Introduction

Trusted Computing Base (TCB)

- Base components that enforce the fundamental protection mechanisms on a computing system
  - Hardware
  - Firmware
  - Software

- TCB vulnerabilities potentially affect the security of the entire system

TCB by TCSEC (Trusted Computer System Evaluation Criteria, aka Orange Book)

The totality of protection mechanisms within a computing system – including hardware, firmware, and software – the combination of which is responsible for enforcing a computer security policy.

A TCB consists of one or more components that together enforce a unified security policy over a product or system.

The ability of a trusted computing base to correctly enforce a security policy depends solely on the mechanisms within the TCB and on the correct input by system administrative personnel of parameters (e.g., a user's clearance) related to the security policy.

TCB by MITRE

Nibaldi, G. H. *Specification of a trusted computing base (TCB)*. MITRE CORP BEDFORD MA, 1979.

A TCB is a hardware and software access control mechanism that establishes a protection environment to control the sharing of information in computer systems. A TCB is an implementation of a reference monitor, […], that controls when and how data is accessed.

TCB fundamental components

- CPU security mechanisms
  - Protection rings
  - Virtualization
  - Other mechanisms
    - E.g. Intel SGX enclaves, etc.

- Operating system security model
  - Computational model
  - Access rights and privileges

TEE (Trusted Execution Environment)

- ▷ Isolated, secure execution environment
- ▷ CPU support
  - ARM TrustZone
- ▷ TEE implementations
  - On-board Credentials (Microsoft/Nokia)
  - <t-base (Trustonic)
  - SecuriTEE (Solacia)
  - QSEE (Qualcomm's Secure Execution Environment)
  - SierraTEE (Sierrawave, open-source)
  - OP-TEE (Linaro, open-source)

Can you trust the operating system?

- Can you trust your operating system if you do not control (or trust) the way it booted?

- Secure bootstrapping
  - TPM attestation
  - UEFI secure boot

- Remote attestation
  - TPM attestation

Can you trust the operating system?

- How can you protect your computation if you don’t trust the operating system?

- Intel SGX (Secure Guard eXtensions)
  - Allow user applications to protect code and data from others within enclaves
  - Enclaves are not observable by code running with different privileges
    - OS kernels, hypervisors, etc.

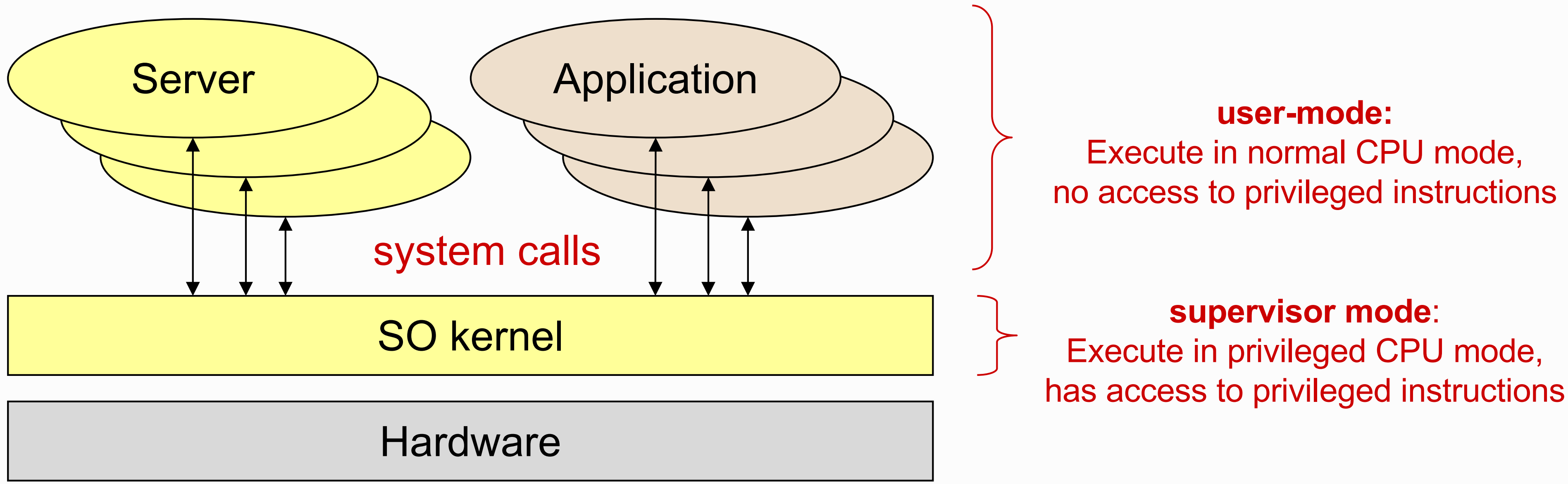
Protection from untrusted code: sandboxes

- Executing applications have a set of privileges and a view over a set of resources

- Sandboxes allow the execution of applications with less privileges or less resources
  - e.g. forbid remote communications
  - e.g. hide the majority of the file system
  - e.g. allow volatile system changes

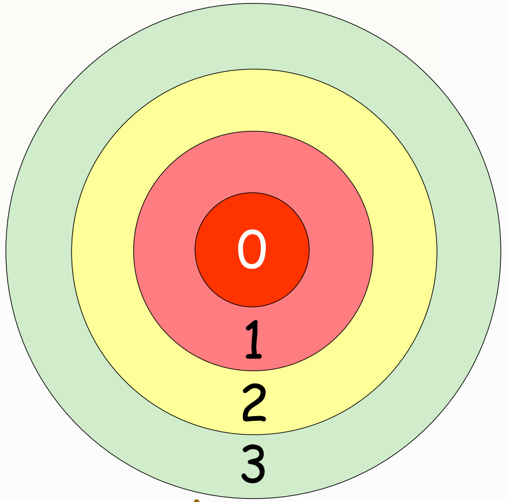
Security in Operating Systems

Operating system



- ▷ Kernel mission
  - Virtualize the hardware
    - Computational model
  - Enforce protection policies and provide protection mechanisms
    - Against involuntary mistakes
    - Against non-authorized activities

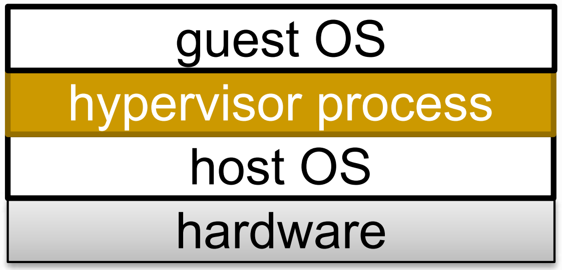
Protection rings



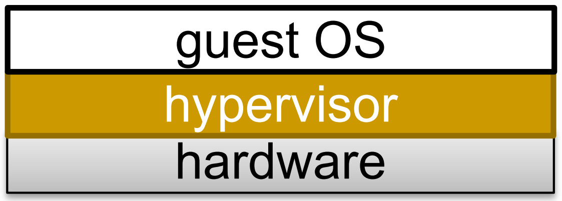
- Different levels of privilege
  - Forming a set of concentric rings
  - Used by CPU's to prevent non-privileged code from running privileged instructions
    - e.g. IN/OUT, TLB manipulation
- Nowadays processors have 4 rings
  - But OS's usually use only two of them
    - 0 (supervisor/kernel mode) and 3 (user-mode)
- Transfer of control between rings requires special gates
  - The ones that are used by system calls (syscalls)

Virtual machines and hypervisors

- Emulation of a particular (virtual) hardware with the existing one (real)



- Hosted virtualization
  - The hypervisor is a process of a given OS (host)
  - The VM runs inside the virtualizer (guest OS)

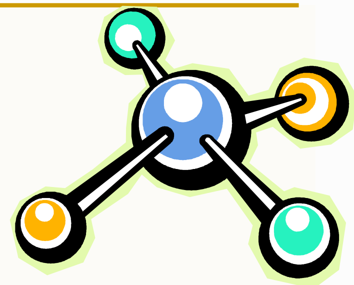


- Bare-metal virtualization
  - The hypervisor runs on top of the host hardware

Execution of virtual machines

- Common approach for hosted virtualization
  - Software-based virtualization
  - Direct execution of guest user-mode code
  - Binary, on-the-fly translation of privileged code (full virtualization)
    - Guest OS kernels remain unchanged
    - No direct access to the host hardware
- Hardware-assisted virtualization (bare-metal)
  - Full virtualization
  - There is a ring -1 below ring 0
    - Hypervisor (or Virtual Machine Monitor, VMM)
  - It can virtualize hardware for many ring 0 kernels
    - No need of binary translation
    - Guest OS's run faster

Computational model



- Set of entities (objects) managed by the OS kernel
  - High-level abstractions supported transparently by low-level mechanisms

- Processes
- User identifiers
  - Users
  - Groups
- Virtual memory
- Files and file systems
  - Directories
  - Files
  - Special files
- Communication channels
  - Pipes
  - Sockets
  - Etc.

- Physical devices
  - Storage
    - Tapes
    - Magnetic disks
    - Optical disks
    - SSD
  - Network interfaces
    - Wired, wireless
  - Human-computer interfaces
    - Keyboards
    - Graphical screens
    - Text consoles
    - Mice
  - Serial/parallel I/O interfaces
    - USB
    - Serial & parallel ports
    - Bluetooth

Computational model: User identifiers

- For the OS kernel a user is a number
  - Established during a login operation
  - User ID (UID)

- All activities are executed on a computer on behalf of a UID
  - The UID allows the kernel to assert what is allowed/denied to processes
  - Linux: UID 0 is omnipotent (root)
    - Administration activities are usually executed with UID 0
  - Windows: concept of privileges
    - For administration, system configuration, etc.
    - There is no unique, well-known identifier for an administrator
    - Administration privileges can be bound to several UIDs
      - Usually through administration groups
      - Administrators, Power Users, Backup Operators
  - Linux: concept of capabilities (similar to privileges)

Computational model: Group identifiers

- Groups also have an identifier
  - A group is a set of users
  - A group can be defined by including other groups
  - Group ID (GID)
- A user can belong to several groups
  - Actual user rights = UID rights + rights of his groups' GIDs
- In Linux all activities are executed on behalf of a set of groups
  - Primary group
    - Typically used for setting file protection
  - Secondary groups

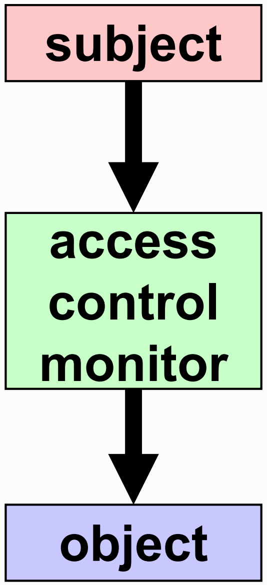
Computational model: Processes

- A process defines the context of an activity
  - For taking security-related decisions
  - For other purposes (e.g. scheduling)

- Security-related context
  - Identity (UID and GIDs)
    - Fundamental for enforcing access control
  - Resources being used
    - Open files
      - Including communication channels
    - Reserved virtual memory areas
    - CPU time used

Access control

- The OS kernel is an access control monitor
  - Controls all interactions of subjects with protected objects
- Objects
  - Hardware
  - Entities of the computational model
- Subjects
  - Usually local processes
    - Through the system call API
    - A system call (or syscall) is not an ordinary function call
  - But also messages from other hosts



Mandatory access controls

- OS kernels have plenty mandatory access control policies
  - They are part of the computational model logic
  - They cannot be overruled not even by administrators
    - Unless they change the OS kernel behavior
- Examples:
  - Kernel runs in CPU privileged modes, user applications run in non-privileged modes
  - Separation of virtual memory areas
  - Inter-process signaling
  - Interpretation of files' access control protections

Protection with ACLs (Access Control Lists)

- Each object has an ACL
  - It says which subjects can do what
- An ACL can be discretionary or mandatory
  - When mandatory it cannot be modified
  - When discretionary it can be tailored
- An ACL is checked when an activity, on behalf of a subject, wants to manipulate the object
  - If the manipulation request is not authorized by the ACL, the access is denied
  - The OS kernel is responsible for enforcing ACL-based protection

Protection with capabilities

- Less common in normal OS kernels
  - Though there are some good examples
- Example: open file descriptors
  - Applications' processes indirectly manipulate (open) files through file descriptors kept by the OS kernel
    - File descriptors are referenced using integer indexes (aka file descriptors for simplicity…)
    - The OS kernel has full control over the contents of open file descriptors
  - Access to open file descriptors can only be granted to other processes through the OS kernel
    - Not really a usual operation, but possible!
  - Changes in the protection of files does not impact existing open file descriptors
    - The access rights are evaluated and memorized when the file is open

Unix file protection ACLs: Fixed-structure, discretionary ACL

- Each file system object has an ACL
  - Binding 3 rights to 3 subjects
  - Only the owner can update the ACL

- Rights: R W X
  - Read (file data) / List directory
  - Write (file data) / create or remove files or subdirectories
  - Execute / use as process' current working directory

- Subjects:
  - An UID (owner)
  - A GID
  - Others

Windows NTFS file protection: Variable-size, discretionary ACLs

- Each file system object has an ACL and a owner
  - 13 types of access rights
  - Variable-size list of subjects
  - Owner can be an UID or a GID
  - Owner has no special rights over the object or its ACL
    - But usually file creators are their initial owners and have Change Permissions rights
- Subjects:
  - Users (UIDs)
  - Groups (GIDs)
    - The group “Everyone” stands for anybody

- Access rights:

File	Directory (folder)
Read (data)	List (files / folders)
Write (data)	Create (files)
Append (data)	Create (folders)
Execute	Traverse
Delete (file)	Delete (folder)
	Delete (files and subfolders)
Read attributes / extended attributes	
Write attributes / extended attributes	
Read permissions	
Change permissions	
Take ownership	

Unix file protection ACLs: Special protection bits

- Set-UID bit
  - Is used to change the UID of processes executing the file

```
creator:Pictures$ ls -la /usr/bin/passwd
-rwsr-xr-x 1 root root 59640 Mar 22  2019 /usr/bin/passwd
```

- Set-GID bit
  - Is used to change the GID of processes executing the file

```
creator:Pictures$ ls -la /usr/bin/at
-rwsr-sr-x 1 daemon daemon 51464 Feb 20  2018 /usr/bin/at
```

- Sticky bit
  - Hint to keep the file/directory as much as possible in memory cache

```
creator:Pictures$ ls -la /tmp
total 108
drwxrwxrwt 25 root    root    4096 Dec 15 13:12 .
```

Privilege elevation: Set-UID mechanism

- It is used to change the UID of a process running a program stored on a Set-UID file
  - If a program file is owned by UID X and the set-UID bit of its ACL is set, then it will be executed in a process with UID X
    - Independently of the UID of the subject that executed the program
- Used to allow normal users to execute privileged tasks encapsulated in administration programs
  - Change the user's password (passwd)
  - Change to super-user mode (su, sudo)
  - Mount devices (mount)

Privilege elevation: Set-UID mechanism (cont.)

- Effective UID / Real UID
  - Real UID is the UID of the process creator
    - App launcher
  - Effective UID is the UID of the process
    - The one that really matters for defining the rights of the process

- UID change
  - Ordinary application
    - eUID = rUID = UID of process that executed **exec**
    - eUID cannot be changed (unless = 0)
  - Set-UID application
    - eUID = UID of **exec**’d application file, rUID = initial process UID
    - eUID can revert to rUID
  - rUID cannot change

Privilege elevation: Set-UID/Set-GID decision flowchart

- exec (path, ...)
  - File referred by path has Set-UID?
  - Yes
    - ID = path owner
    - Change the process effective UID to ID
  - No
    - Do nothing
  - File referred by path has Set-GID?
  - Yes
    - ID = path GID
    - Change the process GID to ID only
  - No
    - Do nothing

Privilege elevation: sudo mechanism

- Administration by root is not advised
  - One “identity”, many people
  - Who did what?
- Preferable approach
  - Administration role (uid = 0), many users assume it
    - Sudoers
    - Defined by a configuration file used by sudo
- sudo is a Set-UID application with UID = 0
  - Logging can take place on each command ran with sudo

Privilege reduction: chroot mechanism (or jail)

- Used to reduce the visibility of a file system
  - Each process descriptor has a root i-node number
    - From which absolute pathname resolution takes place
  - chroot changes it to an arbitrary directory
    - The process' file system view gets reduced

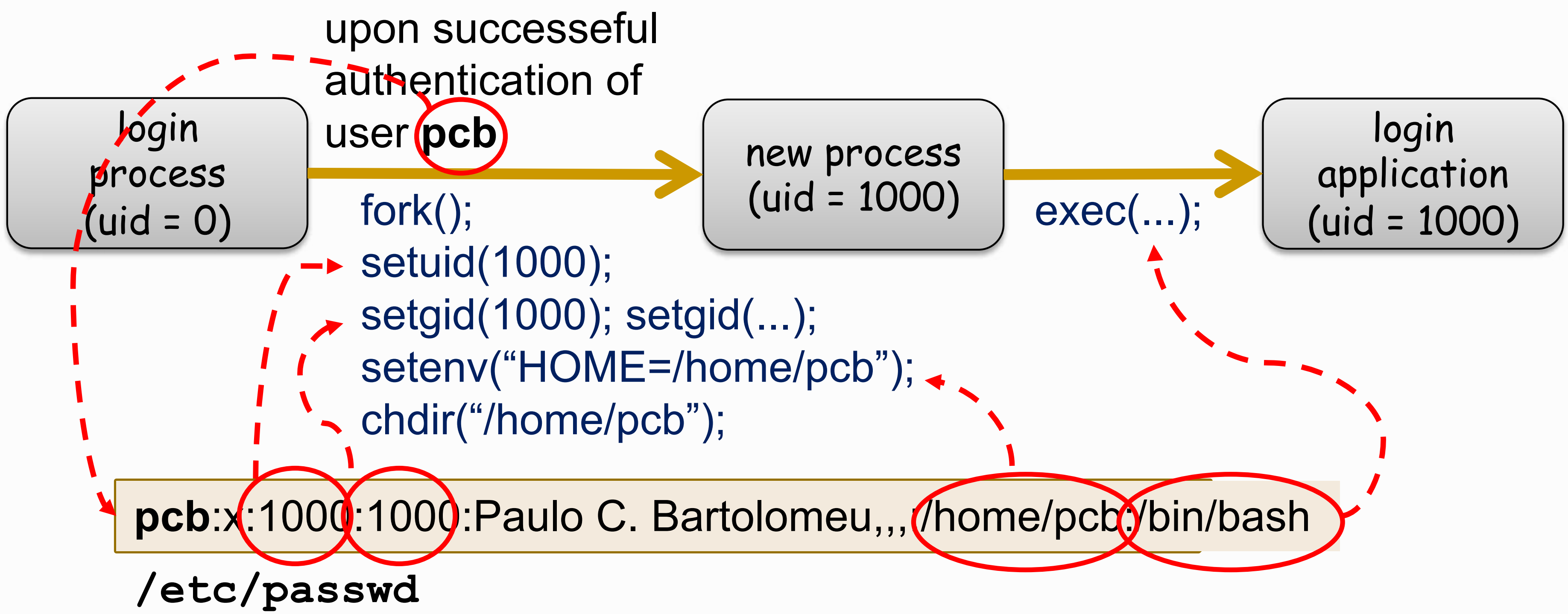
- Used to protect the file system from potentially problematic applications
  - e.g. public servers, downloaded applications
  - But it is not bullet proof!

Linux login: Not an OS kernel operation

- ▷ A privileged login application presents an interface for getting users' credentials
  - A username/password pair
  - Biometric data
  - Smartcard and activation PIN
- ▷ The login application validates the credentials and fetches the appropriate UID and GIDs for the user
  - And starts an initial user application on a process with those identifiers
    - In a Linux console this application is a shell (sh, bash, csh, tcsh, zsh, etc.)
  - When this process ends the login application reappears
- ▷ Thereafter all processes created by the user have its identifiers
  - Inherited through forks

Linux: from login to session processes

- The login process must be a privileged process
  - Has to create processes with arbitrary UID and GIDs
    - The ones of the entity logging in



Login in Linux: Password validation process

- Username is used to fetch a UID/GID pair from /etc/passwd
  - And a set of additional GIDs in the /etc/group file
- Supplied password is transformed using a digest function
  - Currently configurable, for creating a new user (/etc/login.defs)
  - Its identification is stored along with the transformed password
- The result is checked against a value stored in /etc/shadow
  - Indexed again by the username
  - If they match, the user was correctly authenticated

- File protections
  - /etc/passwd and /etc/group can be read by anyone
    - This is fundamental, for instance, for listing directories (why?)
  - /etc/shadow can only be read by root
    - Protection against dictionary attacks

Virtualization on Intel processors

Modes of operation

- real-address mode
  - mode used on power up or after a hard or soft reset
  - 16-bit registers
  - segmented memory space (16*segment+offset)
- protected mode (rings 0 to 3, Intel calls then protection levels)
  - virtual memory, paging, multitasking, 32-bits, 64-bits
- hypervisor mode (ring -1)
- system management mode ("god" mode, ring -2)
- management engine (ring -3, see http://www.isci-conf.org/share/doc/InvitedTalkFengweiZhang.pdf)

Changing the mode of operation

- CLP (current protection level)
- system calls
- interrupts
- gates
  - call gates
  - trap gates
  - interrupt gates
  - task gates
- **`vmxon`**, **`vmxoff`**, **`vmlaunch`**, **`vmenter`**, **`vmexit`**, **`vmresume`** (virtual machine control structure)

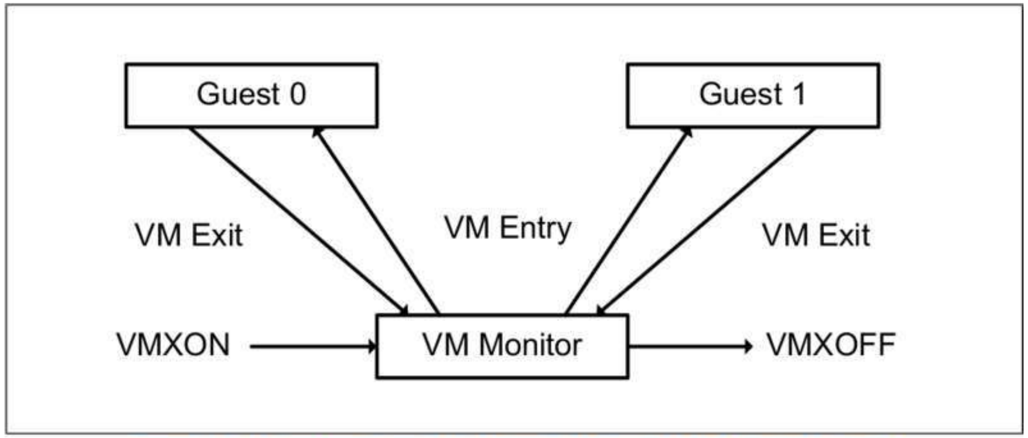


Figure 23-1. Interaction of a Virtual-Machine Monitor and Guests

Images source: Intel® 64 and IA-32 Architectures Software Developer's Manual Volume 3 (3A, 3B, 3C & 3D): System Programming Guide

Virtual memory (paging, 3 levels, 4KiB pages)

- Translates virtual addresses to physical addresses

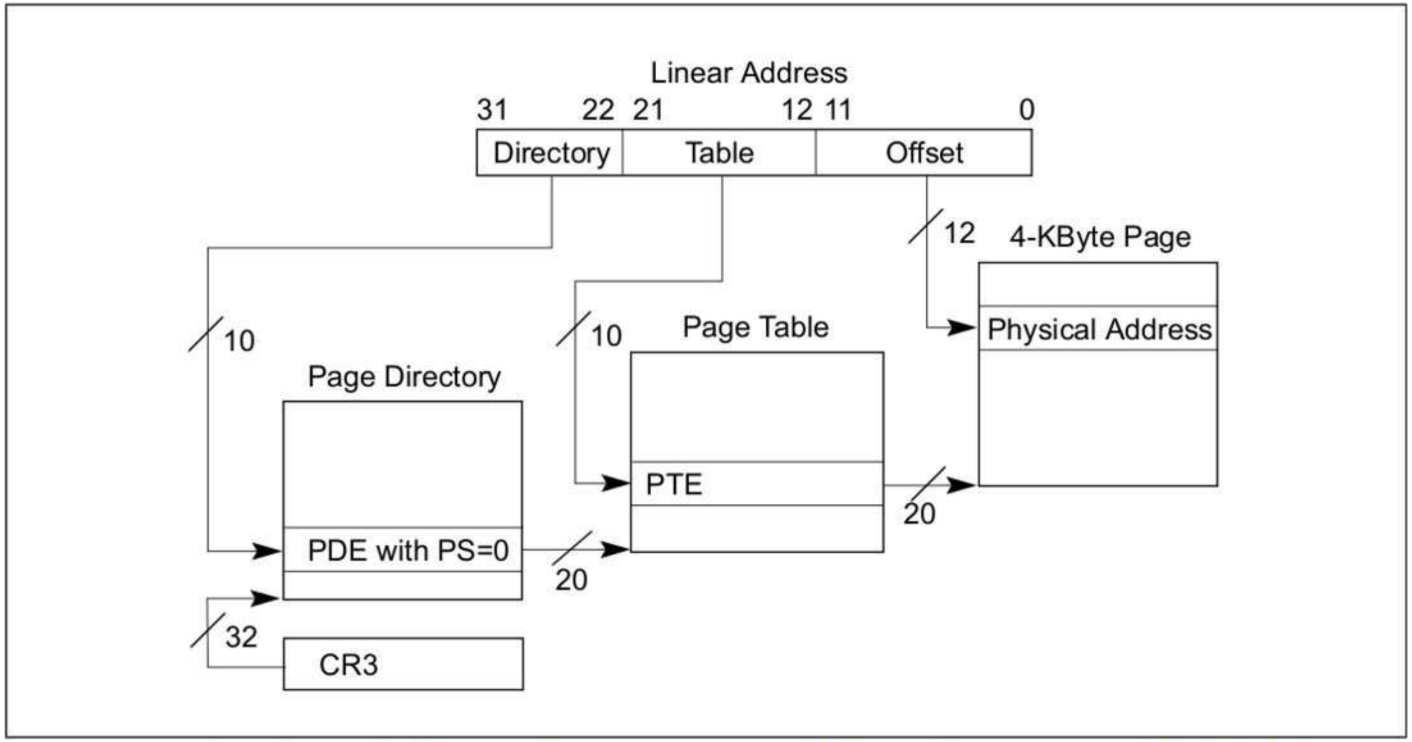


Figure 4-2. Linear-Address Translation to a 4-KByte Page using 32-Bit Paging

Virtual memory (paging, 2 levels, 4MiB pages)

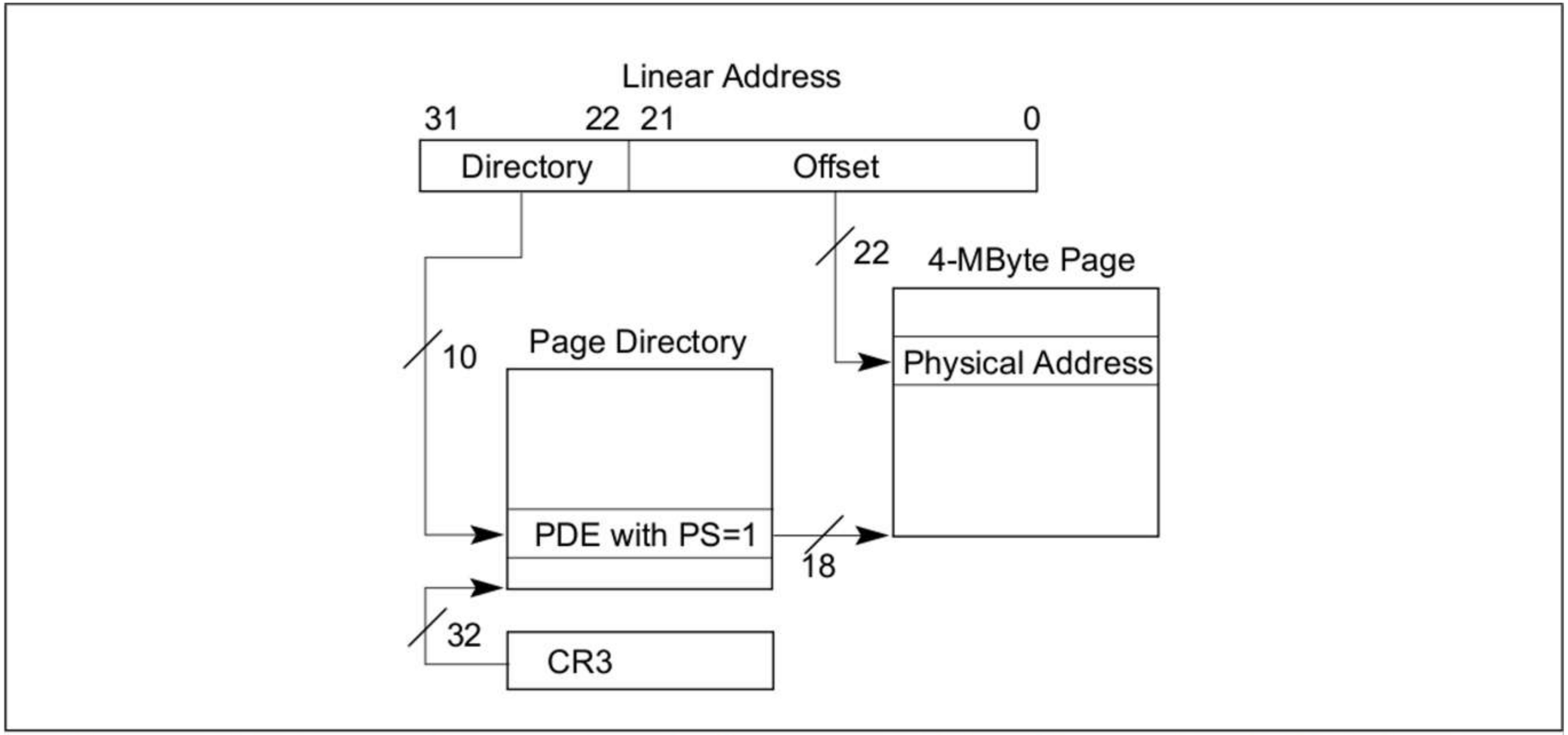


Figure 4-3. Linear-Address Translation to a 4-MByte Page using 32-Bit Paging

Virtual memory (4 levels, 4KiB pages)

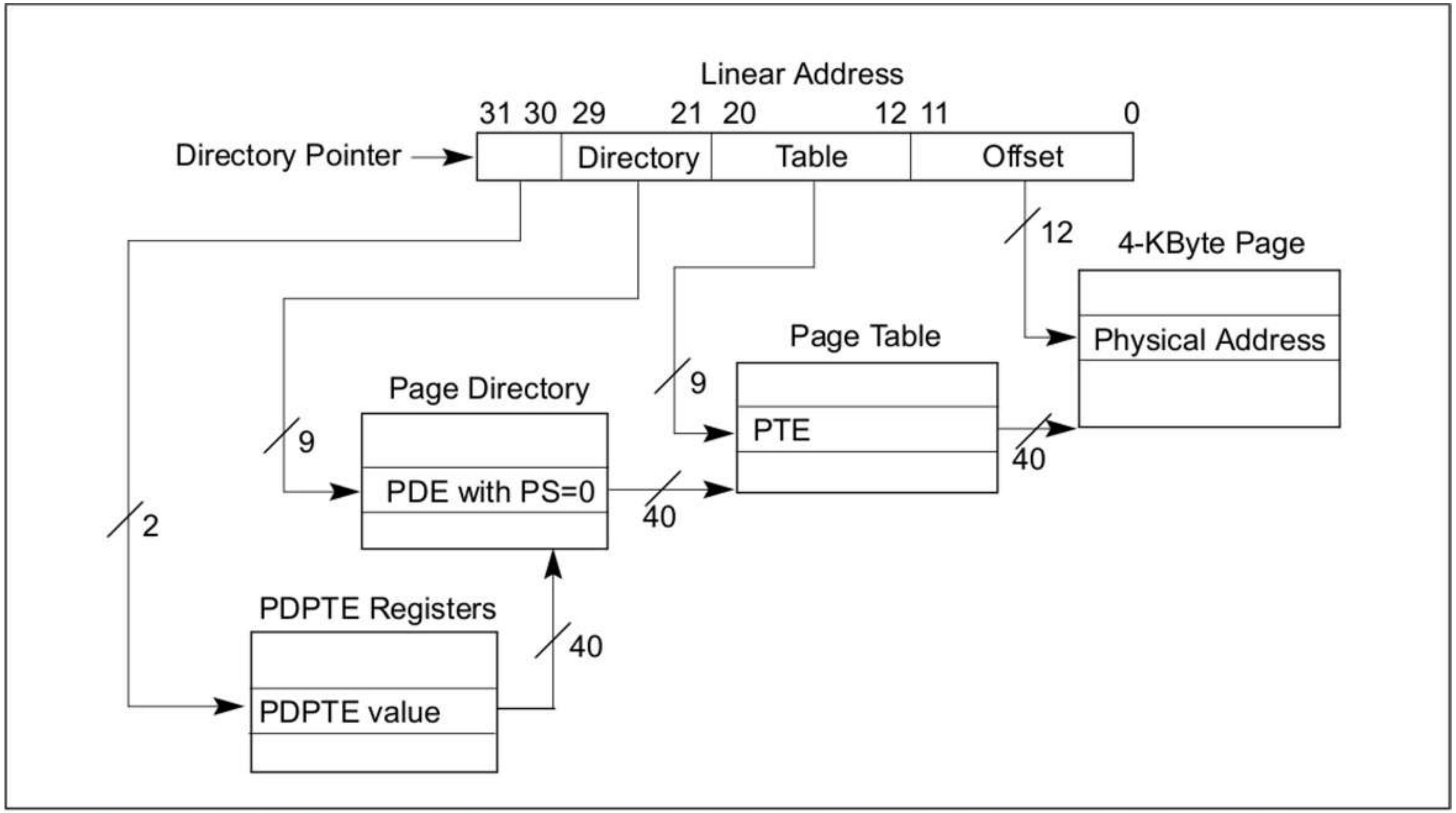


Figure 4-5. Linear-Address Translation to a 4-KByte Page using PAE Paging

Virtual memory (3 levels, 2MiB pages)

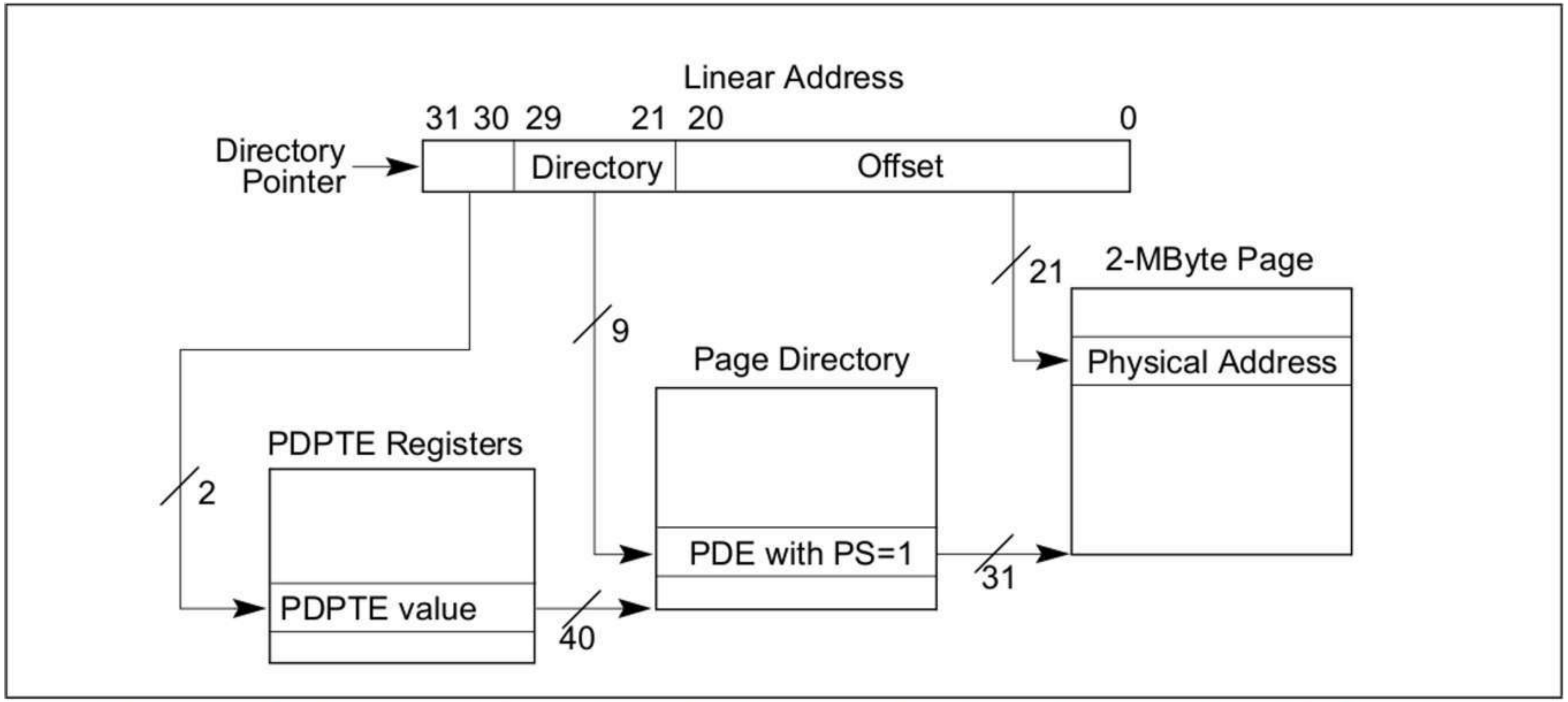


Figure 4-6. Linear-Address Translation to a 2-MByte Page using PAE Paging

Virtual memory (4 level, 4KiB pages)

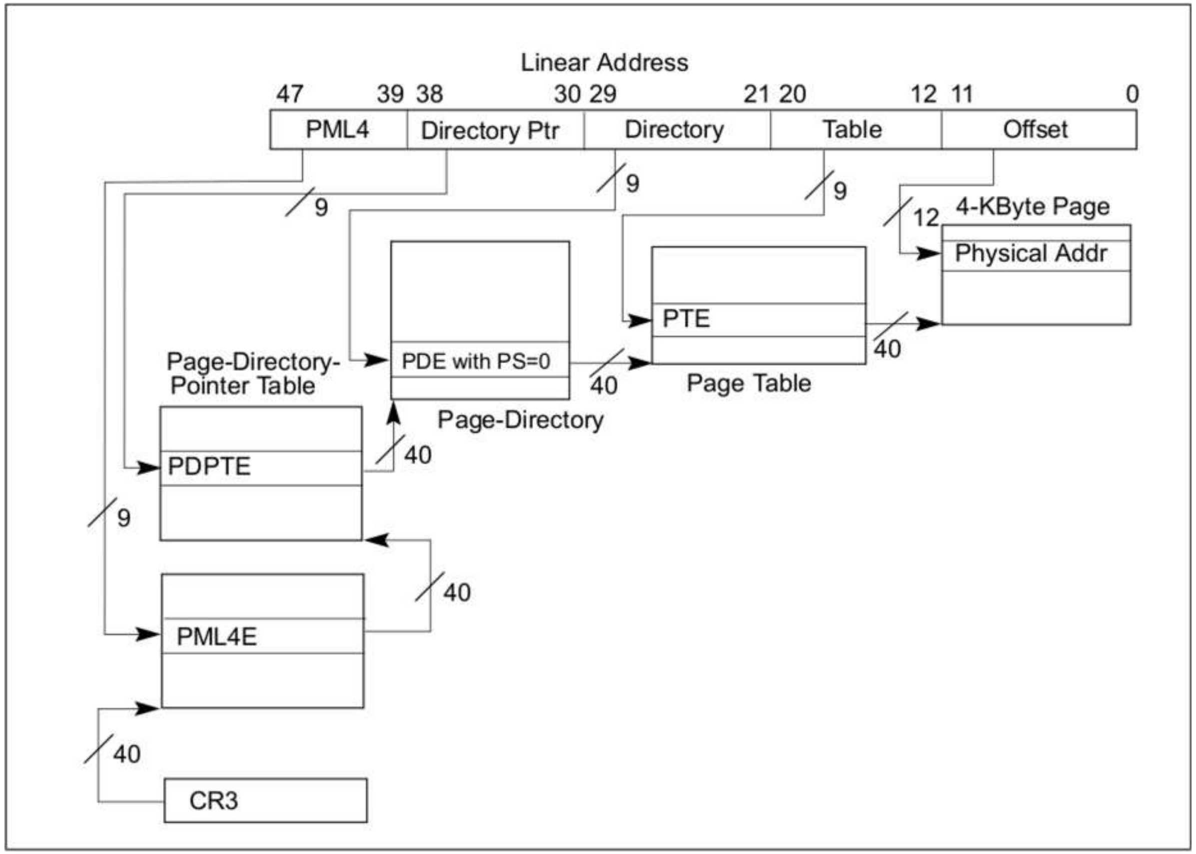


Figure 4-8. Linear-Address Translation to a 4-KByte Page using 4-Level Paging

How to put assembly instructions inside C code

Only C or only assembly

C code:

```
int f(int x)
{
  return 23 * x + 9;
}
```

Corresponding assembly code (Intel processor, AT&T syntax)

```
        .text
        .globl  f
        .p2align 4,,15
f:      imull   $23,%edi,%eax
        addl    $9,%eax
        ret
```

AT&T syntax (for a 64-bit Intel/AMD processor)

- Register names
  - 8-bit %al,%ah,%bl,%bh, …, r8b, …, r15b
  - 16-bit %ax,%bx, …, r8w, …, r15w
  - 32-bit %eax,%ebx,..., r8d, …, r15d
  - 64-bit %rax, %rbx, …, r8, …, r15
- Constants are preceded by a dollar sign ($)
- Destination at the end
- Instruction names include the register size at the end
  - 8 bits (char) b --- addb
  - 16 bits (short) w --- addw
  - 32 bits (int) l --- addl
  - 64 bits (long) q --- addq

Useful links

- https://software.intel.com/content/www/us/en/develop/articles/intel-sdm.html
- https://developer.amd.com/resources/developer-guides-manuals/
- https://www.agner.org/optimize/#manuals
- https://gitlab.com/x86-psABIs/x86-64-ABI
- https://www.felixcloutier.com/x86/index.html

How to put assembly instructions inside C code

C code with an embedded assembly instruction:

```
unsigned long first_one_bit(unsigned long word)
{
  register unsigned long result;

  asm("bsfq %[data],%[result]"
    : [result] "=r" (result)
    : [data]   "r"  (word)
  );
  return result;
}
```

How to put assembly instructions inside C code

A more complex example:

```
unsigned long read_time_stamp_counter(void)
{ // read tsc register (MUST be compiled with -m64)
  unsigned long tmp;

  asm volatile
      (
        "rdtsc ; "
        "shlq $32,%%rdx ; "
        "orq  %%rdx,%%rax"
        : "=a" (tmp)    /* output operands (a=rax register) */
        :               /* no input operands                */
        : "rdx","cc"    /* things that got modified         */
      );
  return tmp;
}
```

The gcc assembly instructions template

To insert assembly instructions inside a C function use the asm keyword as follows:

```
asm [volatile]
(
  assembler_template
  : output_operands
  : input_operands
  : clobbers
);
```

Useful links
- https://gcc.gnu.org/onlinedocs/gcc/Extended-Asm.html

The volatile keyword tells the compiler that the assembly code should not be moved (otherwise, during the optimization phase the compiler may place it in an unintended place.

Details (part 1)

- The assembler_template is a string containing the assembly source code
  - a pattern of the form %%reg refer to the specific register reg
  - a pattern of the form %[name] refers to a register holding one input or output argument (the compiler chooses the register that will be used)
- output_operands is a comma-separated list, possibly empty, of output or input/output parameters
  - each output parameter has the form [name] constraint_string (lvalue) where constraint_string can be (incomplete list):
    - "=r", meaning that the output is stored in a register (the register can be used in an unrelated input)
    - "=&r", meaning that the output is stored in a register (the register can not be used as an input, early clobber)
    - "+r", meaning the argument is used as input and output, stored in a register

Details (part 2)

- input_operands is a comma-separated list, possibly empty, of input parameters
  - each input parameter has the form [name] constraint_string (C_expression), where constraint_string can be (among other possibilities)
    - "r", meaning that the input is stored in a register
    - "m", meaning that the input is stored in a memory position
  - note than input-only operands MUST NOT be modified by the assembly code
- clobbers is a comma-separated list, possibly empty, of things changed by the assembly code; these include specific register names, "cc" and "memory"

Details (part 3)

- It is possible to specify part of a register name using an extension of the %[name]; in particular
  - %b[name] specifies the low byte register name (bits 7..0)
  - %h[name] specifies the high byte register name (bits 15..8)
  - %w[name] specifies the low word register name (bits 15..0)
  - %k[name] specifies the low double word register name (bits 31..0)
    - unfortunately, the letter l is used for labels
  - %q[name] specifies the quad word register name (bits 63..0)

- Register usage conventions:
  - rbx, rbp and r12-r15 need to be saved if they are used
  - return value in rax
  - first 6 integer arguments in rdi, rsi, rdx, rcx, r8, and r9

A more elaborate example

```
void add3(unsigned long a[3],unsigned long b[3])
{ // a += b
  register unsigned long tmp;

  asm volatile(
            "movq\t(%[b]),%[tmp]"
        "\n\taddq\t%[tmp],(%[a])"
        "\n\tmovq\t8(%[a]),%[tmp]"
        "\n\tadcq\t%[tmp],8(%[a])"
        "\n\tmovq\t16(%[a]),%[tmp]"
        "\n\tadcq\t%[tmp],16(%[a])"
        : [tmp] "=&r" (tmp)
        : [a] "r" (a),
          [b] "r" (b)
        : "cc","memory"
      );
}
```

```
        .text
        .p2align 4,,15
        .globl  add3
        .type   add3, @function
add3:
.LFB0:
        .cfi_startproc
#APP
# 5 "z.c" 1
        movq    (%rsi),%rax
        addq    %rax,(%rdi)
        movq    8(%rdi),%rax
        adcq    %rax,8(%rdi)
        movq    16(%rdi),%rax
        adcq    %rax,16(%rdi)
# 0 "" 2
#NO_APP
        ret
        .cfi_endproc
.LFE0:
        .size   add3, .-add3
        .ident  "GCC: (Ubuntu 7.5.0-3ubuntu1~18.04) 7.5.0"
        .section        .note.GNU-stack,"",@progbits
```

Useful assembly instructions (part 1)

- the instruction **`rdtsc`** can be used to read the time stamp counter
  - it is a non-serializing instruction (the processor may reorder its execution)
  - the value returned depends on the core where it was executed
- the instruction **`rdtscp`** can be used to read the time stamp counter and the core signature (usually the code id number)
  - it is a serializing instruction
  - the value returned depends on the core where it was executed
  - **`asm volatile("rdtscp" : "=a" (rax),"=c" (rcx),"=d" (rdx));`**
  - as in the **`rdtsc`** instruction, the counter value is given by **`(rdx<<32)+rax`**
  - the core signature is given by **`rcx`**; on GNU/Linux, its value is the core id that executed the instruction

Useful assembly instructions (part 2)

- the instruction **`cpuid`** can be used to get information about the processor
  - it is a serializing instruction
  - this instruction unconditionally generates a trap (vmexit) when executed in a virtualized environment
  - it can be used when CPL is 3 (least privileged mode)
- the instruction **`invd`** can be used to invalidate a cache line
  - this instruction unconditionally generates a trap when executed in a virtualized environment
  - it can be used only when CPL is 0 (kernel mode)
  - use it only on a memory region whose contents are irrelevant

Useful links
- https://en.wikipedia.org/wiki/CPUID
- https://software.intel.com/content/www/us/en/develop/articles/intel-sdm.html

Useful assembly instructions (part 3)

- the instructions **`rdseed`** and **`rdrand`** are used to generate random numbers on recent Intel/AMD processors
  - the virtual machine hypervisor can set things up so that these instructions generate a trap
  - it can be used when CPL is 3 (least privileged mode)
- the instructions **`in`**, **`out`**, **`rdtsc`**, **`rdmsrd`**, and **`rdpmcd`** can also be used to generate a trap in a virtualized environment (if the hypervisors wants that to happen)

deti universidade de aveiro departamento de eletrónica, telecomunicações e informática

Intel Software Guard Extensions

What is SGX (Software Guard eXtensions)?

- It is a TEE (Trusted Execution Environment).
- Everything outside the processor chip is not trusted.
- In particular, the BIOS (Basic Input/Output System), the SMM (System Management Mode, ring -2), the ME (Intel Management Engine, ring -3), and the OS (Operating System, ring 0) are **not** trusted.
- The SGX code and data is put inside a special container (a SGX enclave).
- The contents of the enclave are signed (they are loaded from an untrusted source…) and can be attested by an external third party.
- The contents of the enclave are **isolated** from the rest of the system.
- The enclave code runs in **ring 3** (least privileged mode).
- All SGX instructions are implemented in microcode. The microcode is an integral part of the trust model (it is trusted).

SGX Enclave Memory

- As mentioned in the previous slide, the trust boundary perimeter is the processor chip (core, cache, and memory controller).
- So, the memory of the SGX enclave, when it resides outside of the processor chip (DRAM) is also encrypted.
- The memory encryption key is chosen at random after every processor reset.
- Values read from memory are checked to see it they match what was written (if not the processor hangs).
- This is done on a cache-line granularity (64 bytes) using an memory integrity tree.
    - For details, see https://eprint.iacr.org/2016/204.pdf
- Very small performance penalty if the SGX enclave memory footprint fits in the processor caches.

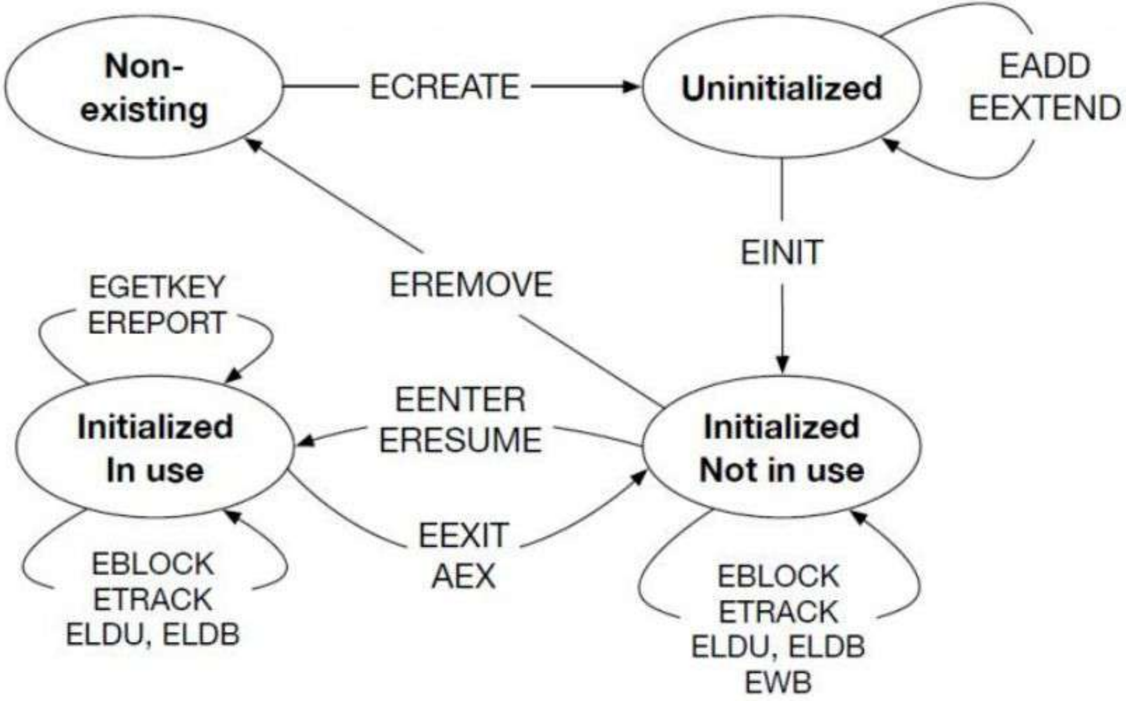
Instructions related to enclaves

- Ring 0 instructions
  - ECREATE, EADD and EINIT are used for Enclave Page Cache (EPC) management --- executed by privileged software such as an OS or a VMM
  - The EPC is an untrusted secure storage area used by the enclave; each 4KiB page has some security attributes that are stored in the Enclave Page Cache Map (EPCM), which is not accessible by software
- Ring 3 instructions
  - EENTER, EEXIT, EGETKEY, EREPORT and ERESUME are used by the user space software to execute functionality within or between enclaves.
- Illegal instructions inside an enclave
  - **`cpuid`**, **`rdtsc`**, input and output instructions, and some others are not allowed
  - **`rdrand`**/**`rdseed`** are allowed and can be virtualized (!?!)

Life cycle of an enclave

https://software.intel.com/content/dam/develop/external/us/en/documents/intelsgx enclavelifecycle.pdf

1. Creation (ECREATE)
2. Loading (EADD, EEXTEND)
3. Initialization (EINIT)
4. Enter/Exit the Enclave (EENTER/EEXIT)
5. Teardown (EREMOVE)



Intel SGX Toolkit (version 2.13) requirements
https://github.com/intel/linux-sgx

- Hardware:
  - Intel 6th generation core processor or newer (but **not** some 10th or all 11th generation desktop processors!)
- 64-bit operating system:
  - Ubuntu 16.04, 18.04 or 20.04 LTS
  - Red Hat 7.6 or 8.2
  - CentOS 8.2
  - Fedora 31
- BIOS support (enabling SGX will reserve up to 128MiB of memory for the exclusive use of SGX enclaves)
- It's also possible to install it on Windows 10 (not covered in these slides)

Intel SGX Toolkit (version 2.13)

- Toolkit components:
  - Intel SGX kernel driver
  - Intel SGX PSW (Platform Software Package)
  - Intel SGX SDK

- Programming languages: **C** and **C++**

- Does my processor and OS support SGX (after BIOS configuration)?
  - `cpuid -1 | grep SGX`
  - If yes:

```
SGX: Software Guard Extensions supported = true
SGX_LC: SGX launch config supported      = true
```

Intel SGX linux driver installation

- Install needed packages:
  - `sudo apt install build-essential ocaml automake autoconf libtool wget python3 libssl-dev dkms`
- Download driver (https://01.org/intel-software-guard-extensions/downloads)
  - `wget https://download.01.org/intel-sgx/sgx-linux/2.13/distro/ubuntu20.04-server/sgx_linux_x64_sdk_2.13.100.4.bin`
- Install the Dynamic kernel Module Support (DKMS) driver:
  - `sudo bash sgx_linux_x64_driver_1.41.bin`
- If you are using secure boot, the kernel module has to be signed, and so this requires generating a new Machine-Owner Key (MOK). Just follow the instructions (a reboot will be required)
- the module location is /lib/modules/5.8.0-48-generic/updates/dkms/intel_sgx.ko and the module name is (obviously) intel_sgx.

Intel SGX PSW installation (on ubuntu)

- Install needed packages:
  - **`sudo apt install libssl-dev libcurl4-openssl-dev libprotobuf-dev`**
- Run the following commands
  - **`echo 'deb [arch=amd64] https://download.01.org/intel-sgx/sgx_repo/ubuntu focal main' | sudo tee /etc/apt/sources.list.d/intel-sgx.list`**
  - **`wget -qO - https://download.01.org/intel-sgx/sgx_repo/ubuntu/intel-sgx-deb.key | sudo apt-key add -`**
  - **`sudo apt update`**
  - **`sudo apt install libsgx-launch libsgx-urts`**
  - **`sudo apt install libsgx-epid libsgx-urts`**

Intel SGX SDK installation (on ubuntu)

- Do the following:
  - `wget https://download.01.org/intel-sgx/latest/linux-latest/distro/ubuntu20.04-server/sgx_linux_x64_sdk_2.13.100.4.bin`
  - `sudo bash sgx_linux_x64_sdk_2.13.100.4.bin`
  - answer no and choose `/opt/intel` as the installation directory
  - copy the contents of `/opt/intel/sgxsdk/environment` to your `.bashrc`
  - `wget https://download.01.org/intel-sgx/latest/linux-latest/as.ld.objdump.gold.r3.tar.gz`
  - `tar xzvf as.ld.objdump.gold.r3.tar.gz external/toolset/ubuntu20.04`
  - `sudo cp -v external/toolset/ubuntu20.04/* /usr/local/bin/`

Intel SGX SDK test (on ubuntu)

- Do the following:
  - `mkdir tmp`
  - `cd tmp`
  - `cp -av /opt/intel/sgxsdk/SampleCode/SampleEnclave .`
  - `cd SampleEnclave`
  - `make SGX_DEBUG=0 SGX_PRERELEASE=1`
  - `./app`
  - `make clean`

- The output should be

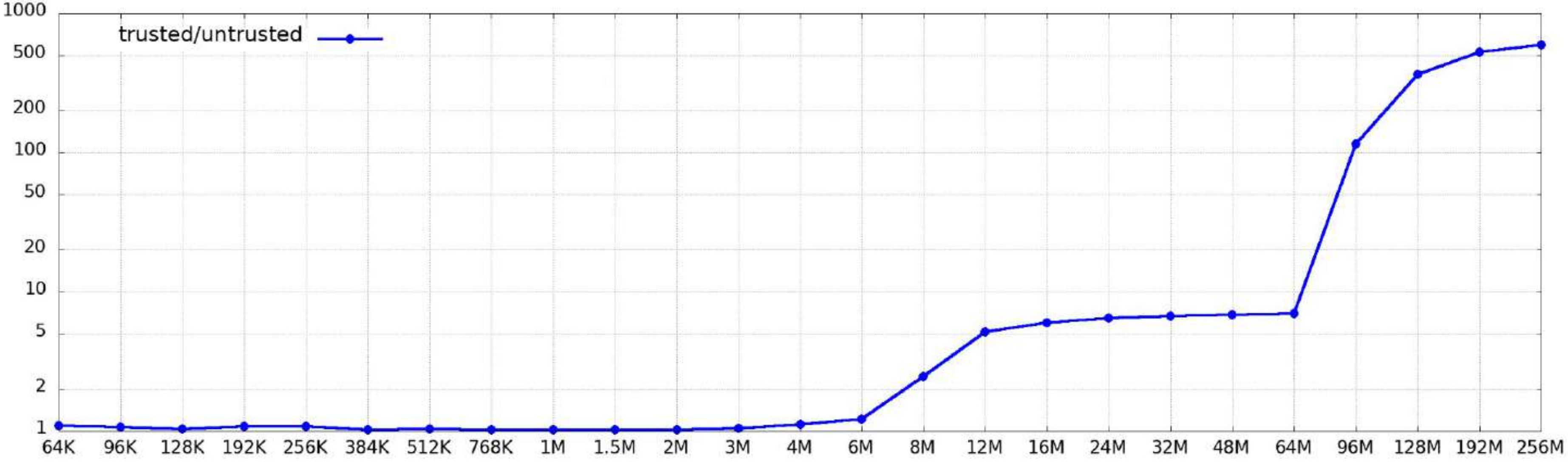
```
Checksum(0x0x7ffeac1ee4f0, 100) = 0xfffd4143
Info: executing thread synchronization, please wait...
Info: SampleEnclave successfully returned.
Enter a character before exit ...
```

Guidelines for designing applications using SGX

- Partition the software into trusted and untrusted components
- Use the SGX SDK tools to create the enclave module (a shared object) --- it implements the trusted component of the software
- The enclave code and data **is not secret**
- Secrets has to be loaded in a secure manner (using an ECDH key exchange for example) from a trusted outside source.
- Enclave data has to be **sealed** (encrypted and signed) if it is stored outside of the enclave
- Enclave data has to be **unsealed** if it is loaded into the enclave
- To minimize side-channels attack vectors, keep the secrets in the sealed state, and only unseal them for as long as it is truly necessary

Performance Overhead

- Creating an enclave is relatively slow (4KiB pages have to be added one at a time)
- Calling an enclave function from outside of the enclave (an **ecall**) or calling a non enclave function from inside the enclave (an **ocall**) takes about 10k clock cycles



Sealing and unsealing

https://software.intel.com/content/www/us/en/develop/blogs/introduction-to-intel-sgx-sealing.html

- Each Intel processor has one unique key, set during manufacturing, not known to Intel (presumably).
- Each SGX enclave has an identity, which is a hash of the enclave log as it goes through every step of the build and initialization process.
- The enclave identity (value of **`MRENCLAVE`**), together with the processor's key, should therefore be truly unique.
- It should be used to seal and unseal data.
- Because the enclave identity changes when the enclave code is modified, migration of the sealed data to a new software version has to be done with extreme care.
- One possibility is to create an encrypted secure channel between the two software versions, and to migrate the data in that way.

SDK documentation

- Developer reference for Linux OS (PDF)
- Intel developer zone --- Software Guard Extensions (online)

Intel SGX SDK compilation modes

- SGX applications can be compiled in several modes:
  - hardware debug mode (signed with Intel's key, code not optimized)
    - `SGX_MODE=HW SGX_DEBUG=1 SGC_PRERELEASE=0`
  - hardware prerelease mode (signed with your key, code is optimized)
    - `SGX_MODE=HW SGX_DEBUG=0 SGC_PRERELEASE=1`
  - hardware release mode (signed with your key, code is optimized, cannot be debugged)
    - `SGX_MODE=HW SGX_DEBUG=0 SGC_PRERELEASE=0`
    - This mode may require a commercial licence
  - simulation mode (in debug mode)
    - `SGX_MODE=SIM SGX_DEBUG=1`

SGX SDK Tools

- Edger8r (**`sgx_edger8r`**)
  - Generates "edge" routines (interface between the untrusted application and the enclave) described in a Enclave Description Language (EDL) file
  - Using it on file XYZ.edl produces files XYZ_[tu]t.[hc] where t=trusted, u=untrusted, h=prototypes, and c=functions
- Enclave signing tool (**`sgx_sign`**)
  - supports key management
- Enclave Memory Measurement Tool (**`sgx_emmt`**)
  - Use it to measure how much memory the enclave uses (needed by the Enclave Configuration File)

Writing Enclave Functions

- Describe each function that may be called from outside of the enclave in the .edl file
- The functions can use special versions of the **C/C++** runtime libraries (available in the SDK)
- System calls are not allowed (use **ocalls** instead; **C** linkage only!)
- Not all **C/C++** language features are available
- The sgx_edger8r tool will take care of the details of making the execution flow enter or leave an enclave
  - Pointer arguments in **ecall** functions must point to untrusted memory
  - Pointer arguments in **ocall** functions must point to trusted memory
  - You may need to copy buffer from untrusted memory to trusted memory
- Keep in mind that the enclave will be statically linked

Some available trusted libraries

- **`libsgx_tstdc.a`** (standard **C** library, math, strings, etc.)
- **`libsgx_tcxx.a`** (standard **C++** libraries, STL)
- **`libsgx_tservice.a`** (seal/unseal, EC DH library, etc.)
- **`libsgx_tcrypto.a`**
- **`libsgx_tkey_exchange.a`**
- **`libsgx_tpcl.a`** (Protected Code Loader, for enclave code confidentiality)

Hello world in an enclave (https://github.com/sangfansh/SGX101_sample_code)

- One enclave function, **`printf_helloworld`**, prints the text "Hello World"
- It cannot do this directly, so it calls an untrusted function, **`ocall_printf_string`**, to do the actual printing
- In this example, for the enclave code, the **`printf`** function is re-implemented so that its output goes to a string
- In the untrusted part, the enclave is loaded and the **`printf_helloworld`** function is called

Hello world in an enclave

- List of files
  - **`Makefile`**
  - **`App/App.cpp`**
  - **`App/App.h`**
  - **`Enclave/Enclave.config.xml`**
  - **`Enclave/Enclave.cpp`**
  - **`Enclave/Enclave.edl`**
  - **`Enclave/Enclave.h`**
  - **`Enclave/Enclave.lds`**
  - **`Enclave/Enclave_private.pem`**

- Relevant parts of the **`Makefile`**:
  - **`SGX_SDK ?= /opt/intel/sgxsdk`**
  - **`SGX_MODE ?= HW`**
  - **`SGX_ARCH ?= x64`**
  - **`SGX_DEBUG ?= 1`**
- You can also add
  - **`SGX_PRERELEASE ?= 0`**
- List your untrusted source code files (the application) in the

  `######## App Settings ########`

  section
- List your trusted source code files (the SGX enclave) in the

  `######## Enclave Settings ########`

  section

- Relevant parts of **`App/App.h`**:

```
#include "sgx_error.h"   /* sgx_status_t     */
#include "sgx_eid.h"     /* sgx_enclave_id_t */

#define TOKEN_FILENAME   "enclave.token"
#define ENCLAVE_FILENAME "enclave.signed.so"

extern sgx_enclave_id_t global_eid;  /* global enclave id */
```

- Relevant parts of **`App/App.cpp`**:

```
int initialize_enclave(void) { /*...*/ }

void ocall_print_string(const char *str){ printf("%s",str); }

int SGX_CDECL main(int argc, char *argv[])
{
  if(initialize_enclave() < 0) return -1;
  printf_helloworld(global_eid);
  sgx_destroy_enclave(global_eid);
}
```

- **`Enclave/Enclave_config.xml`**:

```
<EnclaveConfiguration>
  <ProdID>0</ProdID>                          user defined
  <ISVSVN>0</ISVSVN>                          user defined
  <StackMaxSize>0x40000</StackMaxSize>        stack size
  <HeapMaxSize>0x100000</HeapMaxSize>         heap size
  <TCSNum>10</TCSNum>                         maximum number of threads
  <TCSPolicy>1</TCSPolicy>                    0=bound threads
  <DisableDebug>0</DisableDebug>              0=enclave can be debugged
  <MiscSelect>0</MiscSelect>                  ???
  <MiscMask>0xFFFFFFFF</MiscMask>             ???
</EnclaveConfiguration>
```

- Relevant parts of **`Enclave/Enclave.edl`**:

```
enclave {
  trusted {
    public void printf_helloworld();
  };
  untrusted {
    void ocall_print_string([in,string] const char *str);
  };
};
```

- Relevant parts of **`Enclave/Enclave.h`**:

```
#include <stdlib.h>
#include <assert.h>

#if defined(__cplusplus)
extern "C" {
#endif
void printf(const char *fmt, ...);
void printf_helloworld();
#if defined(__cplusplus)
}
#endif
```

- Relevant parts of **`Enclave/Enclave.cpp`**:

```
#include <stdarg.h>
#include <stdio.h>      /* vsnprintf    */
#include "Enclave.h"
#include "Enclave_t.h"  /* print_string */

void printf(const char *fmt, ...) { char buf[BUFSIZ];
  va_list ap; va_start(ap, fmt);
  vsnprintf(buf, BUFSIZ, fmt, ap);
  va_end(ap); ocall_print_string(buf); }

void printf_helloworld() { printf("Hello World\n"); }
```

Power events

- The enclave page cache is **destroyed** then the processor is put in state S2 or lower
  - S0 --- The CPU is executing instructions, and background tasks are running even if the system appears idle and the display is powered off.
  - S1 --- Processor caches are flushed, CPU stops executing instructions. Power to CPU and RAM is maintained. Devices may or may not power off. This is a high-power standby state, sometimes called “power on suspend.”
  - S2 --- CPU is powered off. CPU context and contents of the system cache are lost.
  - S3 --- RAM is powered on to preserve its contents. A standby or sleep state.
  - S4 --- RAM is saved to nonvolatile storage in a hibernation file before powering off. When powered on, the hibernation file is read in to restore the system state. A hibernation state.
  - S5 --- “Soft off.” The system is off but some components are powered to allow a full system power-on via some external event, such as Wake-on-LAN, a system management component, or a connected device.
- Follow the following advice in order to deal with power events.

Some extra useful links

- [Intel SGX explained]
- https://sgx101.gitbook.io/sgx101/
- SGX Intel tutorial series

ARM TrustZone

SoC and IP

- SoC (System-on-Chip)
  - Tackles the provisioning of complex and application-specific, multifunctional processors
  - The major functional components of a complete end-product are integrated into a single chip

- Intellectual property (IP) modules
  - Pre-designed, reusable electronic components for hardware chips

SoC structure

- A SoC usually contains
  - Processors
  - IPs
    - Namely security IPs
  - Memory elements (RAM, ROM, etc.)
  - Buses

ARM TrustZone

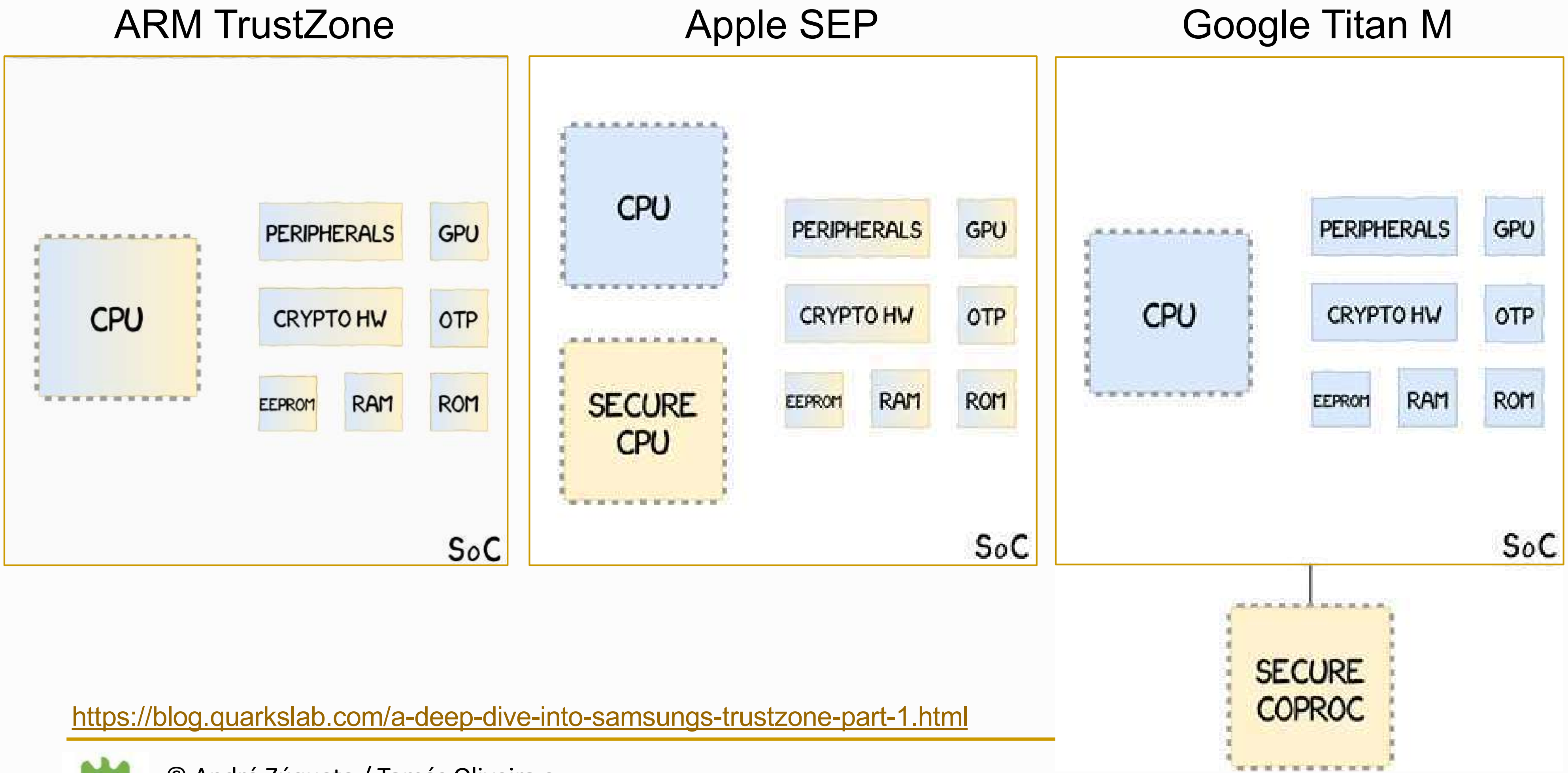
- Set of technologies for packing special security features into a SoC
  - Extra security-related features on processor cores
    - Instructions
    - Bus lines
    - Execution levels
    - Extra logic for dealing with interruptions
  - Security-related IPs

ARM TrustZone: goal

- TEE for ARM-powered embedded systems
  - Providing hardware-based isolation

- It allows to run a trusted system in parallel with the main operation system
  - Rich OS
    - Where most applications will run
  - Secure (or Trusted) OS
    - Where secure (or trusted) applications will run
    - It can be a simple library, and not a full-fledged OS

ARM TrustZone: Comparison with other similar TEEs



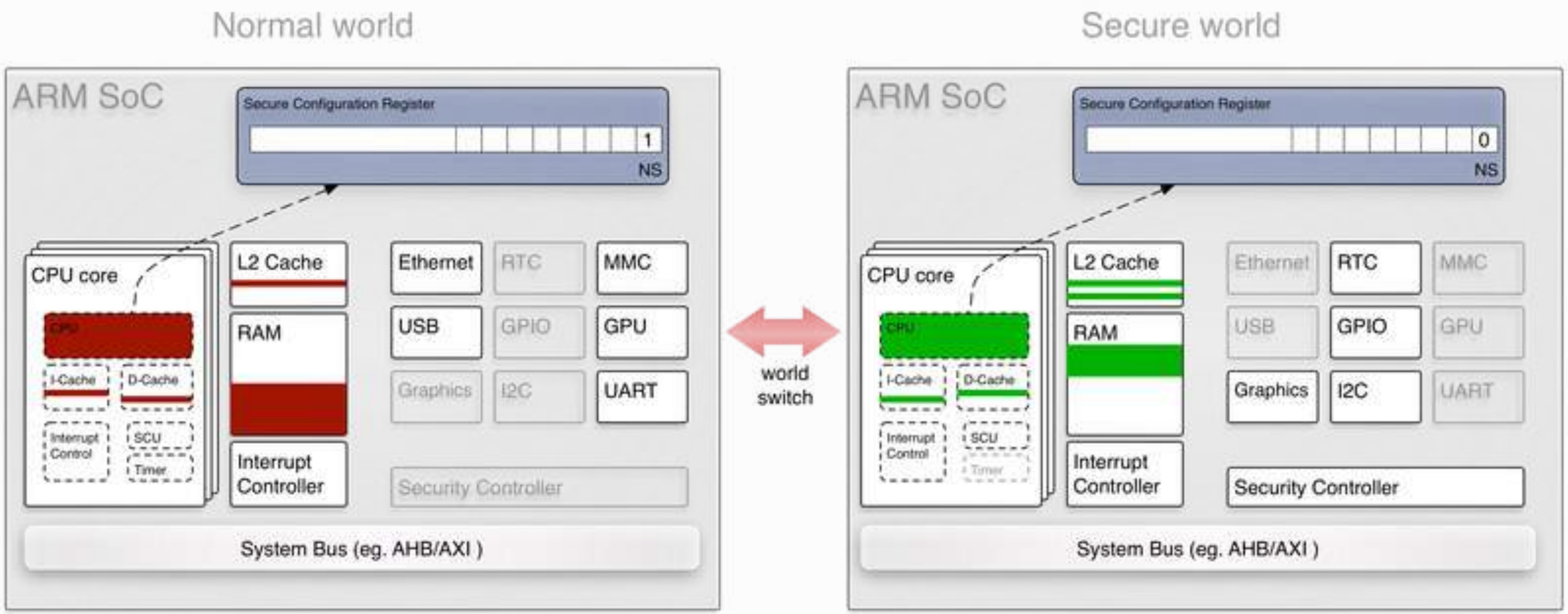
https://blog.quarkslab.com/a-deep-dive-into-samsungs-trustzone-part-1.html

Worlds

- Isolation is achieved by exploring the same CPU in two different worlds (or states)
  - Normal world → for running the Rich OS
  - Secure world → for running the Secure OS
- A CPU flag bit defines the current world
  - NS bit of the SCR (Secure Configuration Register)
  - 0 – Secure state
  - 1 – Non-secure state

Protected hardware resources

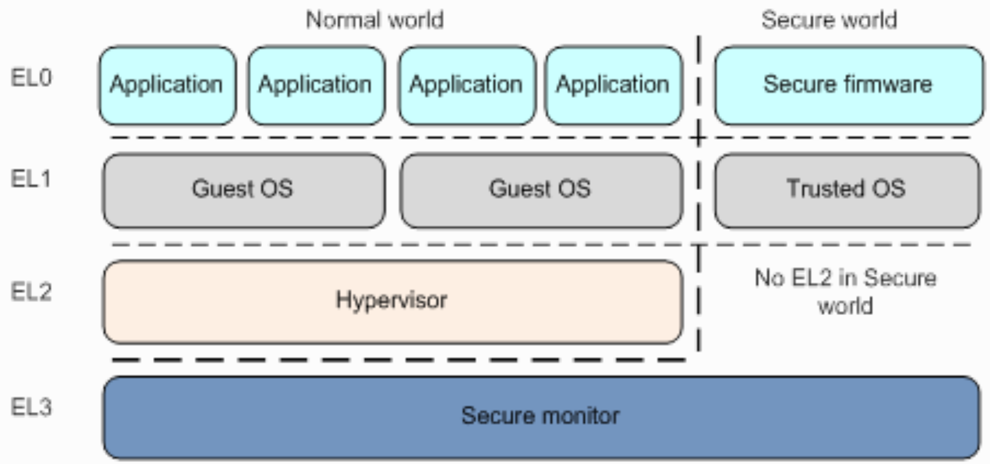
▷ Resources accessible only to the Secure OS



https://genode.org/documentation/articles/trustzone

ARM (v8) exception levels

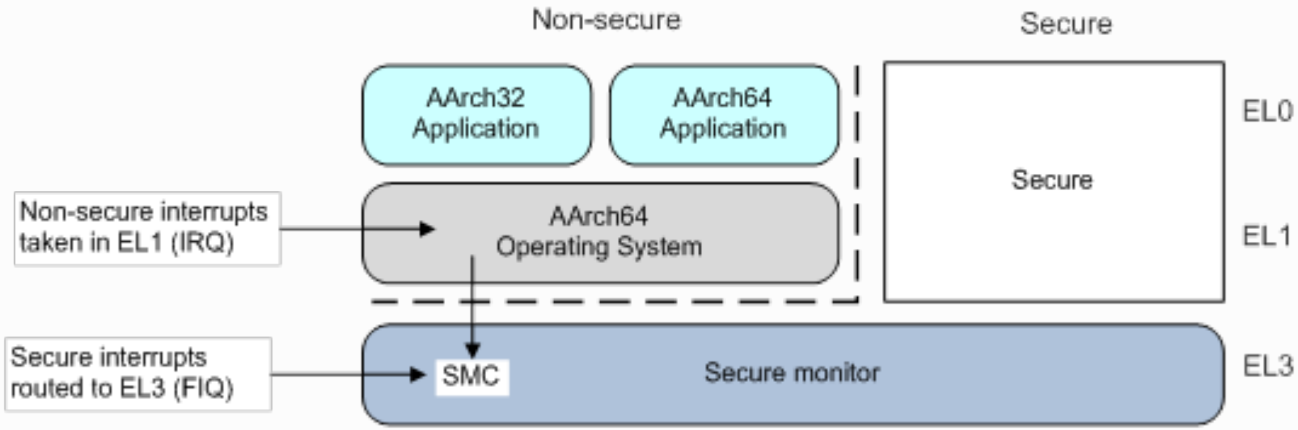
- Similar to run levels
- TrustZone introduces one EL more
  - Secure monitor (EL3)
- Combination of exception levels



https://sergioprado.blog/introduction-to-trusted-execution-environment-tee-arm-trustzone/

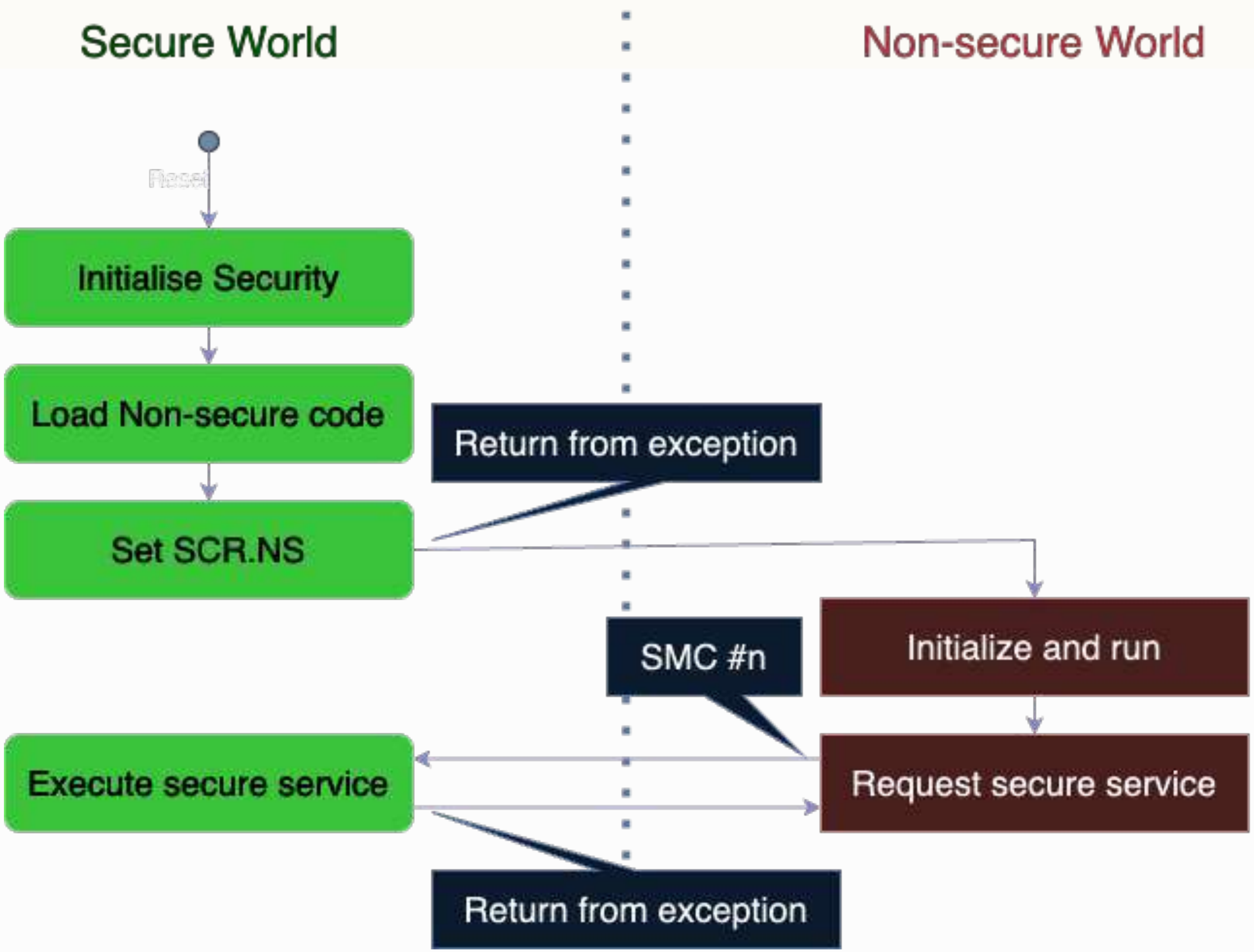
Access to the Secure world

- Calls from the Rich OS
  - SMC (Secure Monitor Call)
  - Typically implemented by Rich OS drivers
- Interrupts from the Secure hardware
  - Must be handled by the Secure OS
- Both enter first in EL3
  - Then are dispatched to the Secure world

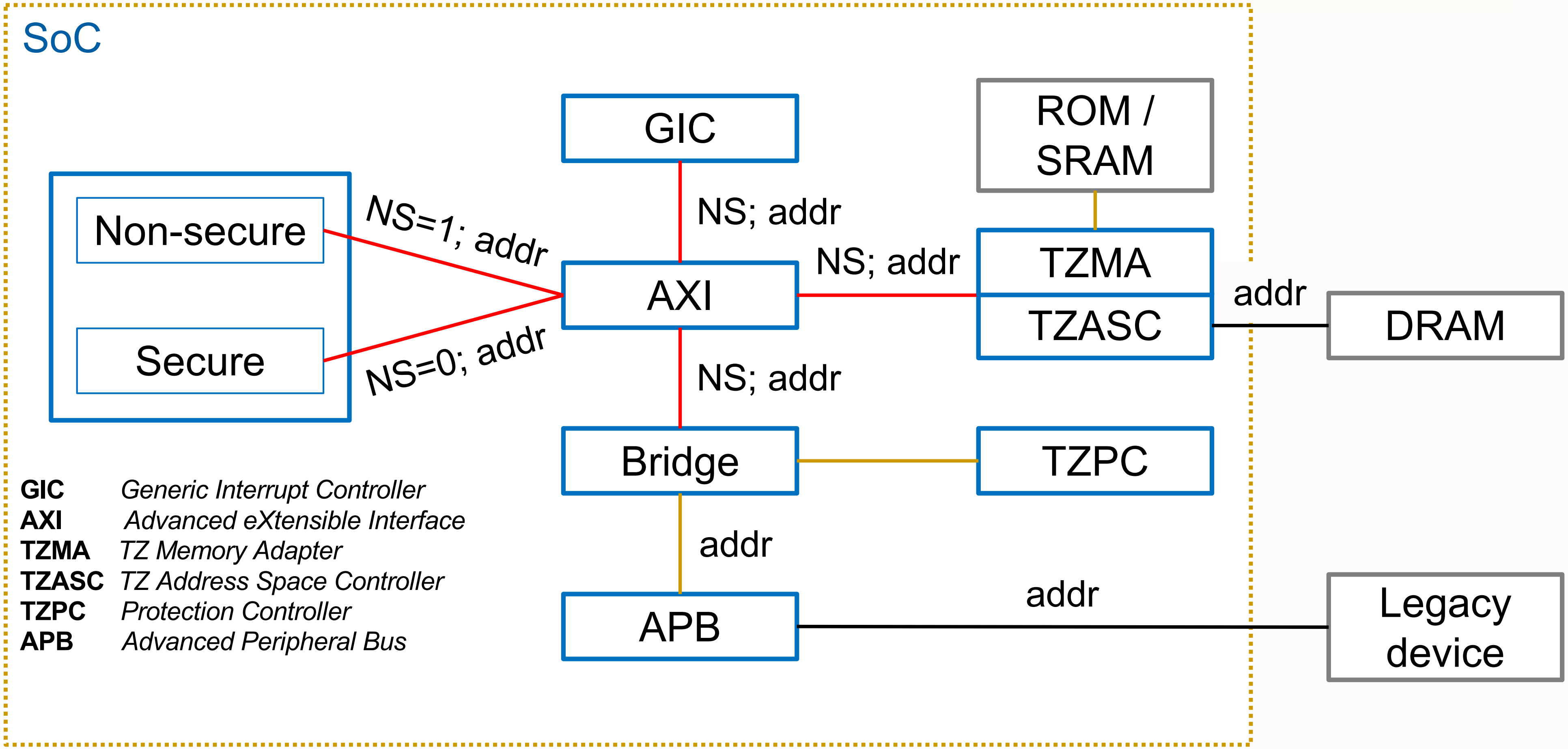


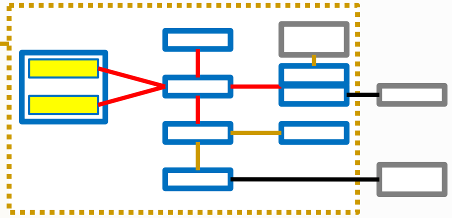
https://sergioprado.blog/introduction-to-trusted-execution-environment-tee-arm-trustzone/

Access to the Secure world



Architecture overview



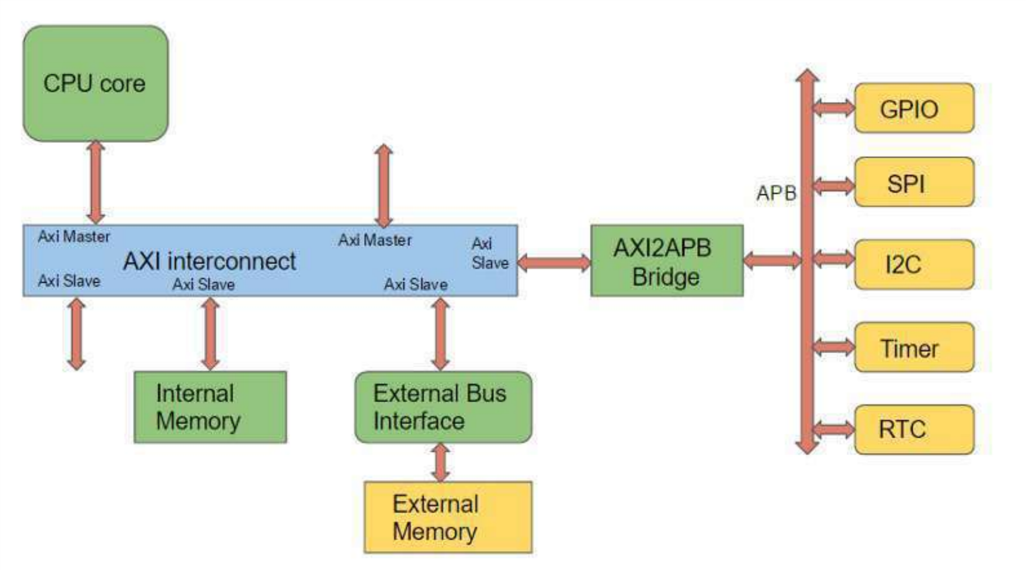


Architectural details: MMU / TLB / Cache Controllers

- 2 separate, virtual MMUs
  - Indexed by NS
- Single TLB
  - But entries keep the value of NS that created them
  - No need to invalidate them when switching between worlds
- The Secure world can still access non-secure memory
  - Extra bit on each entry in the secure translation table
- Single cache
  - Cache lines keep the NS address bit

Architectural details: AXI (Advanced eXtensible Interface)

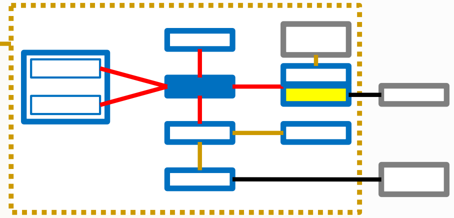
▷ SoC internal bus



▷ Extra NS line for secure read/write operations

- Non-secure master cannot access a resource marked as secure

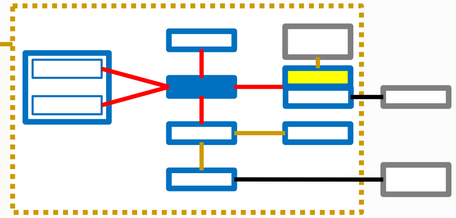
https://anysilicon.com/understanding-amba-bus-architecture-protocols



Architectural details: TZASC (TZ Address Space Controller)

- Allows a dynamic classification of AXI slave memory-mapped devices as secure or non-secure
  - Partitioning of single memory units
- Controlled by the Secure world

Architectural details: TZMA (TZ Memory Adapter)



- Keeps a classification of in-SoC memory areas as secure and non-secure
  - ROM or SRAM
- Non-secure accesses cannot access secured memory areas
- Controlled by the Secure world

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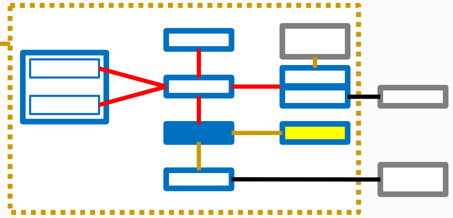
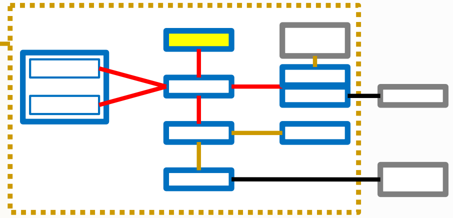
Architectural details: TZPC (TZ Protection Controller)



- Allows to dynamically set the security of a peripheral connected to the APB (Advanced Peripheral Bus)
  - Protects non-secure access requests to reach peripherals marked as secure

- Controlled by the Secure world

Architectural details:
GIC (Generic Interrupt Controller)



- Classifies interrupts as secure or non-secure
  - Once set, cannot be changed
- Interrupts can be normal or fast (high-priority)
  - Secure interrupts usually have higher priority
- Interrupts with a security classification different from the current world force the switching to Monitor (EL3)
- Controlled by the Secure world

TrustZone bootstrap

- A TZ-enable ARM SoC boots on the secure world
  - It allows the Secure world to configure the TZ-related components to enforce a given security policy
- The configuration data can be
  - Embedded in the SoC ROM
  - Provided by external peripherals and validated with information in SoC ROM
    - e.g. must contain a signature validated with a in-SoC public key

Linux kernel namespaces

namespaces

- A **namespace wraps a global system resource in an abstraction** that makes it appear to the processes within the namespace that they have their own isolated instance of the global resource;
- Changes to the global resource are visible to other processes that are members of the namespace, but are invisible to other processes;
- One use of namespaces is to implement containers.

Linux Programmer's Manual: *$man namespaces*

In a nutshell: restrictions and translations

- Extend the CHROOT concept to other resources
  - CHROOT enables each process to have a different notion of the file system root
- Restrictions
  - Limit the number of resources a process can use
- Translations
  - Access resources with a name different from the one the process thinks it is using

Advantages

- Enforce the Principle of Least Privilege
  - Processes cannot make use of resources they don’t need for the application they run
  - If their application gets compromised, the processes will prevent their misbehavior to access forbidden resources

Process namespace

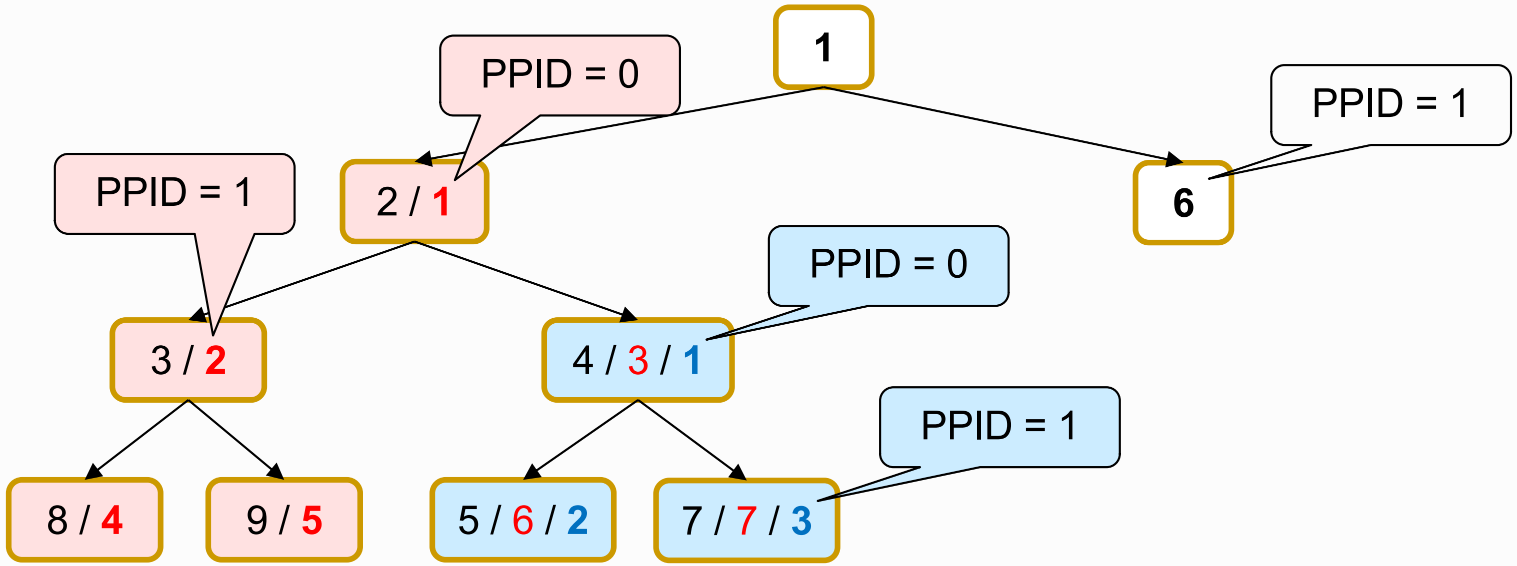
- Process namespaces **isolate the process ID number space**, meaning that processes in different PID namespaces can have the same PID;
- Process namespaces allow containers to provide functionality such as **suspending/resuming the set of processes** in the container and migrating the container to a new host while the processes inside the container maintain the same PIDs;
- PIDs in a **new PID namespace start at 1**, somewhat like a standalone system, and calls to fork or clone will produce processes with PIDs that are unique within the namespace.

Linux Programmer's Manual: *$man pid_namespaces*

Process namespace

- UNIX processes form a parent-child tree
  - Process identifiers (PIDs) are global
- The process namespace creates nested trees
  - Processes within inner namespaces cannot access processes of outer namespaces by their PID
- A process can have many PIDs
  - One for each namespace it belongs

Process namespaces



Network namespace

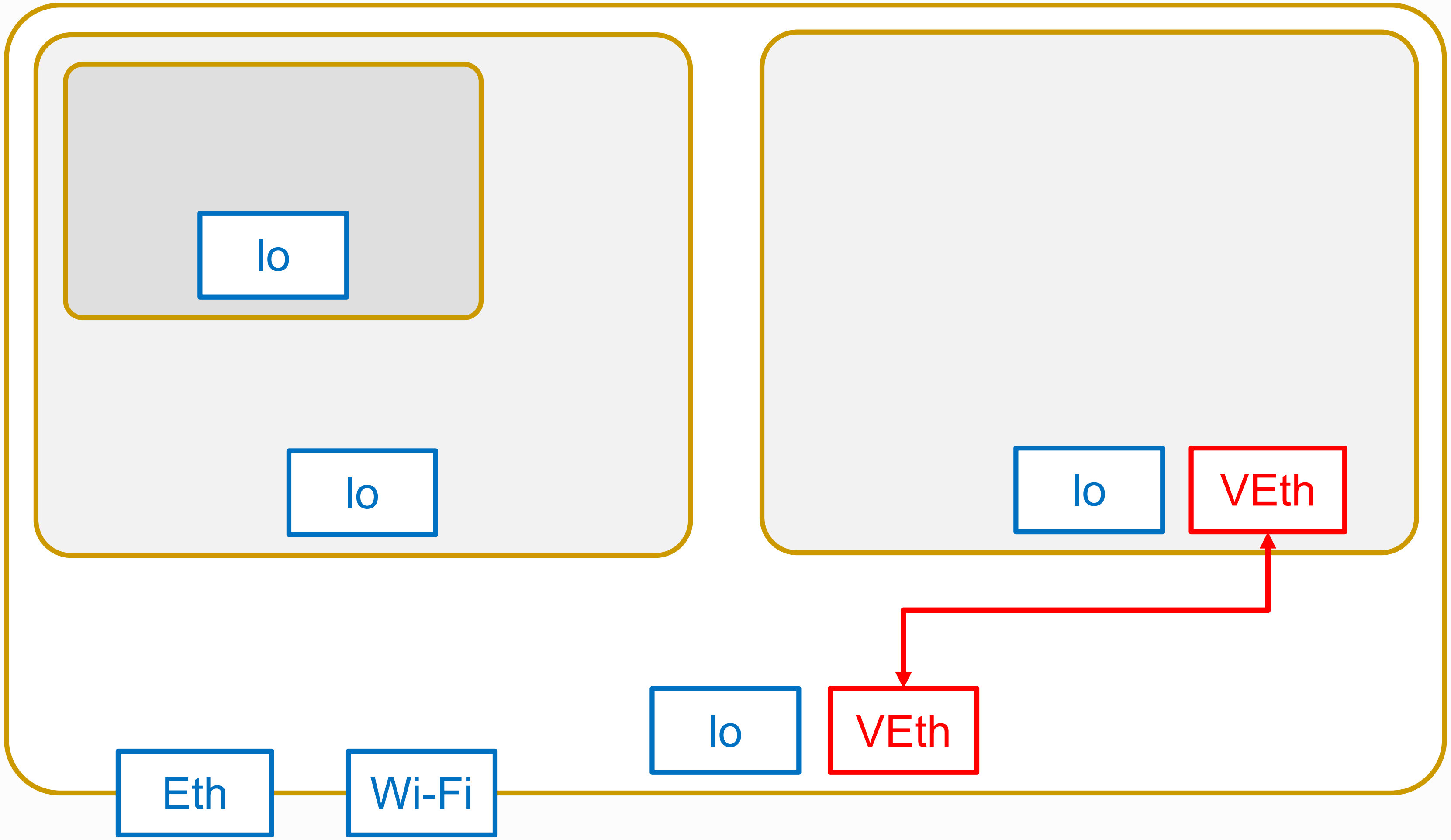
- **Network namespaces provide isolation of the system resources associated with networking**: network devices, Ipv* protocol stacks, IP routing tables, firewall rules, port numbers, etc;
- A physical network device can live in exactly one network namespace. When a network namespace is freed, its physical network devices are moved back to the initial network namespace;
- A **virtual network (veth) device pair provides a pipe-like abstraction** that can be used to create tunnels between network namespaces and can be used to create a bridge to a physical network device in another namespace. When a namespace is freed, the veth devices that it contains are destroyed.

Linux Programmer's Manual: *$man network_namespaces*

Network namespace

- Linux network interfaces include
  - Physical interfaces (ETH, Wi-Fi, etc.)
  - Virtual interfaces (loopback, etc.)
- A network namespace is a separate set of network interfaces
  - All virtual
  - Including loopback

Network namespaces



Mount namespace

- **Mount namespaces provide isolation of the list of mount points seen by the processes in each namespace instance**. The processes in each of the mount namespace instances will see distinct single-directory hierarchies;
- The views provided by the (/proc/[pid])/mounts, mountinfo, and mountstats files correspond to the mount namespace in which the process with the PID [pid] resides;
- If a namespace is created using **clone**, the mount point list of the child's namespace is a **copy of the mount point list in the parent's namespace**. If the it is created using **unshare**, the mount point list of the new namespace is a **copy of the mount point list in the caller's previous mount namespace**.

Linux Programmer's Manual: *$man mount_namespaces*

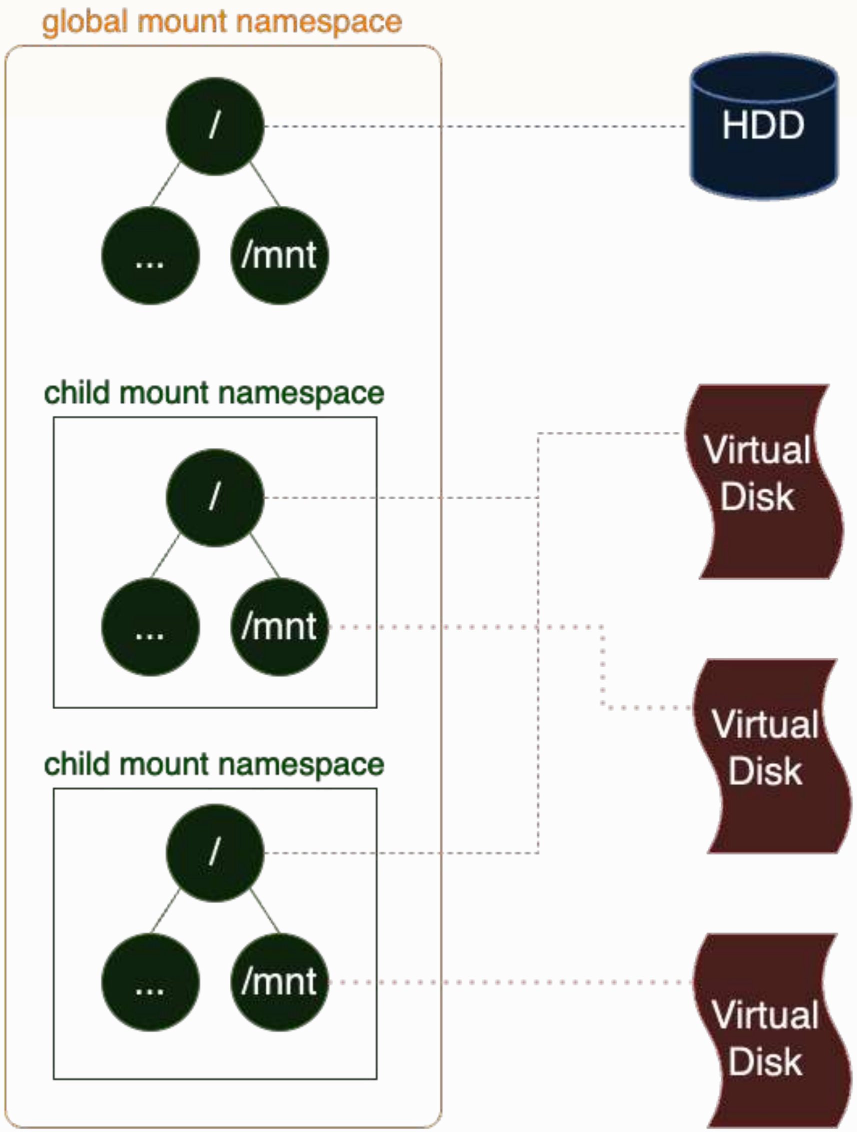
Mount namespace

- A file system includes many mounts
  - Namely / is usually mounted on a storage device

- A new mount namespace allows processes in inner namespaces to change mount points without affecting outer namespaces

- This is beneficial to mount entire file systems to different devices or even files

Mount namespaces



UTS namespace

- **UTS namespaces provide isolation of two system identifiers: the hostname and the NIS domain name**. These identifiers are set using sethostname and setdomainname, and can be retrieved using uname, gethostname, and getdomainname;
- Changes made to these identifiers are visible to all other processes in the same UTS namespace, but are not visible to processes in other UTS namespaces;
- When a process creates a new UTS namespace using clone or unshare with the CLONE_NEWUTS flag, the hostname and domain of the new UTS namespace are copied from the corresponding values in the caller's UTS namespace.

Linux Programmer's Manual: *$man uts_namespaces*

UTS namespace

- ▷ Hosts have a name and a domain name
- ▷ A new UTS namespace allows processes on it to change those names without affecting the names in outer spaces
  - This is beneficial to “simulate” the execution of applications in arbitrary hosts

User namespace

- User namespaces isolate security-related identifiers and attributes, in particular, user IDs and group IDs, the root directory, keys and capabilities;
- A process's user and group IDs can be different inside and outside a user namespace. In particular, a process can have a normal unprivileged user ID outside a user namespace while at the same time having a user ID of 0 inside the namespace;
- In other words, the process has full privileges for operations inside the user namespace, but is unprivileged for operations outside the namespace.

Linux Programmer's Manual: *$man user_namespaces*

User namespace

- Allows to create a process with all capabilities but with an arbitrary UID & GID mapping
  - The process keeps the UID and GIDs
  - But these need to be mapped to specific values
  - No mapping → 65534 (nobody)

- The mapping is a per-process, one time operation
  - /proc/[PID]/uid_mapping

LXC
Linux Containers

Container

- A container is a self-contained, standard unit of software that encapsulates an application and its dependencies to facilitate its deployment in many computing environments

- Container packaging can naturally enforce the sandboxing of applications
  - By limiting the possible interactions of the contained application with the computing environment where its container is executed

LXC containers

- Sort of Linux virtual host without virtualization
  - LXC containers use the host Linux kernel
  - But they use other namespaces for isolation
    - Processes
    - Network
    - Mount
- An LXC container is a small Linux distribution that boots on top of a running kernel
  - And has an API to be controlled from host applications

LXC containers: Privileged and unprivileged

- Privileged
  - When the containers’ UID 0 is mapped to the host’s UID 0
  - Protection of container’s abuses rely on the proper tuning of extra protections on the host’s kernel
    - AppArmor, SELinux, capabilities, etc.
- Unprivileged
  - When the containers’ UID 0 is mapped to a host’s UID different from 0
  - Processes escaping from the containers’ sandboxing will have no special privileges in the host

AppArmor

Mandatory access control for specific applications

Purpose

- Enable a system administrator to impose access control boundaries to specific applications
  - Using per-application profiles

- It allows to implement fine-grained access control policies to system resources on a per-application basis

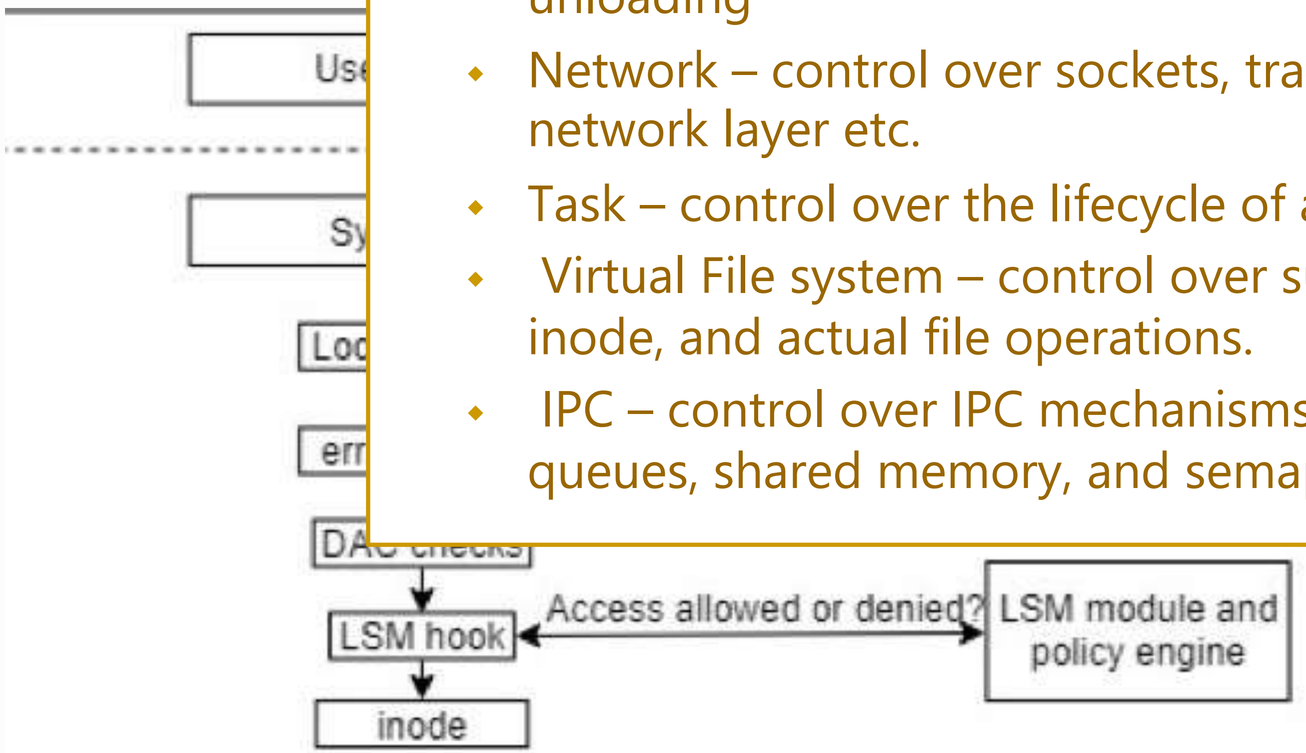
Enforcement

- It works on the kernel
  - As a Linux Security Module

- Linux Security Modules (LSM)
  - Linux kernel framework
    - Since 2.6
  - Provides “hooks” for arbitrary module inspection of system calls that are about to provide access to relevant system objects

Enforcement

- Hooks provided by Linux Security Modules
  - Module – control over module loading and unloading
  - Network – control over sockets, transport layer, network layer etc.
  - Task – control over the lifecycle of a task
  - Virtual File system – control over superblock, inode, and actual file operations.
  - IPC – control over IPC mechanisms like message queues, shared memory, and semaphores.



Benefits

- Control the objects used by one application
  - The Linux access control model is based on user identities and capacities
  - But these do not allow to limit the universe of objects that an application can access
    - e.g. an application can create a TCP connection to an IP address but not necessarily to any IP address
- Control the exposure of an application
  - An application can have multiple interfaces
  - But these interfaces may not need to be explored by all local or remote applications

Attack prevention

- It helps to reduce the attack surface of specific applications
  - Applications run with the minimum possible set of privileges for a given purpose
    - Least privilege principle
  - Any attack that compromises an application in order to behave differently from the expected have a high probability to be detected and blocked
    - e.g. execution of other binary files
    - Ideal for preventing zero-day attacks
  - Application's hidden behaviors may be detected and blocked when triggered
    - e.g. Trojan Horses

Enforcement policies

- No profile for an executing binary
  - No control
- There is a profile for an executing binary
  - The profile's access controls are enforced

Enforcement policies

- Processes: default allow
  - Processes are not by default bound to profiles
  - Bounding is required prior to exec a file
    - Enabled by writing “exec profile_name” at /proc/self/attr/apparmor
  - Binding a profile to an application with a specific profile can be done with aa-exec

- Profiles: default deny (whitelisting)
  - When a profile is used, everything is denied by default
  - Exceptions must be explicitly allowed by the profile
  - However, there are exceptions (e.g. rlimits)

Enforcement modes

- Kill
  - Access controls are enforced
  - Access violations terminate the process
  - /sys/module/apparmor/parameters/mode → kill
- Enforce
  - Access controls are enforced
  - Access violations are not allowed
    - Errors are returned
  - /sys/module/apparmor/parameters/mode → enforce
- Complain
  - Access controls are not enforced
  - Access violations just are reported (in system log files)
  - Profiles can be installed in complain mode with apparmor_parse -C
  - Installed profiles are moved to complain mode with aa-complain

Logging and auditing

- Access violations can be logged
  - For posterior auditing
  - Logged violations can be used to interactively improve profiles with aa-logprof
- Auditing definitions
  - Per profile / profile rule
  - Global

    /sys/module/apparmor/parameters/audit

Profile auditing types

- Profiles can specify a global auditing
  - All matched rules within a profile produce a log entry
  - Noisy!
- Profile rules can individually specify their audit
  - Produce a log when matched

Global auditing types

- normal
  - Profiles' audit types are respected
- quiet_denied
  - No logging of denials
  - Overrides profile/rule individual auditing
- quiet
  - No logging
  - Overrides profile/rule individual auditing
- all
  - All rules of all profiles produce a log when matched

Profiles’ loading and enforcement

- Profiles are loaded in the kernel
  - And associated to an executable file (defined in the profile)
- Profiles are associated with processes upon an exec syscall
  - If there is a profile for the loaded executable file
- Profiles can be modified in run-time
  - Processes associated to the profile will reflect the modifications
- New profiles loaded for an executable file are not enforced in existing processes using that file without any profile

Profiles: what they can control

- File access
- Exec
- Capabilities
- Network
- UNIX sockets
- Mount
  - mount / remount / unmount
  - pivot_root
- Signals
- Dbus
- ptrace
- rlimits

Profiles

- Text files
  - Compiled and installed with apparmor_parser

- Skeleton profiles
  - Default empty profiles to start with
  - Generated with aa-easyprof for a given application

Skeleton profile

```
# vim:syntax=apparmor
# AppArmor policy for apparmor_parser
# ###AUTHOR###
# ###COPYRIGHT###
# ###COMMENT###

#include <tunables/global>

# No template variables specified

"/usr/sbin/apparmor_parser" {
  #include <abstractions/base>

  # No abstractions specified

  # No policy groups specified

  # No read paths specified

  # No write paths specified
}
```

- Comments
- Global variables
- Base abstractions

Profile syntax: variables

- @{var_name}
  - @{var_name}=…
    - Variable assignement
  - @{var_name}
    - Variable value
- Defined internally
  - Preconfigured
    - /etc/apparmor.d/tunables
  - Automatic
    - @{profile_name}

Profile syntax: includes

- include filename
  - Or #include filename
  - CPP like
- Filenames
  - include "/absolute_path"
  - include "relative_path"
  - include <magic_path>
    - From /etc/apparmor.d by default
- Existing includes
  - Abstractions
    - include <abstractions/…>
    - Minimum, harmless access to fundamental resources
  - Variable definitions
    - include <tunable/…>

Profile syntax: feature ABI

- Application Binary Interface

- abi filename
  - Absolute, relative or magic

- The file contains the feature set used in the profile
  - Currently <abi/3.0>
  - Already included in <abstractions/base>

- This is used to adjust kernel features to the profiles' use of features

Profiles syntax: filename wildcards

- /dir_path/*
  - All files in directory /dir_path
- /dir_path/*/
  - All directories in directory /dir_path
- /dir_path/**
  - All files and directories under directory /dir_path
- /dir_path/**/
  - All directories under directory /dir_path

Profiles syntax: file permissions

- r: read
- w: write
- a: append
  - Cannot truncate
- m: memory map
  - Useful for shared libraries
- l: link
  - Add a name to an existing file
- k: lock
  - File access synchronization

TPM
(Trusted Platform Module)

Contents mainly extracted from:

A Practical Guide to TPM 2.0: Using the Trusted Platform Module in the New Age of Security,
Will Arthur and David Challener

TPM

- Cryptographic coprocessor
  - Present on most commercial general-purpose computers

- Although nearly ubiquitous, it is mostly invisible to users
  - But it is crucial for computer owners to protect their cryptographic assets

History

- 2003 - TPM 1.1b

- 2005-2009 - TPM 1.2
  - Standard software interface
    - While keeping previous APIs
  - Mostly standard package pinout
  - Protection against dictionary attacks
  - More privacy-related features
  - Non-volatile RAM
  - Certified Migratable Keys (CMKs)
  - Ability to synchronize an internal timer with an external clock

From TPM 1.2 to 2.0

- In 2000, the TCG chose the TPM hash algorithm
  - Preferring SHA-1 over MD5
  - TPM 1.2 relies a lot on SHA-1
    - Which was first successfully attacked in 2005
- TPM 2.0 was conceived to allow alternative digest algorithms
  - As well as alternatives to all cryptographic algorithms
  - It also introduced symmetric cryptography
    - For implementing hybrid ciphers

Cryptographic concepts: Hash (digest) extends

- Concept
  - X ← hash(original X || Y)
  - X is extended with the value of Y
- Hash extends cannot be set to a chosen value
  - Due to the properties of hash functions
- Use in TPM
  - To implement PCRs (Platform Configuration Registers)
  - To create audit logs
  - To create policies relatively to the TPM authentication

Cryptographic concepts: Tickets

- Data structure that contains an HMAC computed over some data
- Tickets are "signed" using an HMAC
  - Computed with a key that only the TPM knows
- Tickets are information that the TPM can recognize latter as produced by itself
  - Without having to store it

Cryptographic concepts: Symmetric ciphers

- Confidentiality of private TPM data
  - Using keys that only the TPM knows
- Confidentiality of communications
  - Using keys agreed with peers
- Ad hoc encryptions/decryptions
  - Using keys provided by requesters

Cryptographic concepts: Symmetric cipher modes

- Block modes: ECB, CBC
  - Data needs to be multiple of block size -> Padding
- Stream modes: CFB, OFB, CTR
  - To be used when data is not block aligned
- Integrated integrity control
  - HMAC-based Encrypt-then-MAC
  - HMACs computed with nonces for replay prevention

Cryptographic concepts: Endorsement keys (EKs)

- Key pairs that identify TPM devices
  - They are certified by the TPM manufacturer
  - Their X.509 certificate can highlight the TPM device features
- These keys can be used to certify other TPM keys
  - Produced by the TPM
  - Those certificates do not use X.509

Use cases

- Host identification
  - To authorize its participation in protected environments
- Host data encryption
  - Files, file systems, highly sensitive date (passwords)
- Key storage
  - Encrypted with the TPM public key
  - Encrypted keys can be stored anywhere

Use cases

- Random number generation
  - Fundamental to generate their own keys and nonces
- NVRAM for storing critical data
  - Root keys of certification chains
  - Endorsement keys (EKs)
  - State to be achieved during a controlled bootstrap
    - Used by Intel **Trusted Execution Technology**

Use cases

- PCRs (Platform Configuration Registers)
  - They keep hash extends
  - Those hash extends can report sequences of measurements
  - They can be used as authentication signals
    - Secrets can be unlocked only when they have a given value
    - In 2.0 they can be unlocked if matching a value signed by a trusted party (to avoid PCR fragility)
      - Non-Brittle PCRs

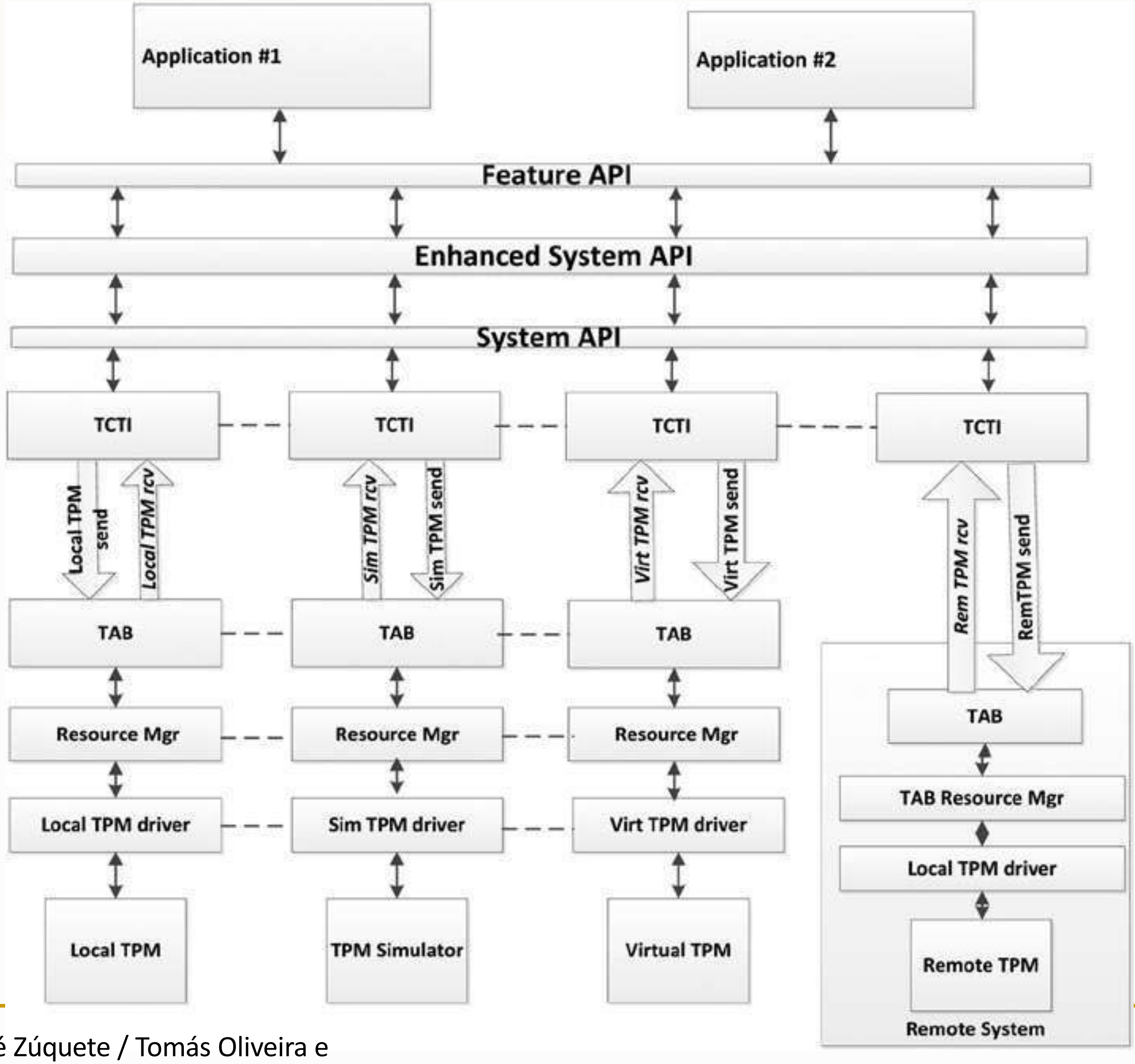
Use cases

- Privacy enhancement
  - Storage of password-protected secrets with delay mechanisms to prevent guessing attacks
  - Attestation Identity Keys (AIKs), or simply AKs
    - Can be used to identify the host (or owner) in different scenarios
  - Direct anonymous attestation (DAA)

TPM Software Stack (TSS)

- TCG software standard
  - Applications written to the TSS should work on any system that implements a compliant TSS
- Many layers
  - Feature API (FAPI)
  - Enhanced System API (ESAPI)
  - System API (SAPI)
  - TPM Command Transmission Interface (TCTI)
  - TPM Access Broker (TAB)
  - Resource Manager (RM)
  - Device Driver

TSS overview



TPM concepts: Policies and authorizations

- An authorization is granted after the satisfaction of a security policy
  - A policy states what needs to be done to unlock the authorization
  - e.g. can read after providing a correct password

TPM entities

- Permanent
- Non-volatile indexes
- Objects
- Non-persistent entities
- Persistent entities
- Entity names

TPM entities: Permanent

- Defined by the specification
  - Cannot be created nor deleted

- Persistent hierarchies
- Ephemeral hierarchies
- Dictionary attack lockout reset
- PCRs
- Password authorization session
- Platform NV enable

TPM permanent entities: Persistent hierarchies

- Their elements persistent across power-off
- Each one has an authorization and a policy
- Platform
- Storage
- Endorsement

TPM permanent entities:
Ephemeral hierarchies

- Their elements disappear across power-offs
  - But the hierarchies do not
- Have an authorization and a policy
- NULL hierarchy

TPM permanent entities: Dictionary attack lockout reset

- A mechanism designed to overrule lockout states entered upon an excessive number of authentication failures

- Has an authorization and a policy

TPM permanent entities: PCRs

- Arrays of registers
  - Accessed by index
  - Organized in banks by algorithm
- Each has an authorization and a policy
  - For updating only
  - Reading is always allowed

TPM permanent entities: Password authorization session

- Sessions help to organize several commands under a common authorization policy
- Password authorization sessions are special
  - They only last for a command
  - Thus, they are implicit (thus, permanent)

TPM permanent entities: Platform NV enable

- The access to non-volatile (NV) platform data is controlled by this control

- Platform NV data belongs to the platform hierarchy

TPM non-volatile (NV) indexes

- A kind of pointer (or handle) to NV storage
  - With a structure unknown to the TPM
- Have more attributes than objects
  - Which have a structure known by the TPM
- Each one has an authorization value and a policy
  - Authorizations can be changed by the index owner
  - Policies cannot be changed
- They belong to a hierarchy
  - And are cleared when the hierarchy is cleared

TPM NV index types

- Ordinary
  - Can contain any value, of arbitrary length
- Counter
  - Can contain an increment-only 64 bit value
  - Initialized to the largest value that any counter has ever had in the TPM
- Bit field
  - 64-bit array
  - Initialized at zero, bits can only be set (never reset)
- Extend
  - Similar to a PCR

TPM objects

- Key or data
- Each one has an authorization data and a policy
  - Authorizations can be changed by the object owner
  - Policies cannot be changed
- They belong to a hierarchy
  - And are cleared when the hierarchy is cleared
- Their use requires a TPM non-persistent entity: the session

TPM non-persistent entities

- They disappear on power-on
  - Reset (upon reboot)
  - They can be saved out of the TPM
    - But not reloaded after a power cycle
- Are preserved across restarts and resumes
  - These operations send a different order to the TPM
- Authorization sessions

TPM persistent entities

- An object that the owner of a hierarchy sets to persist across power cycles
- Usually, keys
  - And just a few, since the TPM has a small persistent memory

TPM entity names

- Names prevent the reuse of handles
  - They are given to entities that can reuse handles
  - They are unique entity identifiers
- Permanent entities have no name
  - Their handle is constant
- Other entities have a name that is a hash of their public data

TPM hierarchies

- Hierarchy is a collection of related entities
  - Managed as a group
  - Can be enabled or disabled
- They include:
  - Permanent entities
    - Hierarchy handles
  - A private, random cryptographic root
    - Seed
  - Key trees
    - Starting on a primary key
  - NV indexes
  - A private proof value
    - To check whether a value was produced by the TPM

Platform hierarchy

- Intended to be in control of the platform manufacturer

- It is always configured by the manufacturer firmware upon a boot
  - Which can also enable or disable it

Storage hierarchy

- Intended to be in control of the platform owner
  - Company
  - End user
- Intended for non-privacy-sensitive operations
- All its contents can be cleared by the owner
  - Useful when changing owners

Endorsement hierarchy

- Intended to be in control of the platform user
- The TPM chip generates its seed when first powered on
  - Endorsement primary seed
- Several primary keys are derived from the seed
  - And certified by the TPM manufacturer
    - Certification attests they belong to a genuine TPM
  - Usually these are encryption/decryption keys
    - And not signing keys

Key management

- Can generate keys internally
  - And export them
  - Public keys can be exported unprotected
  - Private keys can be exported protected
    - Wrapped
- Can import keys
  - Previous exported by itself
  - Produced by others

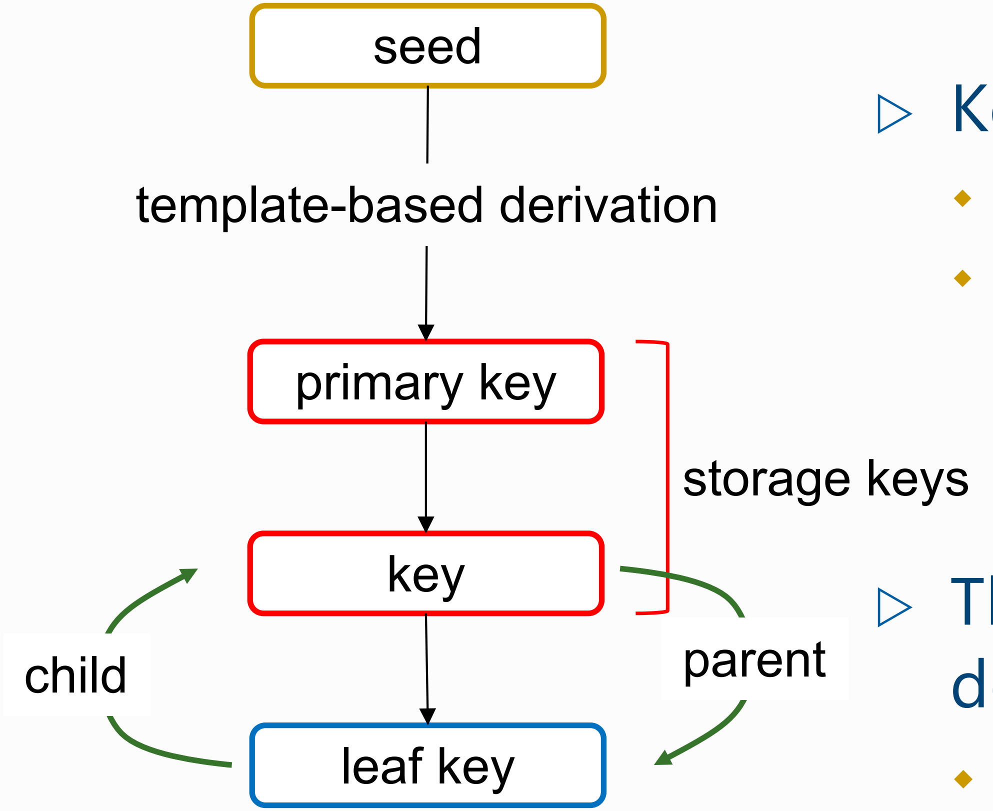
Key management:
TPM as a key cache

- Many times keys must be used within the TPM confined environment
  - But the TPM resources should not limit their number
- Solution
  - Off-load keys to external repositories (wrapped)
  - Import keys of interest
  - Use cached keys
  - Clear cached keys from TPM

Key trees (aka key hierarchies)

- Sequence of keys
  - Starting from a top-most, primary key
  - Hierarchies can have several key trees
- Primary keys are generated from hierarchy seeds
  - And a public template
  - Template:
    - Algorithm, key size, policy, usage
    - Arbitrary data (kind of label)
- The key derivation is idempotent
  - Same seed, same template → same key

Key tree: storage keys



- ▷ Keys that encrypt keys
  - A storage key is a parent of a child key
  - It can be used to wrap the child key
    - For exporting it
- ▷ They cannot be used for arbitrary decryption
  - It could compromise wrapped child keys

Key trees: changing seeds

- Different seed → different key tree
  - The previous one is naturally flushed

- This should not happen to the endorsement seed
  - Because endorsement keys are pre-certified by the TPM manufacturer
  - Getting the certification again is complex
  - Can only be changed by the platform builder (OEM)
    - This is not an issue for the platform owner
    - New keys can always be created with different templates

Key trees:
Endorsement primary keys

- Need to be certified by the TPM manufacturer
  - The TPM manufacturer uses it to generate candidate primary keys
    - Using well-defined templates
  - The public keys are exported and certified
    - The manufacturer keeps the certificates
  - The keys are removed from the TPM
    - The TPM keeps the seed that allows the recreation of keys with the same templates used by the manufacturer

Key duplication

- Copy of a key into a different hierarchy
  - It continues to exist in the original place
- Primary keys cannot be duplicated
  - Because they cannot be wrapped
  - They are generated from a seed
    - And a template
- Duplication of parent keys can duplicate their children
  - Duplication group

Key attributes

- Type
  - Symmetric
  - Asymmetric
- Usage
  - Signing
  - Encryption
  - Decryption
- Use restrictions
  - Restrict signing
    - Attestation
  - Restrict decryption
    - Storage
- Duplication restrictions
  - Fixed TPM
    - Cannot be duplicated
  - Fixed parent
    - Can only be duplicated under a duplicated parent

Restrict signatures

- Signatures made by the TPM over TPM internal data
  - Mainly for attestation
  - This proves that the data was totally generated by the TPM
- These signatures can also be made over externally provided data
  - Hashed by the TPM
    - Internal hashing produces a ticket that unlocks a restricted signature
  - But the external data cannot reproduce internal values
    - 4-byte magic value (TPM_GENERATED)
    - Used when hashing internal data structures
    - Cannot be in the beginning of the hashed external data

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Sessions

- Maintain state between sequences of commands
- These are the vehicle for authorizations
  - As they configure per-command attributes
    - Encryption/decryption of command/response parameters

Session variations

- Bound / unbound
  - The session is bound to an authorization value
  - The session key is computed with it
  - Calculations depending on the session key are affected

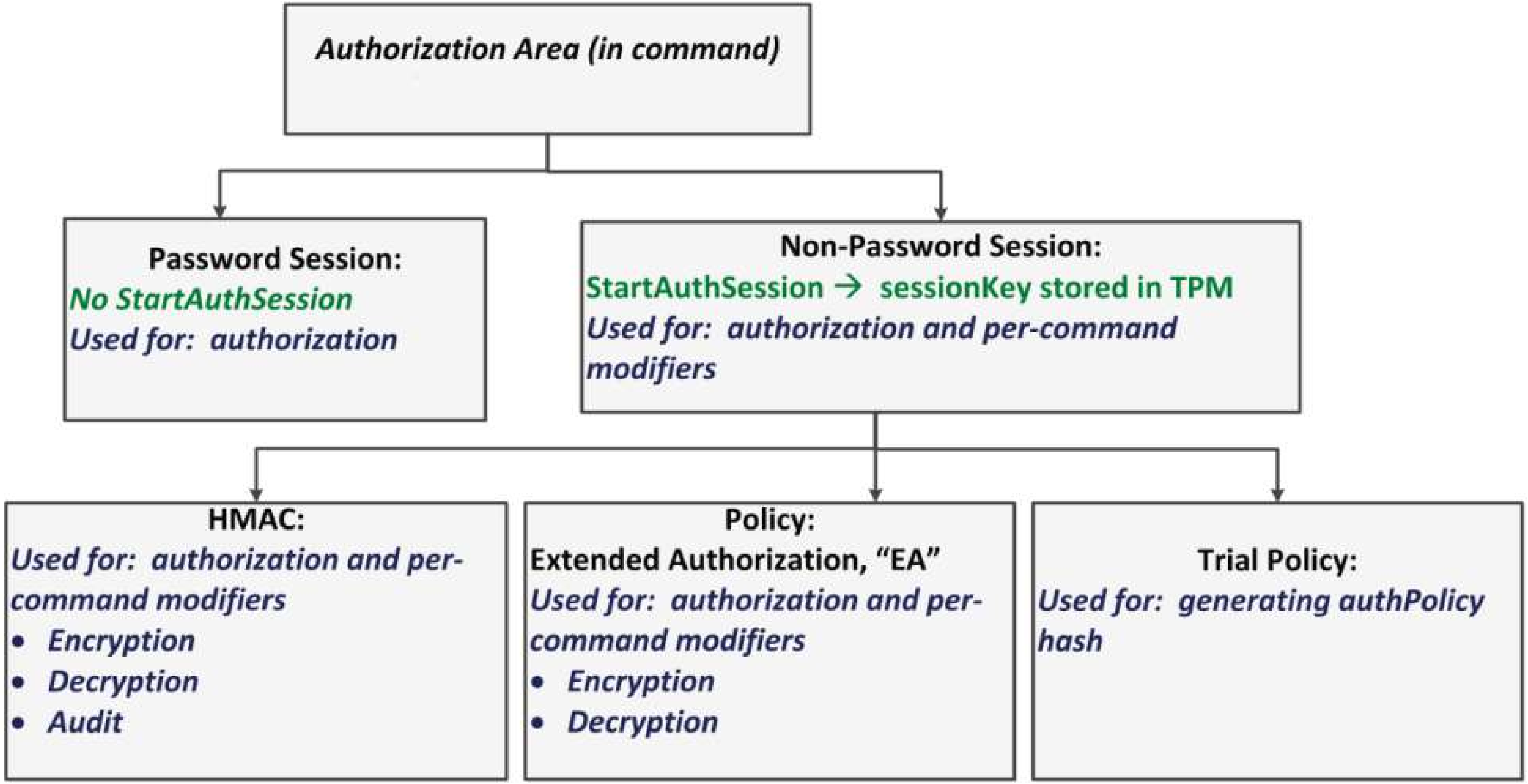
- Salted / unsalted
  - Extra entropy for the session key

Session use modifiers

- Per-command modifiers

- Continue
  - Keep the session after a successful command
- Decrypt
  - Part of the request goes encrypted
- Encrypt
  - Part of the response should come encrypted
- Audit
  - The command is to be audited

Session types



Session types: Password

- Single-command session
  - A permanent entity
- Operation depends on the password
  - The password is provided in cleartext
  - It is meant to be used locally

Session types:
HMAC

- A password is uploaded to the TPM
  - authValue
  - A one-time operation
- Each session interaction has an HMAC computed with the shared authValue
  - Both request and response
  - Each also used a nonce
    - The TPM nonce changes on each response

Session types:
Policy (Enhanced Authorization)

- Are build on top of HMAC session

- Use policies to compute a shared secret
  - Logical expressions
  - Sequences of commands
  - Internal and external state

Authorization roles

- 3 roles
  - USER
  - ADMIN
  - DUP
- Entities' attributes for authorization
  - userWithAuth
  - adminWithPolicy

	Set	Clear
userWithAuth	password HMAC policy	policy
adminWithPolicy	policy	password HMAC policy

Bootstrap security

Initial steps: AEGIS

Arbaugh, William A., David J. Farber, and Jonathan M. Smith. *A secure and reliable bootstrap architecture*. IEEE Symposium on Security and Privacy. 1997.

- Assuming that a host hardware is valid, integrity of a higher layer can be guaranteed iif
  - The integrity of the lower layers is checked
  - Transitions to higher layers occur only after integrity checks on them are complete

- The resulting integrity "chain" inductively guarantees system integrity

AEGIS goal

- Without a secure bootstrap, the operating system kernel cannot be trusted
  - Since it is launched by an untrusted process
  - Designers of trusted systems often avoid the problem by including boot components in the TCB
- AEGIS was a secure bootstrap process
  - Ensuring the integrity of bootstrap code

AEGIS approach

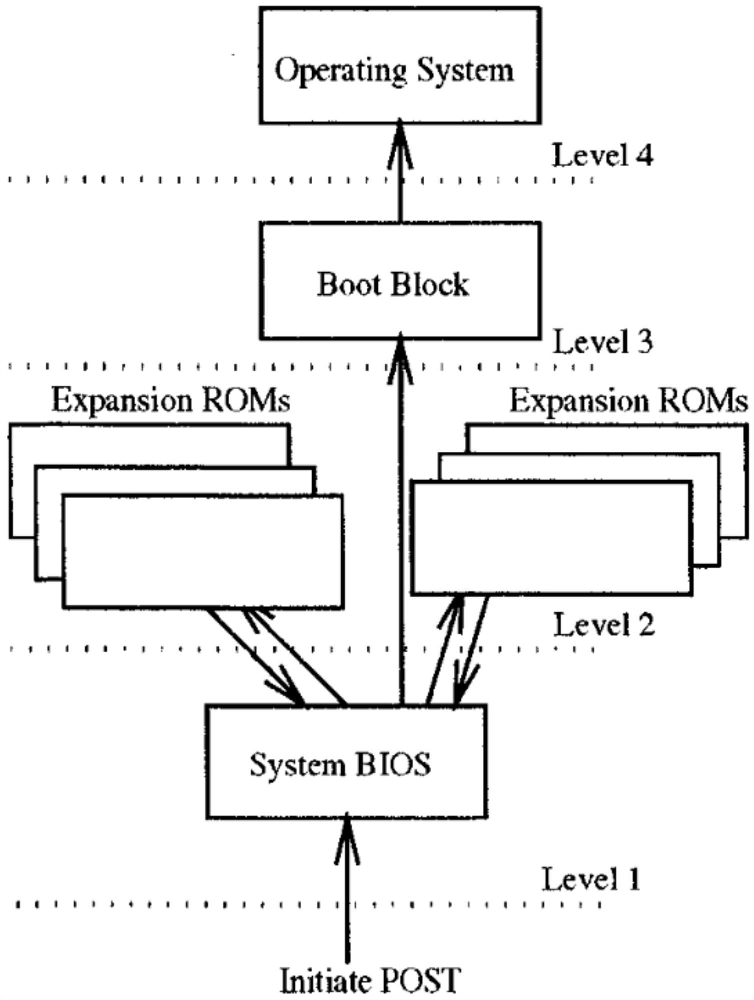
- It constructs a chain of integrity checks
  - Beginning at power-on
  - Continuing until the final transfer of control from the bootstrap process to the operating system
- Integrity checks are hard to circumvent
  - Match of a computed cryptographic hash value with a **stored digital signature** associated with each component

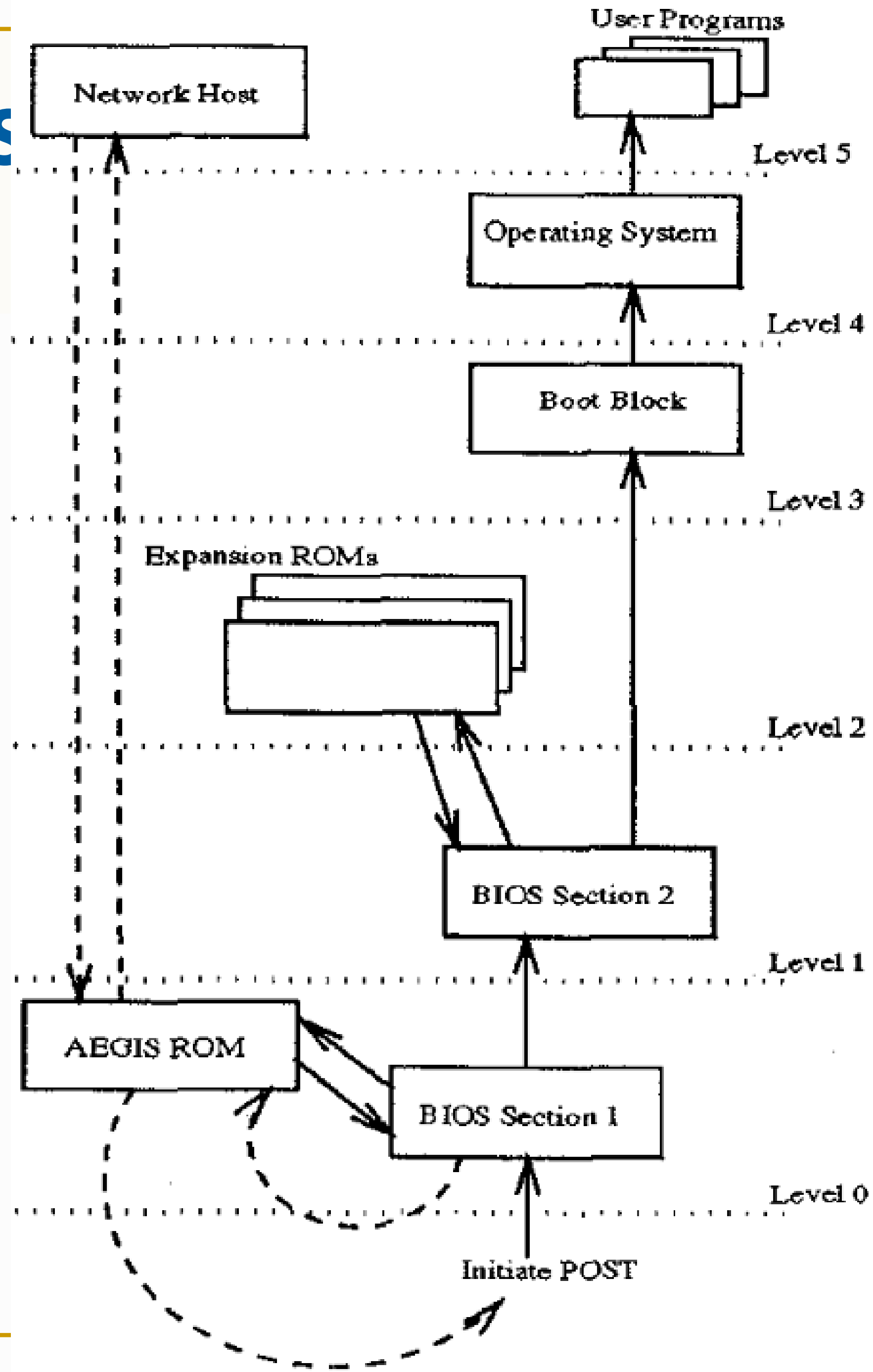
AEGIS guaranteed secure boot process

- Two mechanisms guarantee the boot process ends up in a secure state
  - Even in the event of integrity failures outside of a minimal section of trusted code

- 1st - No code is executed unless it is either explicitly trusted or its integrity is verified prior to its use
- 2nd – Upon an integrity failure, a process can recover a suitable, verified replacement module

AEGIS boot process





Trusted computing: chains of trust

- Trust is built upon measurements
  - If one can measure, one can evaluate
  - In this case, we want to measure code that executes
    - Not what the code does, but what the code is
    - The evaluation is performed before the actual execution
- Chains of trust
  - Trust that code R is correct, and measures other code, run R
  - If R needs to run code A, measures A, registers measure, runs A
  - If A needs to run code B, measures B, registers measure, runs B
  - At the end, all ran code was measured
    - And a tampered code will be detectable by its measurement by the predecessor

Root of Trust Measurements

- Static (SRTM)
  - Part of the BIOS/UEFI
  - The first code that runs upon a power-on
  - Initiates the boot chain of trust
- Dynamic (DRTM)
  - ACM (Authenticated Code Module)
    - Stored in the BIOS, authenticated by the CPU
  - Requires a special, secure CPU mode
    - Intel TXT (Trusted eXecution Technology)
    - AMD SVM (Secure Virtual Machine)

SRTM and DRTM

- SRTM ensures a trusted chain until a bootloader
  - Inclusive
  - Meaning that all the code executed until the bootloader can be evaluated
- DRTM ensures a trusted OS boot
  - Meaning that all the code executed during the OS boot can be evaluated

Trusted Computing Platform Alliance (TCPA)

Reid, Jason, et al. *Privacy and trusted computing*. 14th Int. Workshop on Database and Expert Systems Applications. 2003.

- TCPA uses the following definition of trust:
  - "A trusted component, operation, or process is one whose behaviour is predictable under almost any operating condition and which is highly resistant to subversion by application software, viruses, and a given level of physical interference."

TCPA: desirable trustworthiness

- The platform owner and user should be able to trust its configuration of the platform
  - e.g., that it is not running malicious or unauthorized software that could compromise sensitive information

- Remote attestation
  - A platform should be able to attest information about its current configuration to another platform in a manner that the second platform can trust
  - It allows an entity to authenticate the software configuration of a platform that is not under its control

TCPA-related architectural modifications

- Trusted Platform Module (TPM)
  - Cryptographic component in the platform
  - Provides a range of cryptographic primitives
    - Random number generation
    - Hashing
    - Symmetric encryption/decryption
    - Asymmetric key pair generation, enc/dec, sign/verify
    - Protected storage for keys

TPM types (1/5): Discrete

- ▷ Implemented by a discrete chip
- ▷ Chip designed, built and evaluated for the highest level of security
  - Can resist tampering with the chip
  - Can resist probing and freezing with all sorts of sophisticated attacks
- ▷ Highest level of security

TPM types (2/5): Integrated

- A hardware TPM
  - But integrated into a chip that provides other functions
- Resistant to software bugs
  - But not designed to be tamper-resistant
- Security is very high

TPM types (3/5): Firmware

- Implemented in protected software
  - The code runs on the main CPU
    - A separate chip is not required.
  - The code runs is in a protected execution environment
    - Trusted Execution Environment (TEE)
    - The TEE separates it from the rest of the programs running on the CPU
  - Secrets needed by the TPM can be kept in the TEE
    - Creating a more difficult path for hackers

- No tamper resistance
  - Depends on many additional aspects to keep it secure (e.g. TEE)

- Security is high

TPM types (4/5): Software

- Implemented in software
- Good for developing a TPM-based prototype
- Its security is not an issue

TPM types (5/5)

- Virtual
  - For cloud environments
- Provided by the hypervisor
- Security is high

TPM types and needs

Trust element	Security level	Security features	Relative cost	Typical application
Discrete	Highest	Tamper resistant HW	$$$	Critical system
Integrated	Higher	HW	$$	Gateways
Firmware	High	TEE	$	Entertainment systems
Software	N/A	N/A	¢¢	Testing & prototyping
Virtual	High	Hypervisor	¢	Cloud environment

https://trustedcomputinggroup.org/wp-content/uploads/TPM-2.0-A-Brief-Introduction.pdf

TCPA root of trust

- Core Root of Trust for Measurement (CRTM)
  - BIOS trust boot block
- The CRTM takes a hash of the BIOS before executing code other than CRTM
  - The result is stored in a TPM register
  - Platform Configuration Register (PCR)

TPM PCR (Platform Configuration Register)

- A register that can not be deleted or set
  - It can only be cleaned on power-on or extended
- Its value results from a hash chain
  - Each new value stored is hashed with its value
    - Becoming the new value
    - PCR_{i+1} = hash(PCR_i , value to extend)
  - All stored values are logged for validation
- The goal of a PCR is to act as a log validator

TPM PCR banks

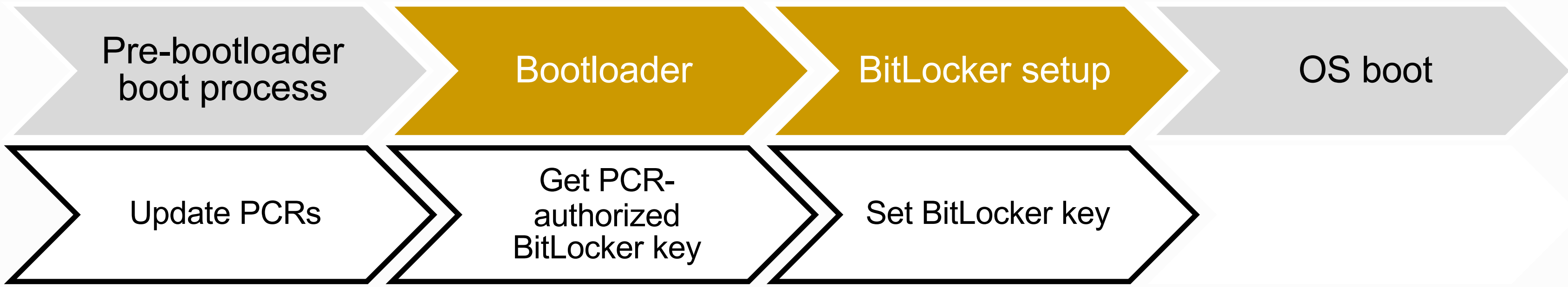
- Groups of PCR registers per hashing function
- Banks can be deactivated by the BIOS
  - The BIOS can only use banks for which it knows (implements) the hash function
- Banks' allocation (24 PCR)
  - 0-7: SRTM
  - 8-15: OS measurements
  - 16-23: DTRM

TPM authorization PCR

- An authorization PCR is one which value is used to unlock a TPM secret
  - e.g. a disk encryption key
  - e.g. VPN endpoint authentication key
- It allows a system that boots as expected to have access to secrets without human intervention

TPM authorization PCR example

- Microsoft BitLocker
  - BitLocker encrypts the file system
  - The secret key can be stored inside TPM
  - The secret key can be automatically recovered upon a boot performed as expected
    - It is recovered by the Microsoft boot loader
  - Otherwise, the Windows OS will not launch



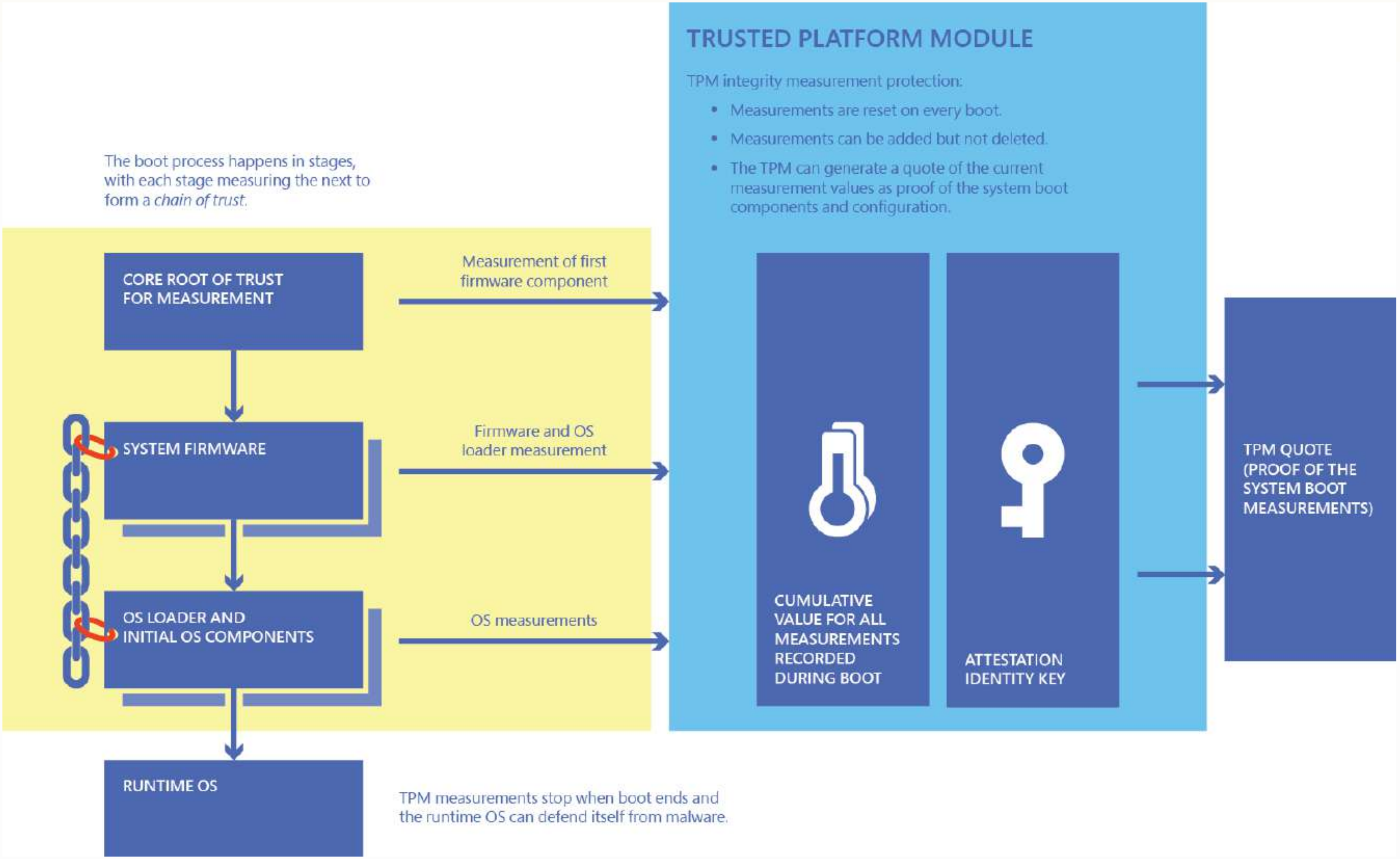
TCPA boot modes

- Secure boot
  - Boot is terminated if a PCR value does not match an expected value
- Authenticated boot (or trusted boot)
  - Values are stored in PCR registers along the boot
  - This values can be checked a posteriori
  - The platform can end up in any arbitrary state

MS Windows measured boot

- Authenticated boot
- TPM records with the chain of measurements of software components and configuration information through the initialization of the Windows operating system
  - Previously the measurement chain stopped at the Windows Boot Manager component
  - The measurements in the TPM were not helpful for understanding the starting state of Windows
- Measured information
  - Software: kernel, early-launch anti-malware drivers, and boot drivers
  - Configuration settings: malware signatures, Windows security features

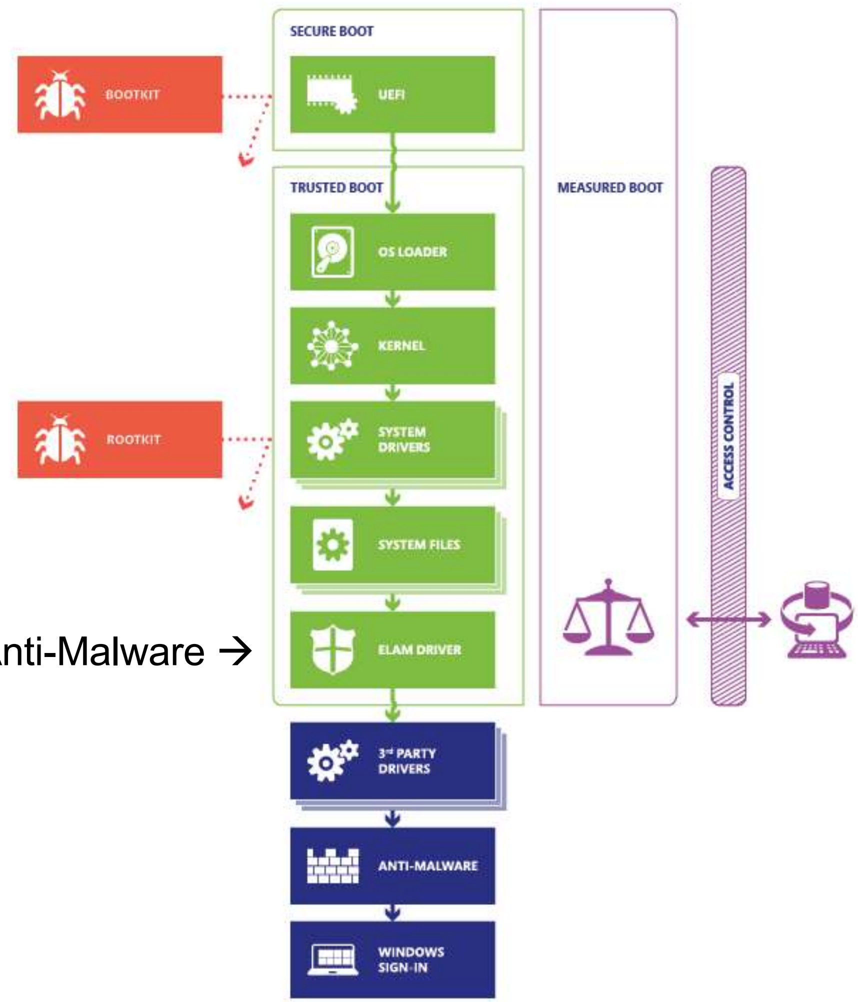
MS Windows measured boot



https://docs.microsoft.com/en-us/windows/security/information-protection/tpm/how-windows-uses-the-tpm

MS Windows 10 measured boot

ELAM – Early Lauch Anti-Malware →



https://docs.microsoft.com/en-us/windows/security/information-protection/secure-the-windows-10-boot-process

TCPA remote attestation

- Remote verification that a host booted properly
  - That the boot process ran as expected
  - It does not mean the system is secure!

- It relies on authenticated boots
  - The TPM provides all PCR values of the last boot
  - This data set is signed by the TPM device
  - PCR quote
    - Signed PCR report
    - Includes a nonce provided to ensure freshness

TPM-based attestation

- Endorsement key pair
  - A key pair generated by the TPM
    - Cannot be deleted
    - Private key is never released
  - Used to sign/verify TPM assertions
  - Used to send confidential data to a TPM
- Endorsement public key certification
  - Usually performed by the TPM manufacturer

TPM attestation with pseudonymous

- The endorsement key never changes
  - Thus, it reveals a host on its attestation

- Identity credentials
  - Temporary credentials used in attestation
  - They are generated by the TPM
  - The public key is certified by a Privacy Certification Authority
  - The endorsement key pair is used to get that certification

Trusted Platform identity credentials: Requirements

- TPM endorsement credential
  - Endorsement public key certificate
  - To attest that the TPM is genuine
- Platform credential
  - Signed by a Platform Entity (e.g. manufacturer)
  - To attest that a given TPM has been integrated in a platform
- Conformance credential
  - Signed by a Conformance Entity
  - To attest that the TPM & the platform designs conform with TCPA

Trusted Platform identity credentials: Issuing protocol

- TP generates a new identity key pair
  - IdPriv, IdPub
- TP sends a new identity request to a Privacy Certification Authority (PCA) including:
  - IdPub, EndCred, PlaCred, ConCred, Sign(BindData)
- IdPriv is used to generate a signature on BindData, which encompasses the hash of the PCA's public key and IdPriv.
  - The signature is attached to the request.

https://ieeexplore.ieee.org/document/1232052

Trusted Platform identity credentials: Issuing protocol

- On receipt of the request, the Privacy CA(PCA) verifies the submitted credentials and the signature.
  - If the verification is successful, the PCA proceeds to create the identity credential (IdCred), essentially a certificate on IdPub signed by the Privacy CA.
- PCA sends Identity Credential to TP
  - Encrypted with EndPub of the TPM
  - Enc(IdCred, EndPub)

UEFI (Unified Extensible Firmware Interface)

- Current firmware interface for PCs
  - Replacing Basic Input and Output System (BIOS)
- Its goal was to define a standard way for the operating system to communicate with the platform firmware during the boot process
  - Instead of the former primary mechanism, software interrupts
- UEFI allows for modular firmware design
  - Enables hardware and system designers a greater flexibility in designing firmware for modern computing environments

UEFI secure boot

- Firmware validation process
  - Defines how platform firmware manages security certificates, validation of firmware, and a definition of the interface (protocol) between firmware and the operating system
- Goal: validate an OS bootloader

UEFI secure boot keys

- Platform Key (PK)
  - (Usually only one) asymmetric key pair
  - Should be under control of the platform owner
- Key Exchange Key (KEK)
  - Set of Asymmetric key pairs
  - Controlled by the OEM and OS vendors
- KEKs can only be changed by the PK owner

UEFI secure boot signature databases

- Forbidden signatures database (blacklist, dbx)
  - Hashes of blacklisted firmware code
- Signature database (whitelist, db)
  - Key or certificates of keys that validate signatures over authorized firmware code
  - Hashes of allowed firmware
- KEK owners can update both databases

UEFI secure boot firmware validation

- Firmware code is not allowed to execute if
  - Its hash is in DBX
- Firmware code is allowed to execute if
  - It is signed by a key in DB; or
  - Has its hash in the DB; or
  - Is signed by a KEK key

UEFI storage of secure boot keys and DBs

- They are stored in UEFI secure variables
  - Each variable is bound to a public key
    - Set upon its creation
  - Variables can only be changed if an authentication descriptor is provided
    - With a signature made with the corresponding private key
  - Authentication descriptors cannot be reused
    - To avoid replay attacks

UEFI setup and user modes

- Setup mode
  - PK, KEK, db and dbx can be changed without checks
  - Secure boot is off
- User mode
  - PK, KEK, db and dbx cannot be changed without verification
    - PK, KEK → requires PK signature
    - db , dbx→ requires a KEK signature

NSA Boot Security: Modes and Recommendations

- Legacy (BIOS or CSM) boot
- UEFI native boot
- Secure boot standard mode
- Secure boot custom mode
- UEFI or legacy boot with TPM auditing
- UEFI secure boot with TPM auditing

NSA Boot Security: Modes and Recommendations

- Legacy (BIOS or CSM) boot
  - Many computing devices feature a legacy boot mode called Basic Input/Output System (BIOS) mode or Compatibility Support Module (CSM).
  - Legacy boot modes are intended to be used with older peripherals, hardware, and software lacking support for Unified Extensible Firmware Interface (UEFI)2 standards.
  - Compatible with decades of solutions and protocols.
  - Least restrictive solution in terms of security features.
  - Processor vendors are discontinuing legacy mode support starting in 2020.

NSA Boot Security: Modes and Recommendations

- UEFI native boot
  - Unified Extensible Firmware Interface (UEFI) adheres to standards defined by the UEFI Forum.
  - Hardware, software, peripheral, system vendor, and solution providers collaborate to define common interfaces, variables, protocols, feature sets, and structures for use on modern computing platforms.
  - Binaries are arranged in the form of modules. Modules can be patched, replaced, added, removed, or otherwise altered individually as needed.
  - Some modules can execute in parallel to accelerate boot time.
  - Some modules can fail or enter error states without affecting a device's ability to boot.

NSA Boot Security: Modes and Recommendations

- UEFI native boot
  - UEFI relies upon Secure Boot or vendor-specific boot protection solutions – no validation or protection of the boot process is granted simply by choosing UEFI over legacy mode.
  - Some older hardware and software do not function in UEFI mode.

NSA Boot Security: Modes and Recommendations

- Secure boot standard mode
  - Secure Boot is a signature and hash-checking mechanism added to the UEFI boot process.
  - Each firmware and software executable at boot time must have an associated signature or hash. Secure boot validates signatures using RSA-2048 public key certificates.
  - System firmware, component firmware, bootloaders, kernels, and other boot-time executables are validated by Secure Boot to provide a boot-time anti-malware solution.
  - Secure Boot signing authorities may make mistakes in granting signatures or loading hashes.
  - Bootloaders that ignore Secure Boot and boot-time malware have been mistakenly signed and released to the public in the past.

NSA Boot Security: Modes and Recommendations

- Secure boot custom mode
  - Custom mode allows the system owner to exert control over Secure Boot's data stores.
  - The system owner assumes full responsibility for signing and hashing trusted content (e.g. bootloaders, kernels) rather than relying upon the ecosystems set up by MSFT and system vendors.
  - Administrators can trust specific hardware components, boot methods, and boot software. Allows system owners such granular control that they can trust an individual version of an OS kernel.
  - Administrative overhead is required to sign binaries and identify the hashes of items that cannot be signed.
  - Systems must be provisioned with a custom Secure Boot. Administrators must create custom Secure Boot update scripts.

NSA Boot Security: Modes and Recommendations

- UEFI or legacy boot with TPM auditing
  - UEFI and Legacy modes can record hashes of firmware components to the Trusted Platform Module (TPM). The TPM must be both activated and enabled for hashes to be written.
  - Hashes normally capture firmware images, firmware configuration, expansion component firmware images, expansion component firmware configurations, and the bootloader.
  - TPM-aware bootloaders can continue logging hashes to describe the kernel, initial file system, and any modules. Kernels, applications, and drivers can log runtime hashes to the TPM too.
  - TPM PCR hash extensions are automated at the firmware level from the earliest stages of boot.
  - Newer versions of Windows and Linux also automatically detect the presence of TPM and begin recording integrity information.

NSA Boot Security: Modes and Recommendations

- UEFI or legacy boot with TPM auditing
  - There is no automatic enforcement mechanism (TPM performs passive observation during boot).
  - Malware is not denied execution privileges at boot time.
  - Any valid UEFI, Legacy, or binary is allowed to execute without signature, hash, or integrity checks.

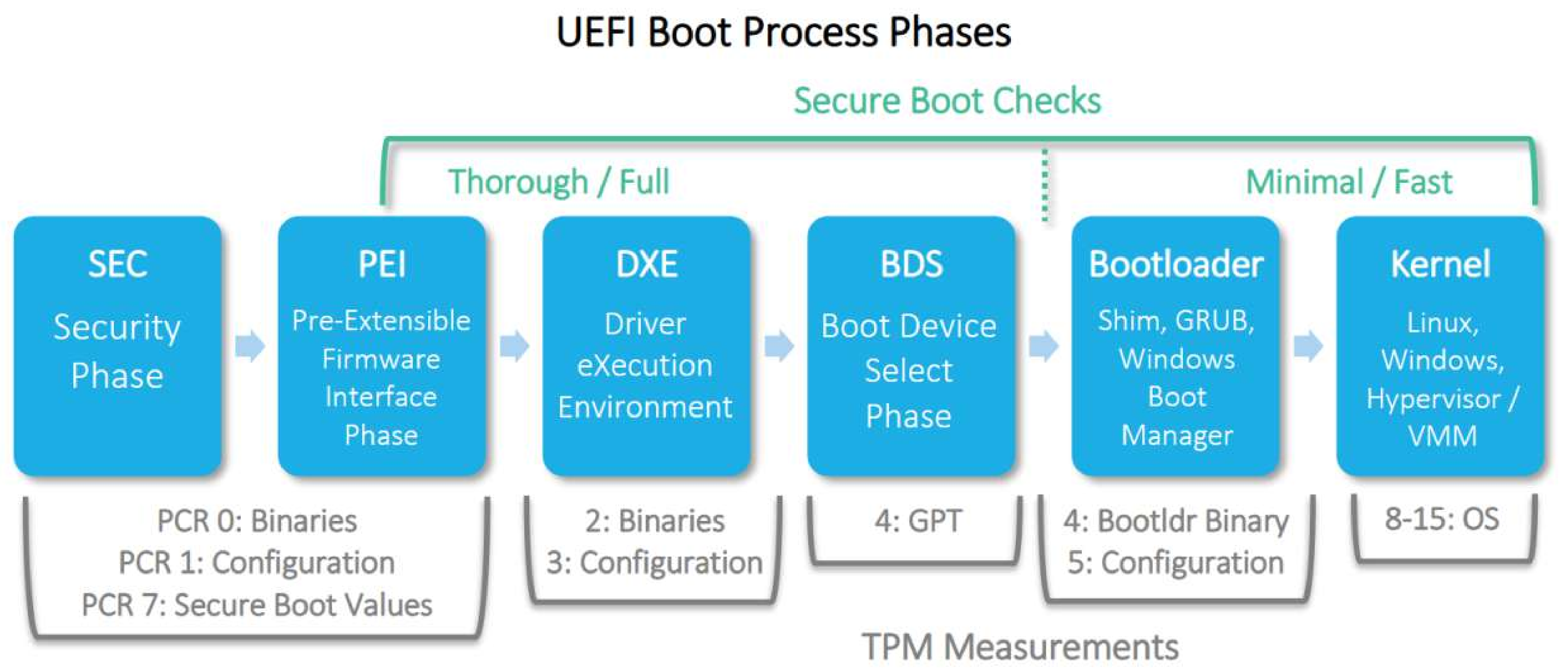
NSA Boot Security: Modes and Recommendations

- UEFI secure boot with TPM auditing
  - Secure Boot can be used in standard mode or custom mode in conjunction with TPM.
  - TPM provides the ability to cover the early-boot blind spot that exists in Secure Boot. Secure Boot allows the flexibility to handle multiple trusted system images, devices, and configurations when necessary.
  - Most restrictive option covered. Windows 10 and newer automatically leverages Secure Boot and TPM when BitLocker is enabled.
  - Requires the most developer and administrator overhead.

NSA Boot Security: Modes and Recommendations

Boot mode	UEFI Secure Boot	TPM auditing
Legacy (BIOS or CSM) boot		
UEFI native boot		
UEFI Secure boot standard mode	X	
UEFI Secure boot custom mode	X	
UEFI or legacy boot with TPM auditing		X
UEFI secure boot with TPM auditing	X	X

UEFI secure boot & TPM measurements



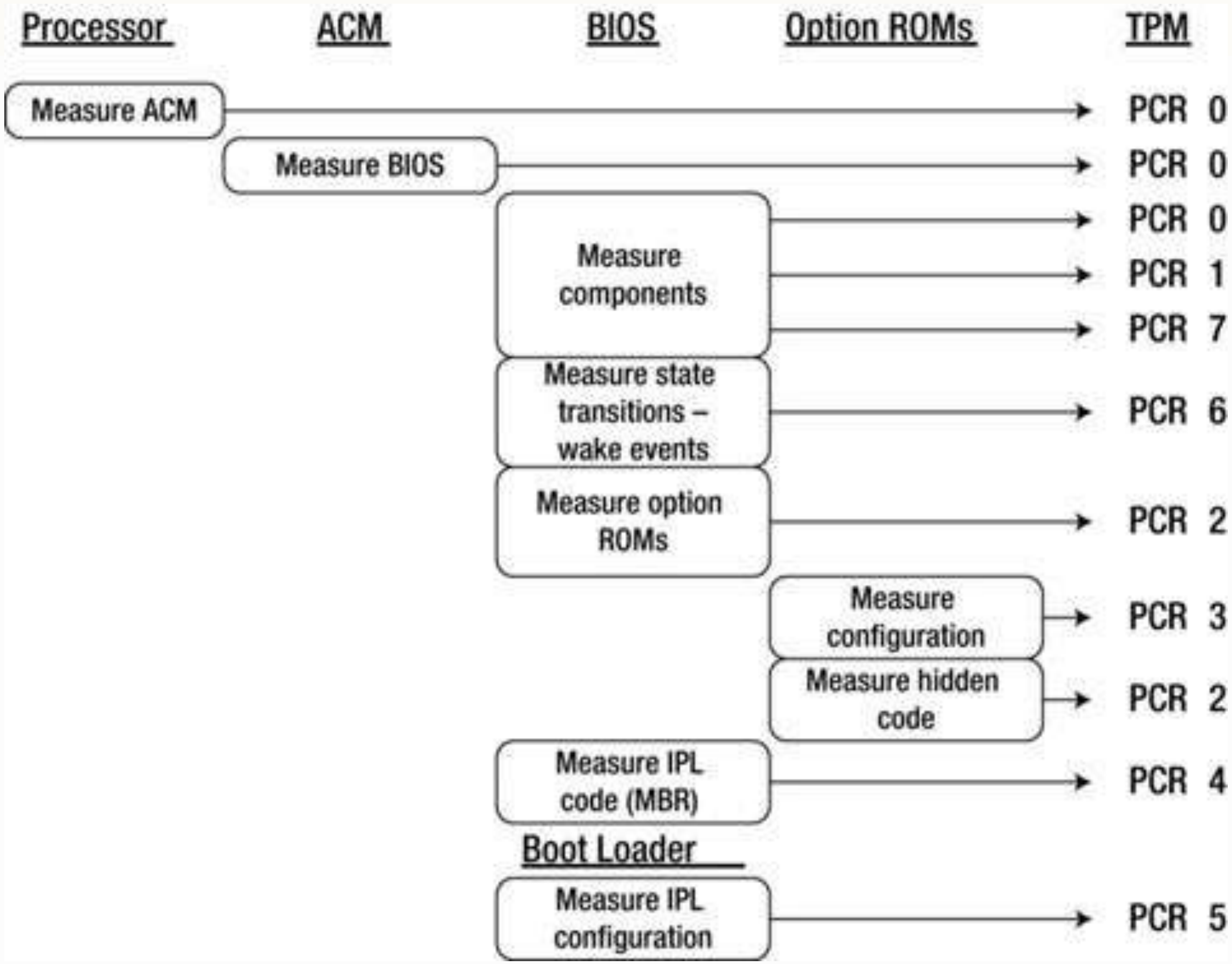
https://media.defense.gov/2019/Jul/16/2002158058/-1/-1/0/CSI-BOOT-SECURITY-MODES-AND-RECOMMENDATIONS.PDF

Intel Trusted Execution Technology (TXT)

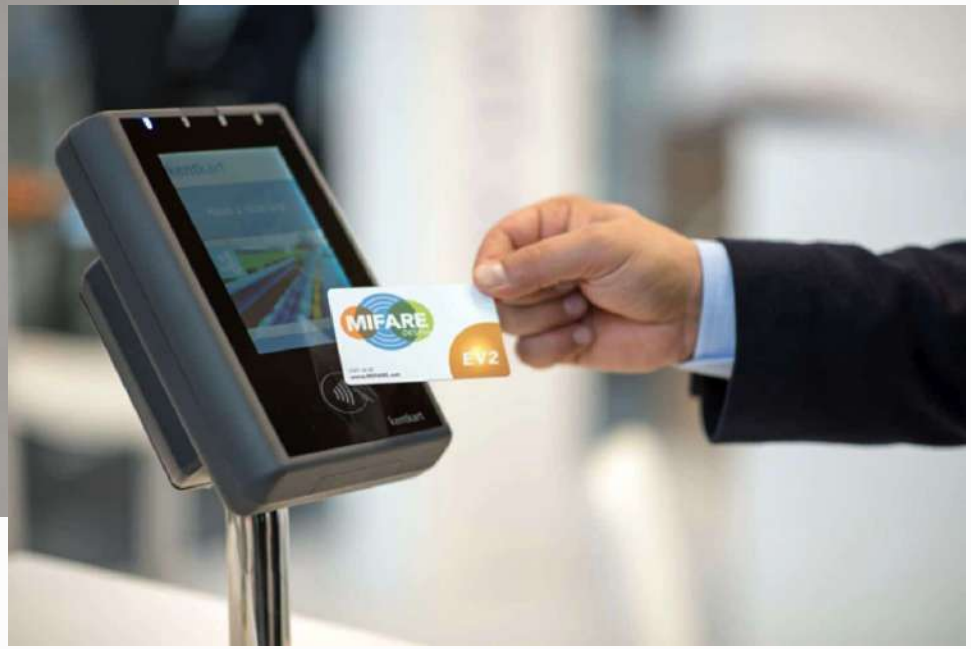
- It is used both for SRTM and DRTM
  - SRTM: Uses a BIOS ACM
  - DRTM: Uses a Secure Initialization (SINIT) ACM
    - This ACM is also stored in the BIOS

- DRTM
  - Uses 2 TPM PCRs
    - PCR 17 - measurement of the SINIT ACM
    - PCR 18 - measurement of the OS

Intel TXT SRTM



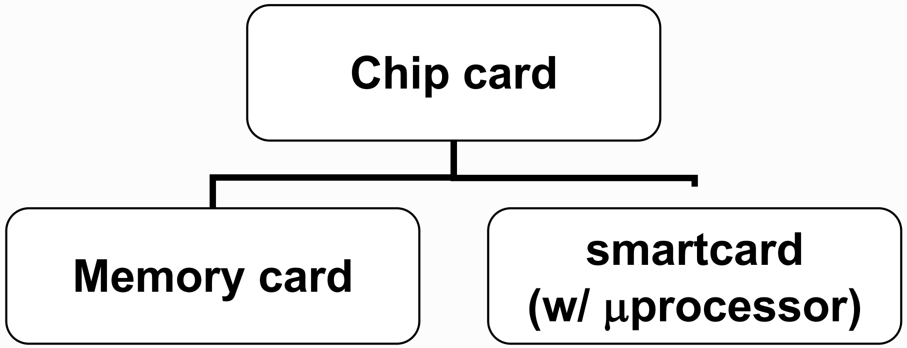
Smartcards



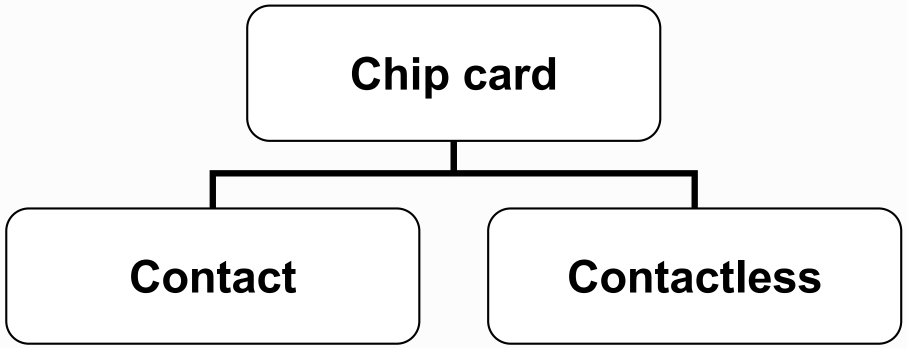
https://pplware.sapo.pt/informacao/saiba-como-renovar-online-o-seu-cartao-de-cidadao/
https://knowtechie.com/security-matters-5-benefits-of-contactless-smart-cards/

Smartcard: Definition

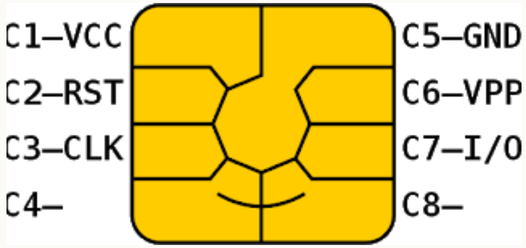
- ▷ Card with computing processing capabilities
  - CPU
  - ROM
  - EEPROM
  - RAM



- ▷ Interface
  - With contact
  - Contactless

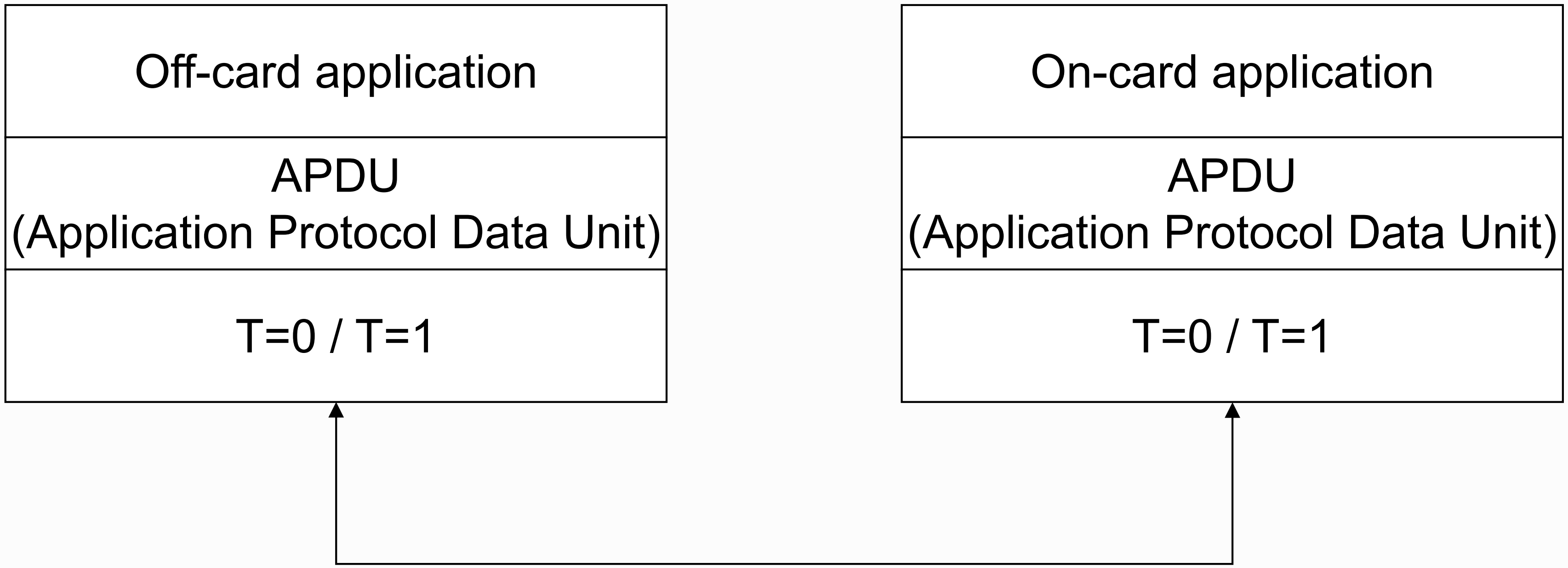


Smartcard: Components



- CPU
  - 8/16 bit
  - Crypto-coprocessor (opt.)
- ROM
  - Operating system
  - Communication
  - Cryptographic algorithms
- EEPROM
  - File system
    - Programs / applications
    - Keys / passwords
- RAM
  - Transient data
    - Erased on power off
- Mechanical contacts
  - ISO 7816-2
    - Power
    - Soft reset
    - Clock
    - Half duplex I/O
- Physical security
  - Tamperproof case
  - Resistance to side-channel attacks

Smartcard applications: Communication protocol stack



T=0 and T=1

- T=0
  - Each byte transmitted separately
  - Slower
- T=1
  - Blocks of bytes transmitted
  - Faster
- ATR (ISO 7816-3)
  - Response of the card to a reset operation
  - Reports the protocol expected by the card

APDU (ISO 7816-4)

header					body	
CLA	INS	P1	P2	Lc	Optional data	Le

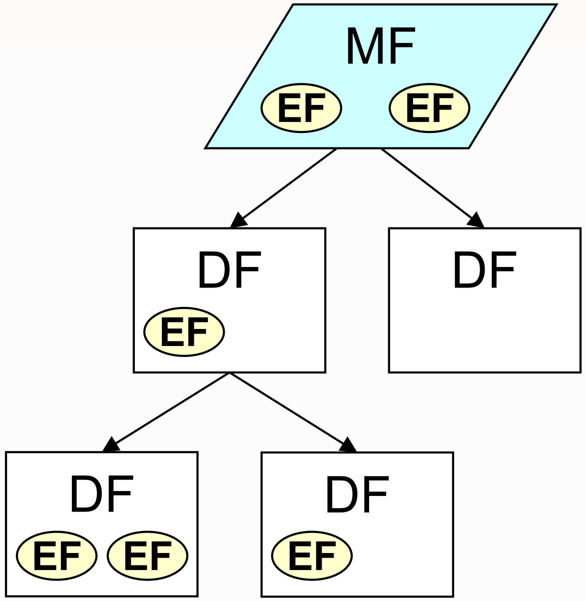
body	trailer	
Optional data	SW1	SW2

- Command APDU
  - CLA (1 byte)
    - Class of the instruction
  - INS (1 byte)
    - Command
  - P1 and P2 (2 bytes)
    - Command-specific parameters
  - Lc
    - Length of the optional command data
  - Le
    - Length of data expected in subsequent Response APDU
    - Zero (0) means all data available
- Response APDU
  - SW1 and SW2 (2 bytes)
    - Status bytes
    - 0x9000 means SUCCESS

Encoding objects in smartcards: TLV and ASN.1 BER

- Tag-Length-Value (TLV)
  - Object description with a tag value, the length of its contents and the contents
  - Each element of TLV is encoded according with ASN.1 BER
- Values can contain other TLV objects
  - The structure can be recursive

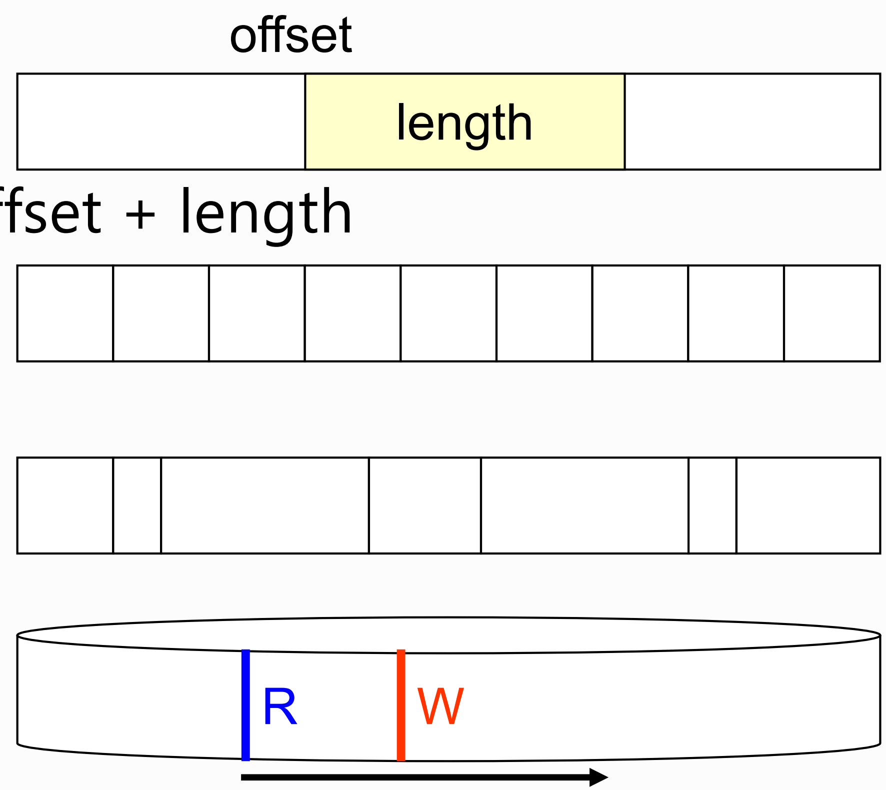
Smartcard:
File system



- ▷ File identification
  - Name or number
- ▷ File types
  - Master File (MF)
    - File system root, ID 0x3F00
  - Dedicated File (DF)
    - Like a directory
    - Can contain other EFs or DF
  - Elementary File (EF)
    - Ordinary data file
    - File size fixed and determined when created

Smartcard:
File system (2/3)

- File system types
  - Transparent
    - Data blocks identified by offset + length
  - Fixed records
    - Indexed records
  - Variable records
    - Indexed records
  - Cyclic
    - Read pointer, write pointer
    - Cyclic increments

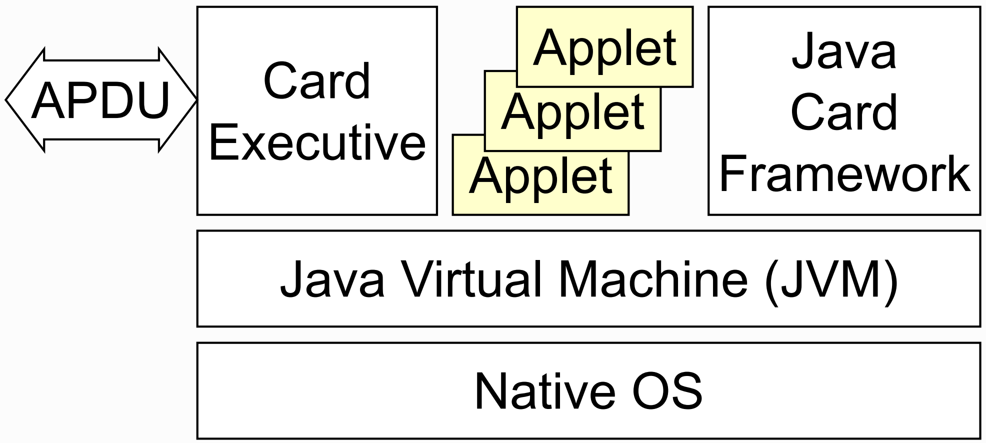


Smartcard:
File system (3/3)

- Access control
  - No restrictions
  - Protected
    - The file access APDU must contain a MAC computed with a key shared between the card and the off-card application
  - External authentication
    - The file access APDU is only allowed if the card already checked the existence of a common shared key with the off-card application
    - Previous login

Java cards

- Smartcards that run Java Applets
  - That use the JCRE
  - The JCRE runs on top of a native OS
- JCRE (Java Card Runtime Environment)
  - Java Virtual Machine
  - Card Executive
    - Card management
    - Communications
  - Java Card Framework
    - Library functions



OpenCard Framework (OCF)

- Goal: facilitate the development of smartcard-based solutions
  - Make the parts of the solution, typically provided by different parties, independent of each other
  - https://www.openscdp.org/ocf
- Parties:
  - Card issuer
    - Card initialization, personalization and issuing
  - Card OS provider
    - Basic, lowest level card behavior
  - Card reader / terminal provider
    - Interfaces that deal with reading from and writing into cards
  - Application / service provider
    - Development of off-card (and possibly on-card) applications

Cryptographic services

- ▷ Ciphers
- ▷ Digest functions

- ▷ Key generation
- ▷ Key management
  - Key import
  - Key export

- ▷ Digital signatures
  - Generation
  - Verification

- ▷ Management of public key certificates
  - Generation
  - Verification

Cryptographic services: Middleware

- Libraries that bridge the gap between functionalities of smartcards and high-level applications
- Some standard approaches:
  - PKCS #11
    - Cryptographic Token Interface Standard (Cryptoki)
    - Defined by RSA Security Inc.
  - PKCS #15
    - Cryptographic Token Information Format Standard
    - Defined by RSA Security Inc.
  - CAPI CSP
    - CryptoAPI Cryptographic Service Provider
    - Defined by Microsoft for Windows systems
  - PC/SC
    - Personal computer/smartcard
    - Standard framework for smartcard access on Windows systems