The SEP Manager user client provides some support for interacting with the control endpoint
  - Used by the SEP Utility (/usr/libexec/seputil)

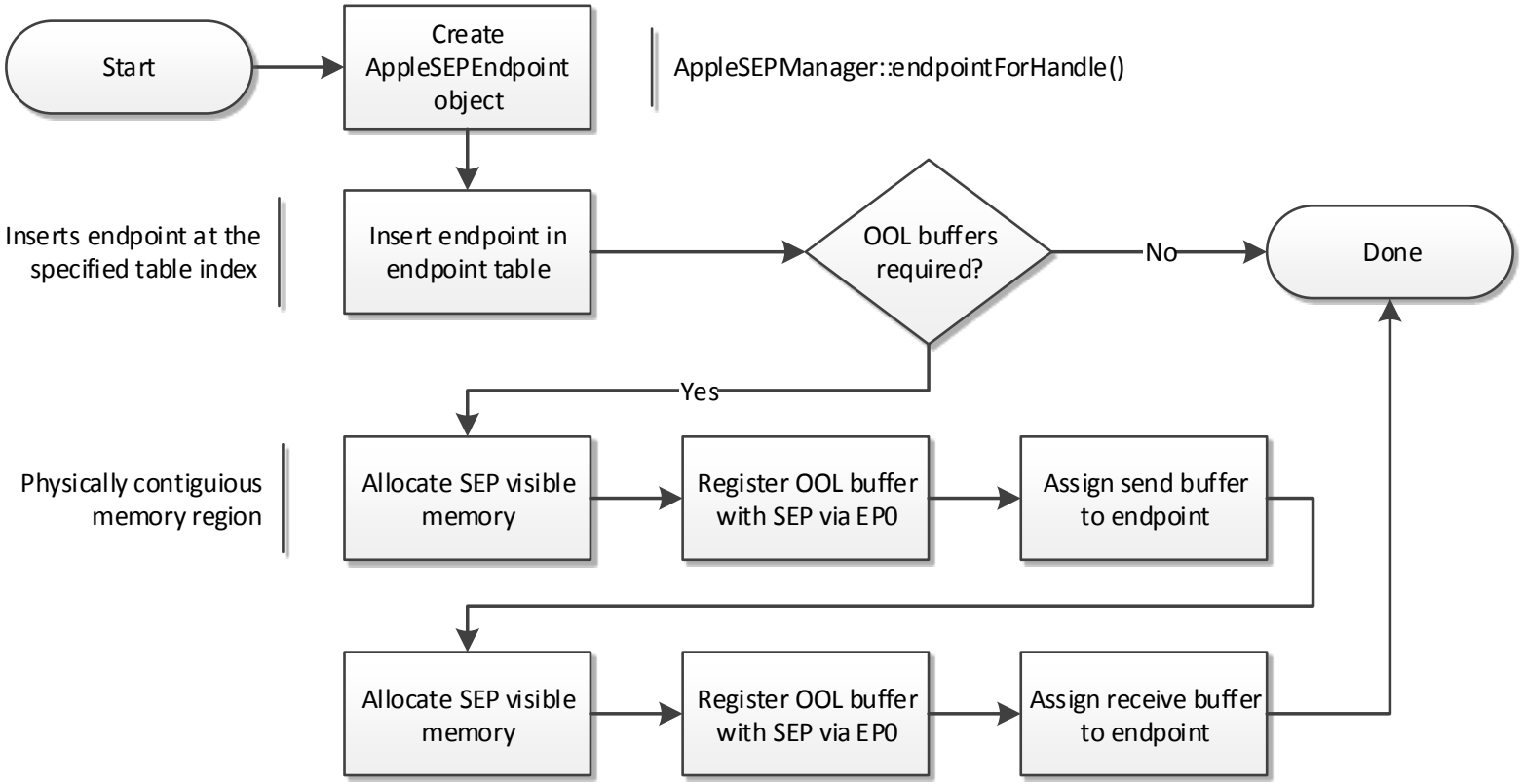
Control Endpoint Opcodes

Opcode	Name	Description
0	NOP	Used to wake up SEP
2	SET_OOL_IN_ADDR	Request out-of-line buffer address
3	SET_OOL_OUT_ADDR	Reply out-of-line buffer address
4	SET_OOL_IN_SIZE	Size of request buffer
5	SET_OOL_OUT_SIZE	Size of reply buffer
10	TTYIN	Write to SEP console
12	SLEEP	Sleep the SEP

Out-of-line Buffers

- Transferring large amounts of data is slow using the interrupt-based mailbox
  - Out-of-line buffers used for large data transfers
- SEP Manager provides a way to allocate SEP visible memory
  - AppleSEPManager::allocateVisibleMemory(…)
  - Actually allocates a portion of physical memory
- Control endpoint is used to assign the request/reply buffer to the target endpoint

Endpoint Registration (AP)



Drivers Using SEP

- Several drivers now rely on the SEP for their operation
- Some drivers previously located in the kernel have had parts moved into the SEP
  - Apple(SEP)KeyStore
  - Apple(SEP)CredentialManager
- Most drivers have a corresponding app in the SEP

SEPOS

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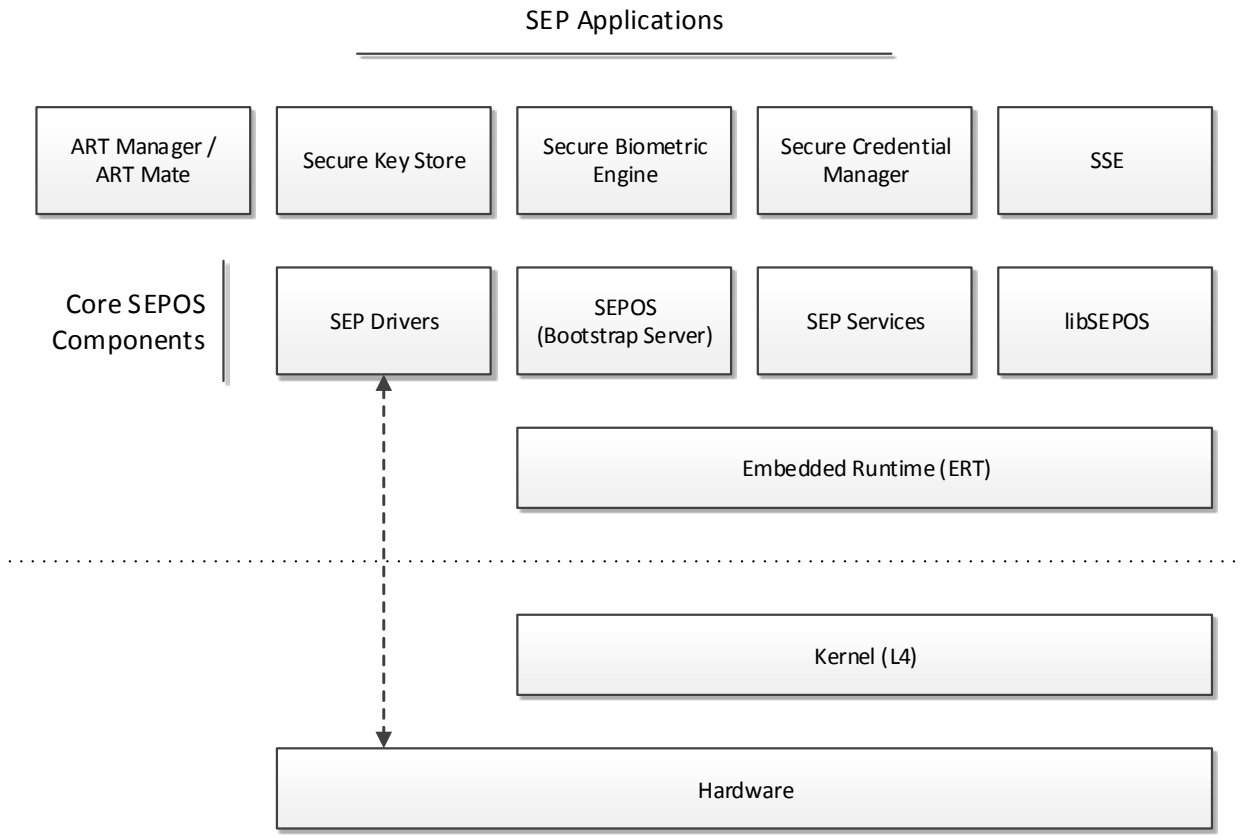
L4

- Family of microkernels
- First introduced in 1993 by Jochen Liedtke
  - Evolved from L3 (mid-1980s)
- Developed to address the poor performance of earlier microkernels
  - Improved IPC performance over L3 by a factor 10-20 faster
- Numerous variants and implementations
  - E.g. L4-embedded optimized for embedded systems

SEPOS

- Based on Darbat/L4-embedded (ARMv7)
  - Custom modifications by Apple
- Implements its own drivers, services, and applications
  - Compiled as macho binaries
- The kernel provides only a minimal set of interfaces
  - Major part of the operating system implemented in user-mode

SEPOS Architecture



Kernel (L4)

- Initializes the machine state to a point where it is usable
  - Initializes the kernel page table
  - Sets up the kernel interface page (KIP)
  - Configures the interrupts on the hardware
  - Starts the timer
  - Initializes and starts the kernel scheduler
  - Starts the root task
- Provides a small set (~20) of system calls

System Calls (1/2)

Num	Name	Description
0x00	L4_Ipc	Set up IPC between two threads
0x00	L4_Notify	Notify a thread
0x04	L4_ThreadSwitch	Yield execution to thread
0x08	L4_ThreadControl	Create or delete threads
0x0C	L4_ExchangeRegisters	Exchange registers wit another thread
0x10	L4_Schedule	Set thread scheduling information
0x14	L4_MapControl	Map or free virtual memory
0x18	L4_SpaceControl	Create a new address space
0x1C	L4_ProcessorControl	Sets processor attributes

System Calls (2/2)

Num	Name	Description
0x20	L4_CacheControl	Cache flushing
0x24	L4_IpcControl	Limit ipc access
0x28	L4_InterruptControl	Enable or disable an interrupt
0x2C	L4_GetTimebase	Gets the system time
0x30	L4_SetTimeout	Set timeout for ipc sessions
0x34	L4_SharedMappingControl	Set up a shared mapping
0x38	L4_SleepKernel	?
0x3C	L4_PowerControl	?
0x40	L4_KernelInterface	Get information about kernel

Privileged System Calls

- Some system calls are considered privileged
  - E.g. memory and thread management calls
- Only root task (SEPOS) may invoke privileged system calls
  - Determined by the space address of the caller
- Check performed by each individual system call where needed
  - is_privileged_space()

Privileged System Calls

```
SYS_SPACE_CONTROL (threadid_t space_tid, word_t control, fpage_t kip_area,
            fpage_t utcb_area)
{
    TRACEPOINT (SYSCALL_SPACE_CONTROL,
         printf("SYS_SPACE_CONTROL: space=%t, control=%p, kip_area=%p, "
                "utcb_area=%p\n",  TID (space_tid),
                control, kip_area.raw, utcb_area.raw));

    // Check privilege
    if (EXPECT_FALSE (! is_privileged_space(get_current_space())))
    {
         get_current_tcb ()->set_error_code (ENO_PRIVILEGE);
         return_space_control(0, 0);
    }

    ...
}
```

Check for root task in L4_SpaceControl system call

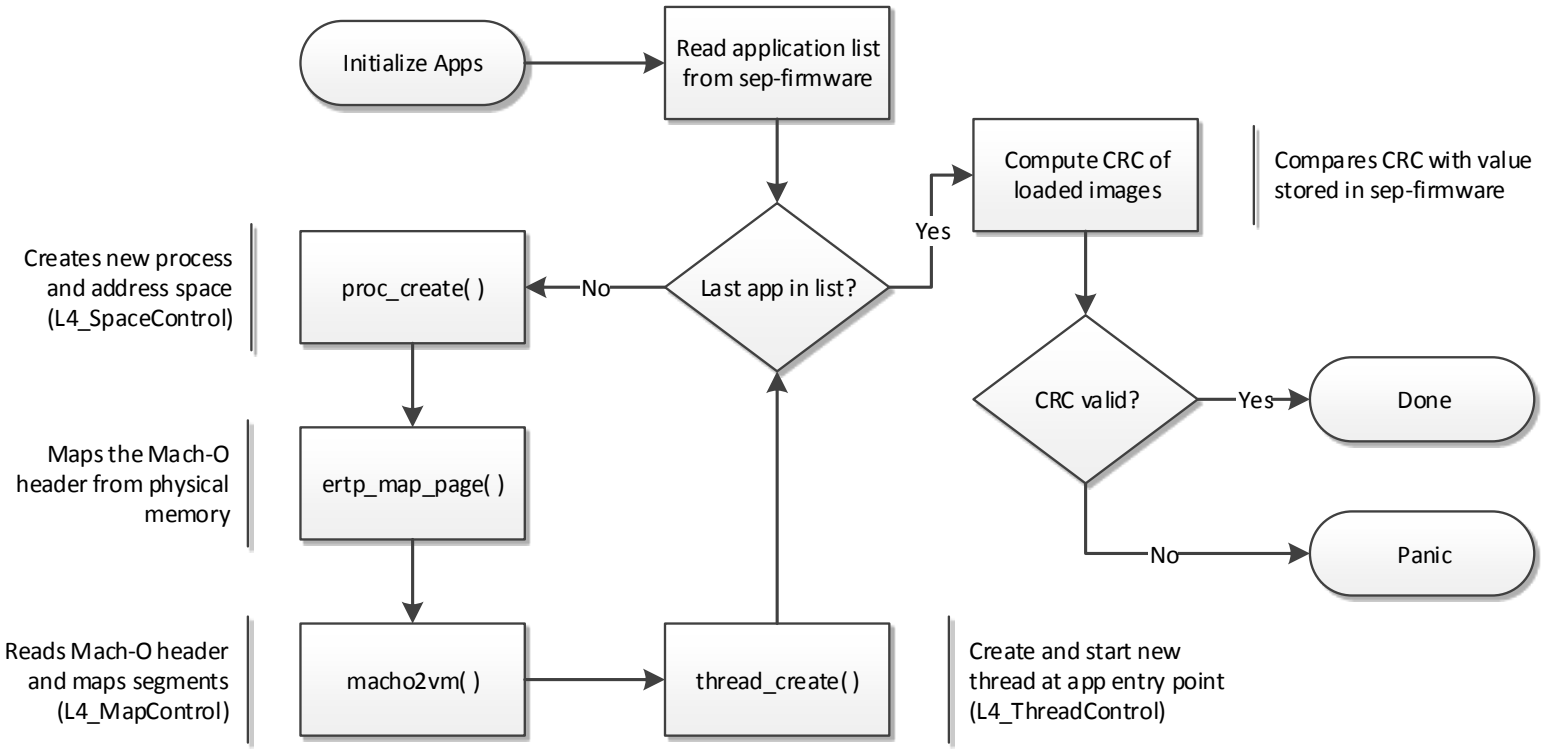
```
INLINE bool is_privileged_space(space_t * space)
{
    return (is_roottask_space(space);
}
```

from darbat 0.2 source

SEPOS (INIT)

- Initial process on boot (root task)
  - Can call any privileged L4 system call
- Initializes and starts all remaining tasks
  - Processes an application list embedded by the sep-firmware
- Maintains a context structure for each task
  - Includes information about the virtual address space, privilege level, threads, etc.
- Invokes the bootstrap server

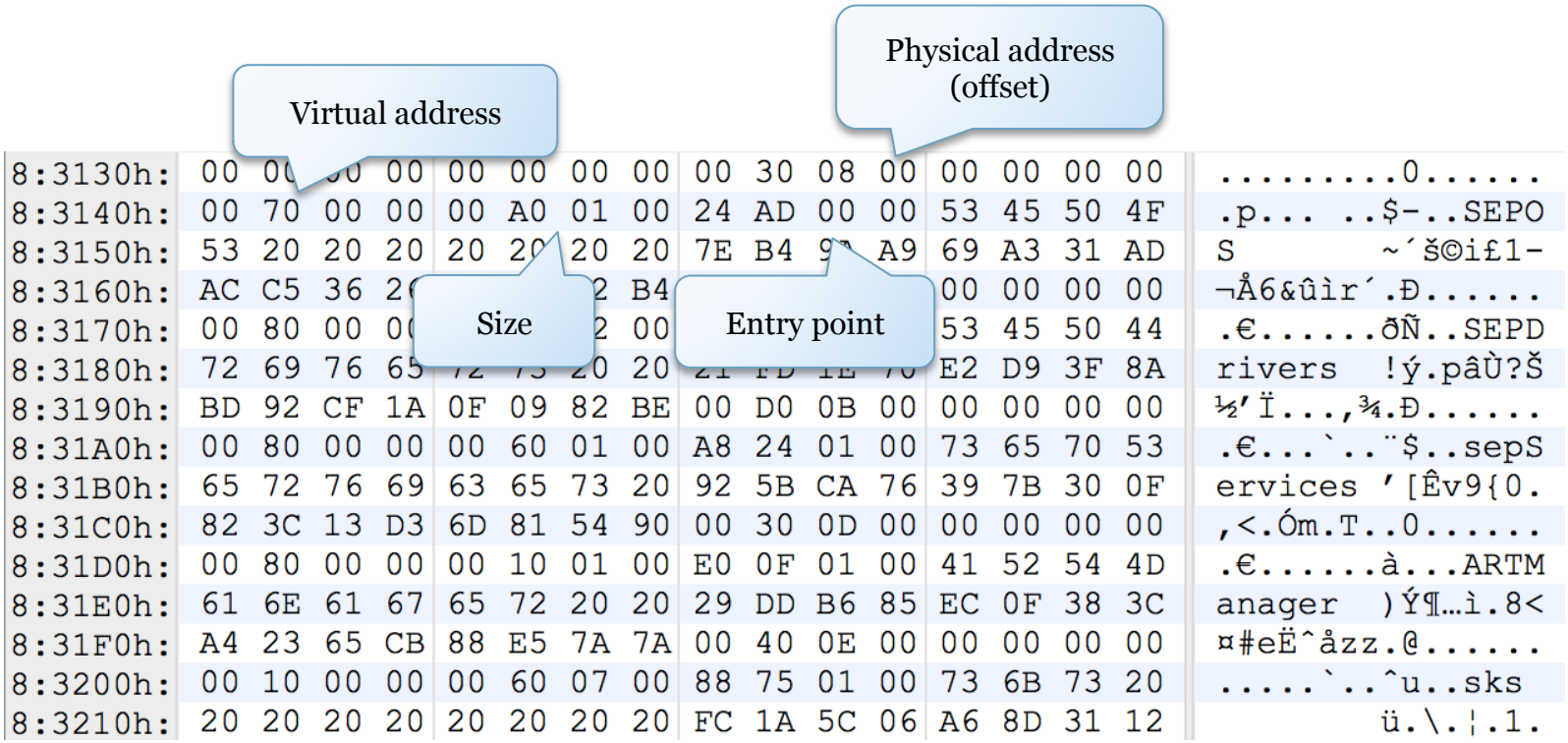
SEPOS App Initialization



Application List

- Includes information about all applications embedded by the SEP firmware
  - Physical address (offset)
  - Virtual base address
  - Module name and size
  - Entry point
- Found 0xEC8 bytes prior to the SEPOS binary in the sep-firmware image

Application List



Bootstrap Server

- Implements the core functionality of SEPOS
  - Exports methods for system, thread and object (memory) management
- Made available to SEP applications over RPC via the embedded runtime
  - ert_rpc_bootstrap_server()
- Enable applications to perform otherwise privileged operations
  - E.g. create a new thread

Privileged Methods

- An application must be privileged to invoke certain bootstrap server methods
  - Query object/process/acl/mapping information
- Privilege level is determined at process creation
  - Process name >= ‘A ‘ and <= ‘ZZZZ’
  - E.g. “SEPD” (SEPDrivers)
- Check is done by each individual method
  - proc_has_privilege(int pid);

sepos_object_acl_info( )

```
int sepos_object_acl_info(int *args)
{
  int result;
  int prot;
  int pid;

  args[18] = 1;
  *((_BYTE *)args + 104) = 1;
  result = proc_has_privilege( args[1] );
  if ( result == 1 )
  {
    result = acl_get( args[5], args[6], &pid, &prot);
    if ( !result )
    {
      args[18] = 0;
      args[19] = prot;
      args[20] = pid;
      result = 1;
      *((_BYTE *)args + 104) = 1;
    }
  }
  return result;
}
```

Call to check if sender's pid is privileged

Entitlements

- Some methods also require special entitlements
  - sepos_object_create_phys()
  - sepos_object_remap()
- Seeks to prevent unprivileged applications from mapping arbitrary physical memory
- Assigned to a process on launch
  - Separate table used to determine entitlements

Entitlement Assignment

```
int proc_create( int name )
{
    int privileged = 0;

    ...

    if ( ( name >= 'A   ' ) && ( name <= 'ZZZZ' ) )
        privileged = 1;

    proctab[ pid ].privileged   = privileged;
    proctab[ pid ].entitlements = 0;

    while ( privileged_tasks[ 2 * i ] != name )
        if ( ++i == 3 )
            return pid;

    proctab[ pid ].entitlements = privileged_tasks[ 2 * i + 1 ];

    return pid;
}
```

```
; _DWORD privileged_tasks[10]
privileged_tasks DCD 'SEPD'
; int[]
                 DCD 2
                 DCD 'ARTM'
                 DCD 6
                 DCD 'Debu'
                 DCD 6
                 DCD 0
                 DCD 0
```

Entitlement Assignment

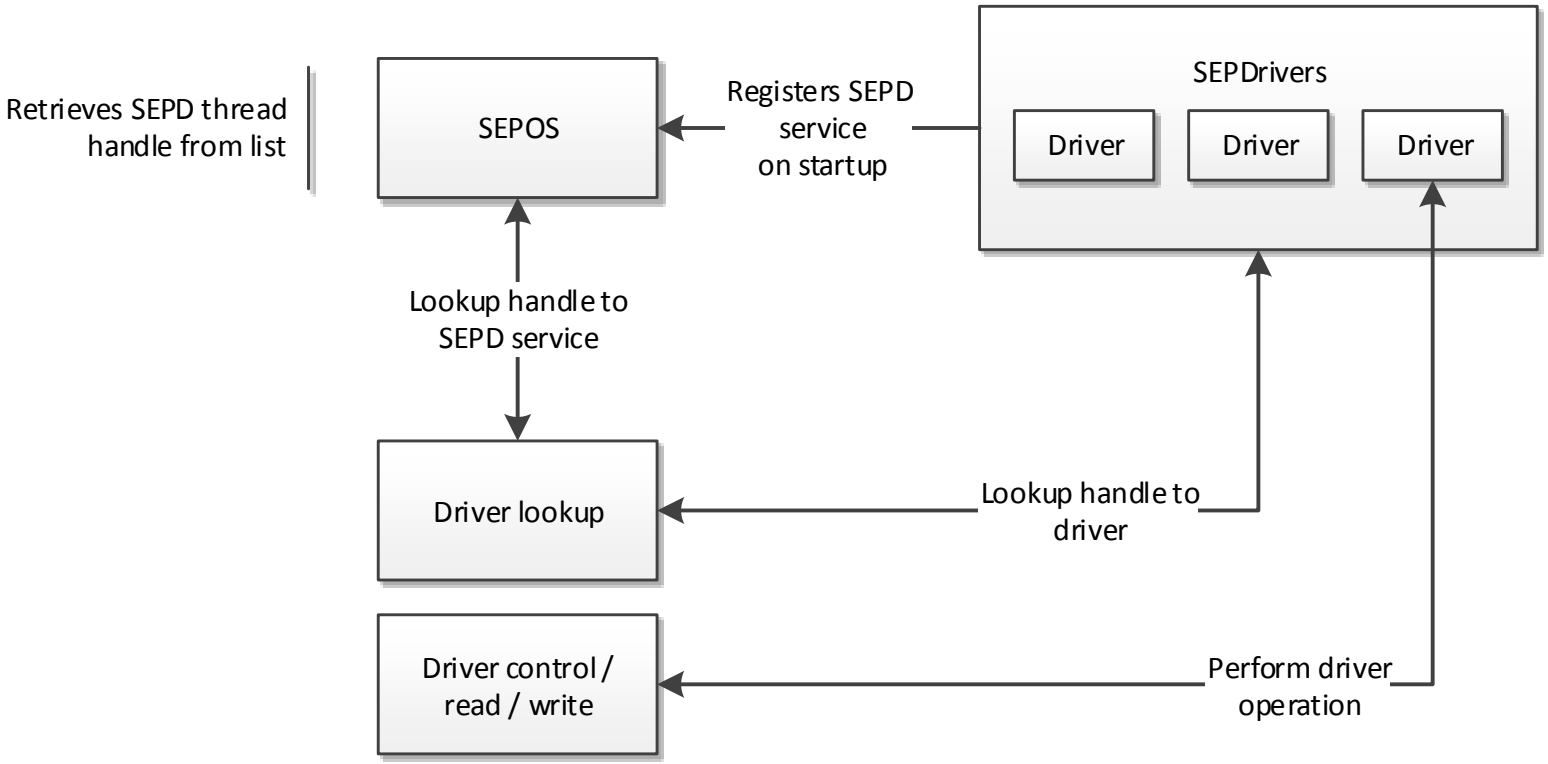
Task Name	Entitlements
SEPDrivers	MAP_PHYS
ARTManager/ARTMate	MAP_PHYS | MAP_SEP
Debug	MAP_PHYS | MAP_SEP

- MAP_PHYS (2)
  - Required in order to access (map) a physical region
- MAP_SEP (4)
  - Same as above, but also needed if the physical region targets SEP memory

SEP Drivers

- Hosts all SEP drivers
  - AKF, TRNG, Expert, GPIO, PMGR, etc.
  - Implemented entirely in user-mode
- Maps the device I/O registers for each driver
  - Enables low-level driver operations
- Exposed to SEP applications using a dedicated driver API
  - Includes functions for lookup, control, read, and write

Driver Interaction



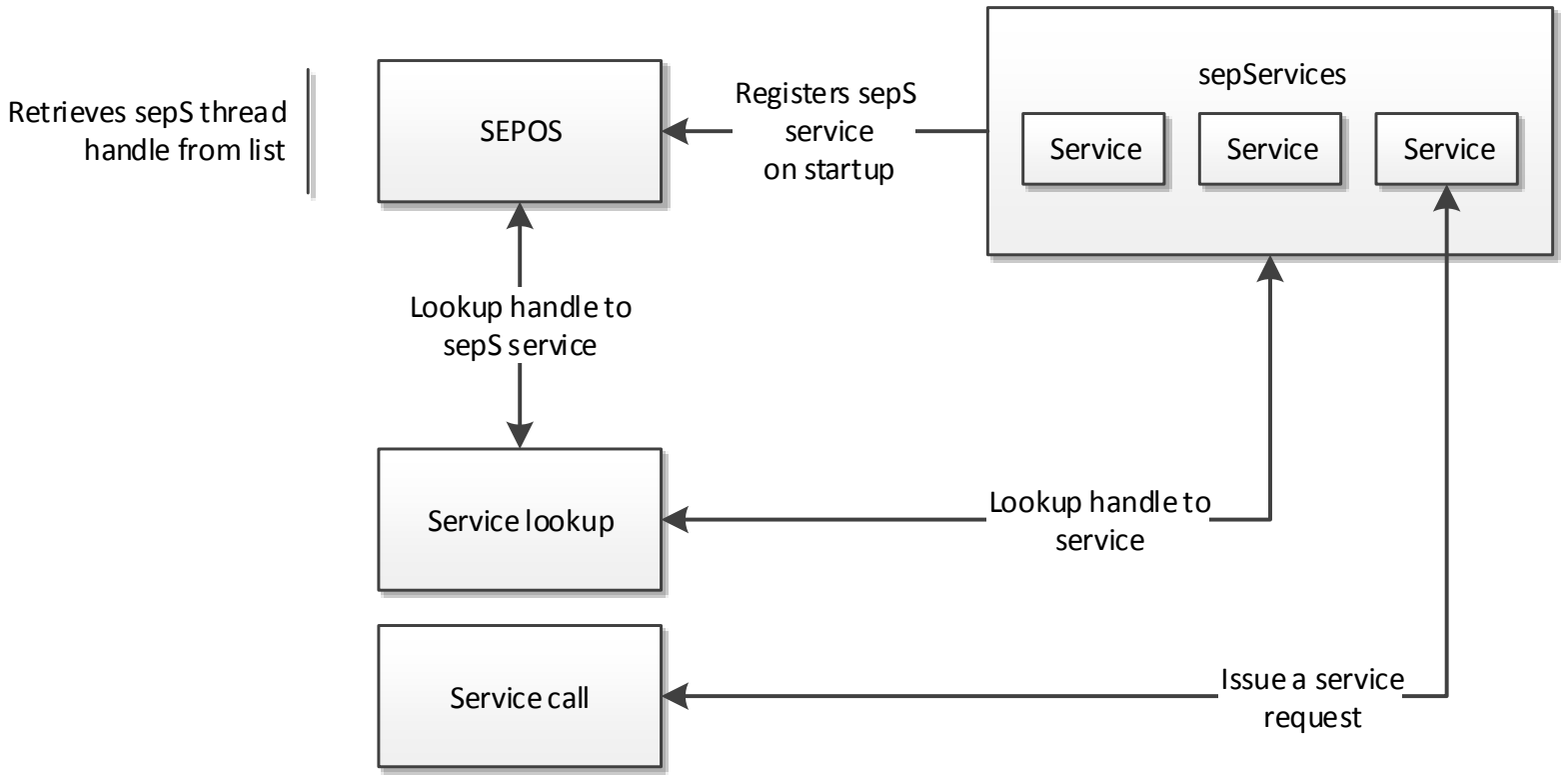
AKF Driver

- Manages AP/SEP endpoints in SEPOS
- Handles control (EP0) requests
  - E.g. sets up objects for reply and response OOL buffers
- SEP applications may register new endpoints to handle specific AP requests
  - AKF_ENDPOINT_REGISTER (0x412C) control request

SEP Services

- Hosts various SEP related services
  - Secure Key Generation Service
  - Test Service
  - Anti Replay Service
  - Entitlement Service
- Usually implemented on top of drivers
- Service API provided to SEP applications
  - service_lookup(…)
  - service_call(…)

Service Interaction



SEP Applications

- Primarily designed to support various drivers running in the AP
  - AppleSEPKeyStore → sks
  - AppleSEPCredentialManager → scrd
- Some apps are only found on certain devices
  - E.g. SSE is only present on iPhone 6 and later
- May also be exclusive to development builds
  - E.g. Debug application

Attacking SEP

Demystifying the Secure Enclave Processor

Attack Surface: SEPOS

- Mostly comprises the methods in which data is communicated between AP and SEP
  - Mailbox (endpoints)
  - Shared request/reply buffers
- Assumes that an attacker already has obtained AP kernel level privileges
  - Can execute arbitrary code under EL1

Attack Surface: AKF Endpoints

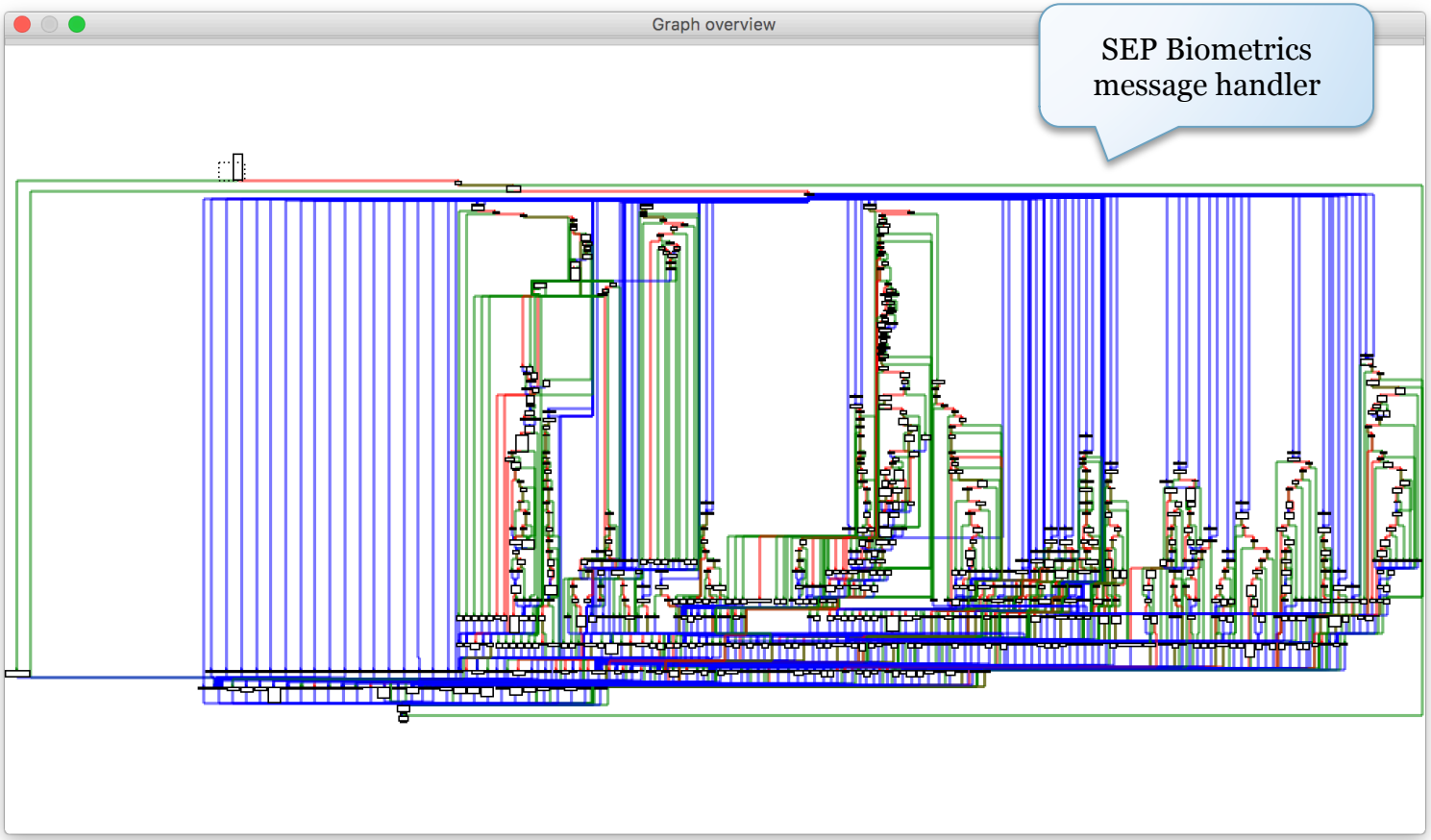
- Every endpoint registered with AKF is a potential target
  - Includes both SEP drivers and applications
- Does not require an endpoint to be registered with the SEP Manager (AP)
  - Can write messages to the mailbox directly
  - Alternatively, we can register our own endpoint with SEP Manager

Attack Surface: AKF Endpoints

Endpoint	Owner	OOL In	OOL Out	Notes
0	SEPD/ep0			
1	SEPD/ep1		✓	
2	ARTM	✓	✓	iPhone 6 and prior
3	ARTM	✓	✓	iPhone 6 and prior
7	sks	✓	✓	
8	sbio/sbio	✓	✓	
10	scrd/scrd	✓	✓	
12	sse/sse	✓	✓	iPhone 6 and later

List of AKF registered endpoints (iOS 9) and their use of out-of-line request and reply buffers

Attack Surface: Endpoint Handler



Attack Robustness

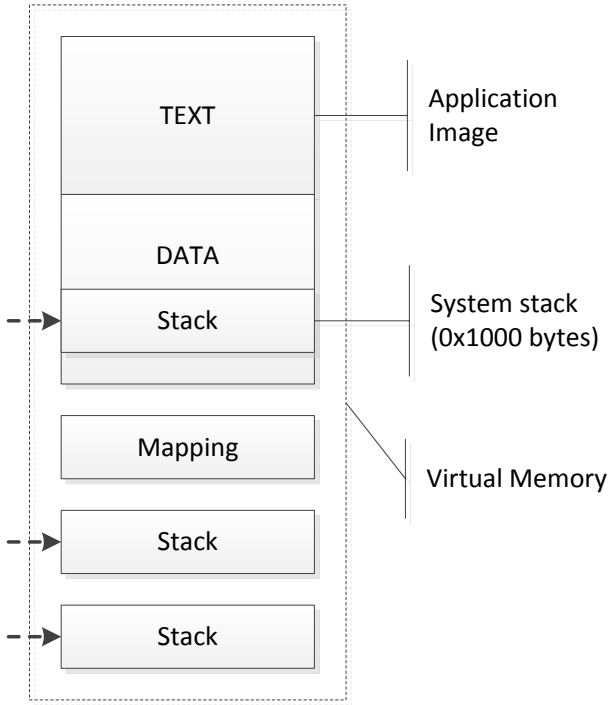
- How much effort is required to exploit a SEP vulnerability?
  - E.g. stack/heap corruption
- Determined by several factors
  - Address space layout
  - Allocator (heap) hardening
  - Exploit mitigations
  - And more

Address Space Layout

- SEP applications are loaded at their preferred base address
  - No image base randomization
  - Typically based at 0x1000 or 0x8000 (depending on presence of pagezero segment)
- Segments without a valid memory protection mask (!= 0) are ignored
  - E.g. __PAGEZERO is never “mapped”

Stack Corruptions

- The main thread of a SEP application uses an image embedded stack
  - A corruption could overwrite adjacent DATA segment data
- Thread stacks of additional threads spawned by SEPOS are mapped using objects
  - Allocated with gaps → "guard pages"



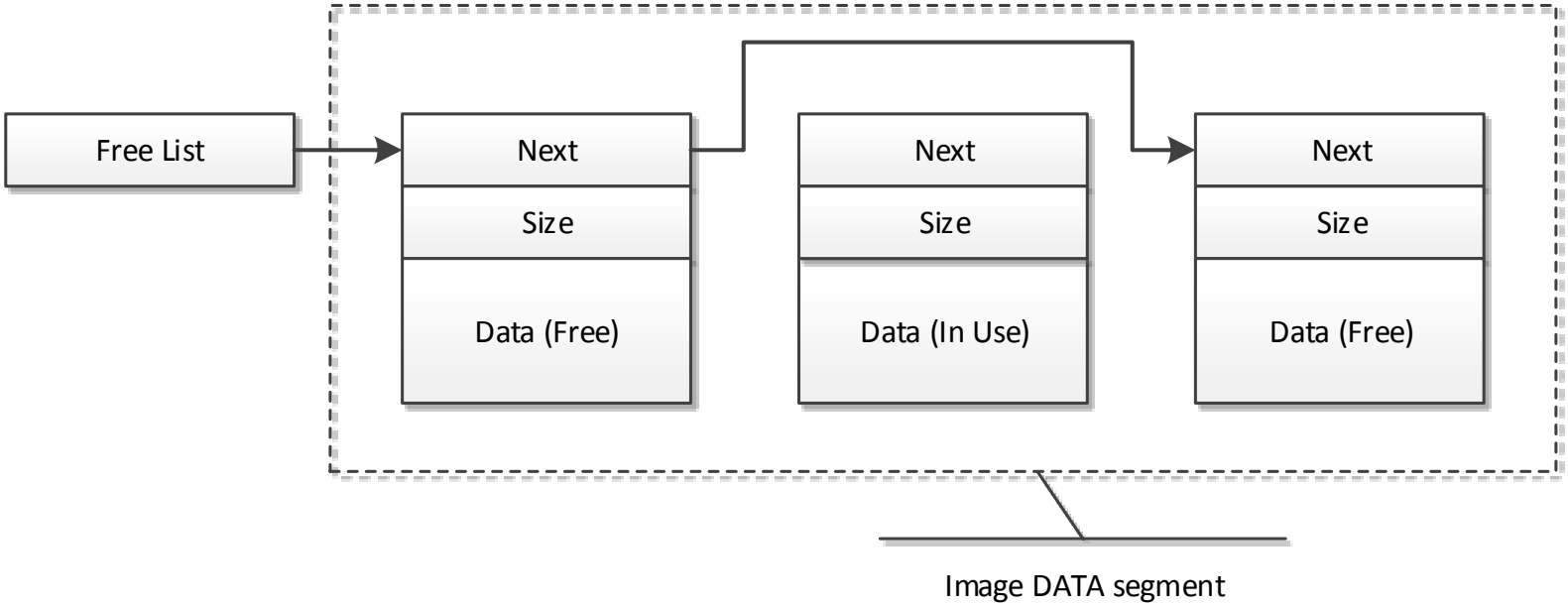
Stack Corruptions

- SEP applications are compiled with stack cookie protection
  - Cookie value is fixed to ‘GARD’
  - Trivial to forge/bypass
- Stack addresses are in most cases known
  - Main thread stack is at a known address
  - Addresses of subsequent thread stacks are predictable

Heap Corruptions: malloc()

- Runtime allocator leveraged by SEP applications
  - K&R implementation
- Singly linked free list (ordered by size) with header that includes pointer and block size
  - struct Header { void * ptr, size_t size };
  - Coalesces adjacent elements on free()
- Size of heap determined on initialization
  - malloc_init(malloc_base, malloc_top);
  - Non-expandable

Heap Corruptions: malloc()



Heap Corruptions: malloc()

- No protection of heap metadata
  - Free list pointers can be overwritten
  - Block size can be corrupted
- Allocation addresses are predictable
  - Malloc area embedded by ___DATA segment in application image
  - Allocations made in sequential order

No-Execute Protection

- SEPOS implements no-execute protection
- Always set when a page is not marked as executable
  - space_t::map_fpage()
  - Sets both XN and PXN bits in page table entries
- Non-secure (NS) bit also set for all pages outside SEP memory region

SEPOS Mitigations Summary

Mitigation	Present	Notes
Stack Cookie Protection	Yes (…)	'GARD' – mostly ineffective
Memory Layout Randomization		
User	No	
Kernel	No	Image base: 0xF0001000
Stack Guard Pages	Yes/No	Not for main thread
Heap Metadata Protection	No	
Null-Page Protection	No	Must be root task to map page
No-Execute Protection	Yes	Both XN and PXN

Attack Surface: BootROM

- Effectively only two major attack surfaces
  - IMG4 Parser
    - Memory Corruption
    - Logic Flaws
  - Hardware based
- Only minor anti-exploit mitigations present
  - No ASLR
  - Basic stack guard
  - One decent bug = game over

Attacking IMG4

- ASN.1 is a very tricky thing to pull off well
  - Multiple vulns in OpenSSL, NSS, ASN1C, etc
- LibDER itself actually rather solid
  - "Unlike most other DER packages, this one does no malloc or copies when it encodes or decodes"
    – LibDER's readme.txt
  - KISS design philosophy
- But the wrapping code that calls it may not be
  - Audit seputil and friends
  - Code is signifigantly more complex then libDER itself

Attack Surface: Hardware

- Memory corruption attacks again data receivers on peripheral lines
  - SPI
  - I2C
  - UART
- Side Channel/Differential Power Analysis
  - Stick to the A7 (newer ones are more resistant)
- Glitching
  - Standard Clock/Voltage Methods
  - Others

External RAM

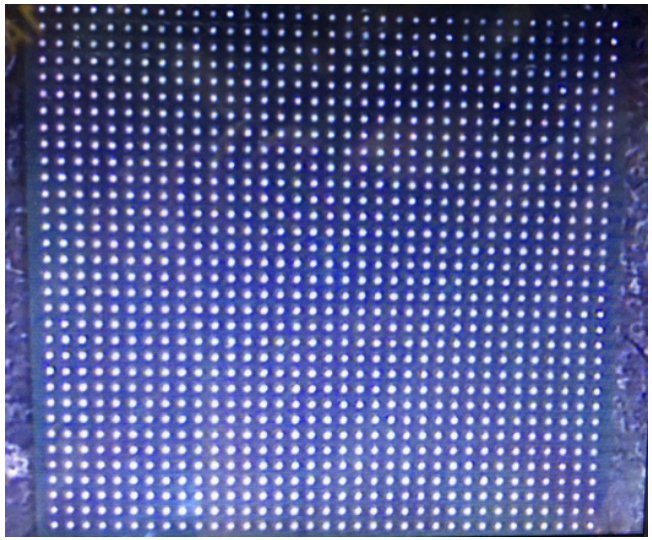
- Encrypted memory has no validation.
  - Can corrupt bits of SEP memory
- When generating the encryption key the "random component" is temporarily stored unencrypted in external RAM.
  - This may allow an attacker to influence generation of the final memory encryption key

Attacking the Fuse Array

- Potentially one of the most invasive attack vectors
  - Requires a lot of patience
  - High likelihood of bricking
- Laser could be used
  - Expensive method - not for us
- Primary targets
  - Production Mode
  - Security Mode

End Game: JTAG

- Glitch the fuse sensing routines
  - Requires a 2000+ pin socket
  - Need to bypass CRC and fuse sealing
  - “FSRC” Pin - A line into fuse array?



A8 SoC Pins

- Attack the IMG4 Parser
  - What exactly do DSEC and DPRO really do?

Conclusion

Demystifying the Secure Enclave Processor

Conclusion

- SEP(OS) was designed with security in mind
  - Mailbox interface
  - Privilege separation
- However, SEP(OS) lacks basic exploit protections
  - E.g. no memory layout randomization
- Some SEP applications expose a significant attack surface
  - E.g. SEP biometrics application

Conclusion (Continued)

- Overall hardware design is light years ahead of competitors
  - Hardware Filter
  - Inline Encrypted RAM
  - Generally small attack surface
- But it does have its weaknesses
  - Shared PMGR and PLL are open to attacks
  - Inclusion of the fuse source pin should be re-evaluated
  - The demotion functionality appears rather dangerous
    - Why does JTAG over lightning even exist?

Thanks!

- Ryan Mallon
- Daniel Borca
- Anonymous reviewers

Bonus Slides

Demystifying the Secure Enclave Processor

SEPOS: System Methods

Class	Id	Method	Description	Priv
0	0	sepos_proc_getpid()	Get the process pid	
0	1	sepos_proc_find_service()	Find a registered service by name	
0	1001	sepos_proc_limits()	Query process limit information	x
0	1002	sepos_proc_info()	Query process information	
0	1003	sepos_thread_info()	Query information for thread	
0	1004	sepos_thread_info_by_tid()	Query information for thread id	
0	1100	sepos_grant_capability()	-	x
0	2000	sepos_panic()	Panic the operating system	

SEPOS: Object Methods (1/2)

Class	Id	Method	Description	Priv
1	0	sepos_object_create()	Create an anonymous object	
1	1	sepos_object_create_phys()	Create an object from a physical region	x (*)
1	2	sepos_object_map()	Map an object in a task's address space	
1	3	sepos_object_unmap()	Unmap an object (not implemented)	
1	4	sepos_object_share()	Share an object with a task	
1	5	sepos_object_access()	Query the access control list of an object	
1	6	sepos_object_remap()	Remap the physical region of an object	x (*)
1	7	sepos_object_share2()	Share manifest with task	

SEPOS: Object Methods (2/2)

Class	Id	Method	Description	Priv
1	1001	sepos_object_object_info()	Query object information	x
1	1002	sepos_object_mapping_info()	Query mapping information	x
1	1003	sepos_object_proc_info()	Query process information	x
1	1004	sepos_object_acl_info()	Query access control list information	x

SEPOS: Thread Methods

Class	Id	Method	Description	Priv
2	0	sepos_thread_create()	Create a new thread	
2	1	sepos_thread_kill()	Kill a thread (not implemented)	
2	2	sepos_thread_set_name()	Set a service name for a thread	
2	3	sepos_thread_get_info()	Get thread information	