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.

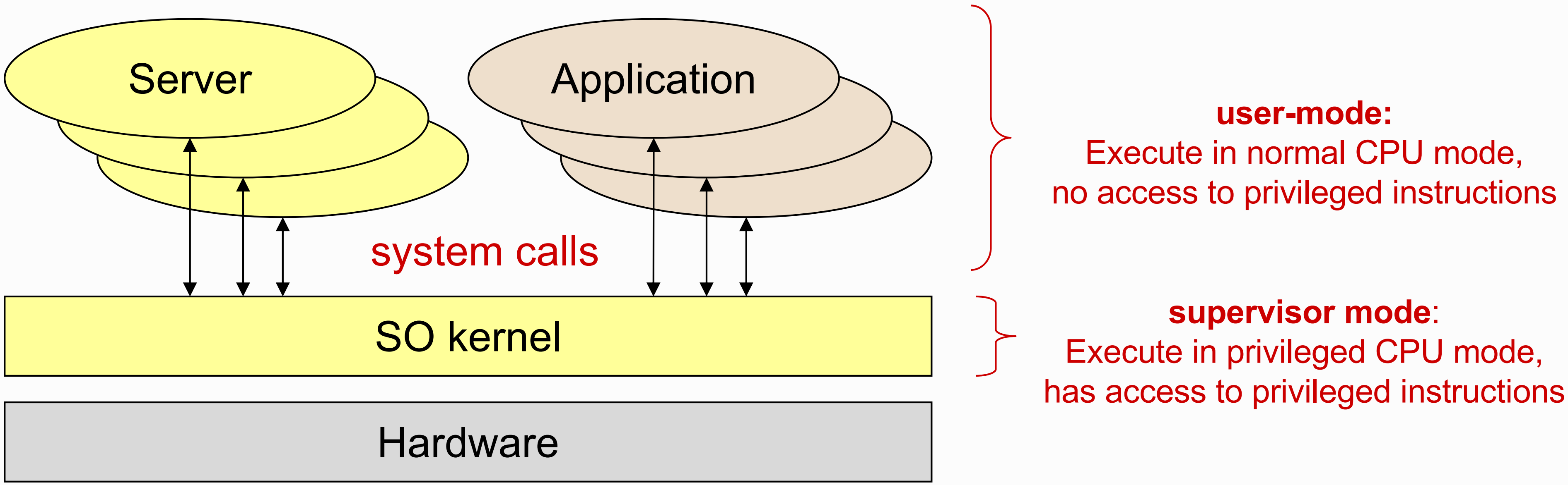
Protection from untrusted code: sandboxes

- 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

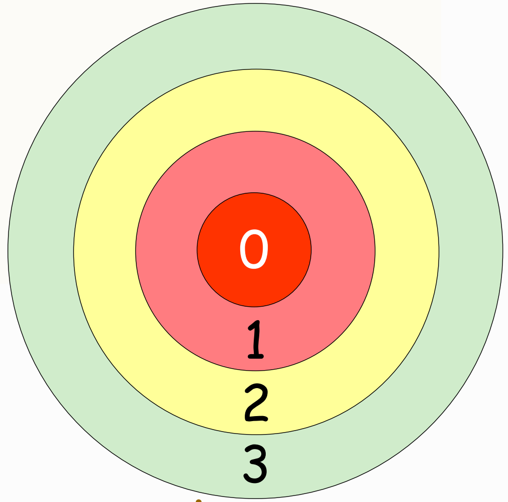
Security in Operating Systems

Operating system



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

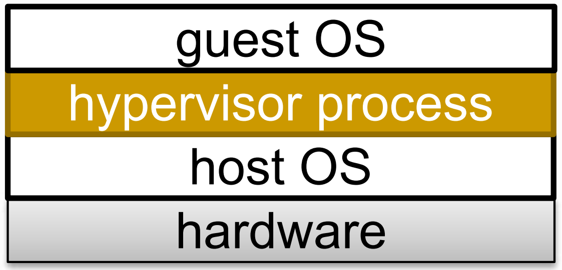
Protection rings



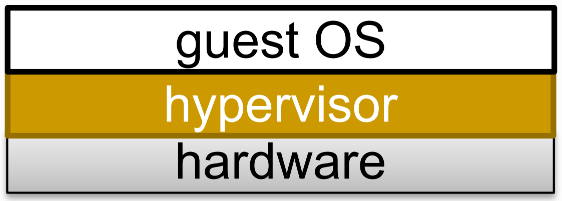
- Different levels of privilege
  - Forming a set of concentric rings
  - Used by CPU's to prevent non-privileged code from running privileged instructions
    - e.g. IN/OUT, TLB manipulation
- Nowadays processors have 4 rings
  - But OS's usually use only two of them
    - 0 (supervisor/kernel mode) 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)

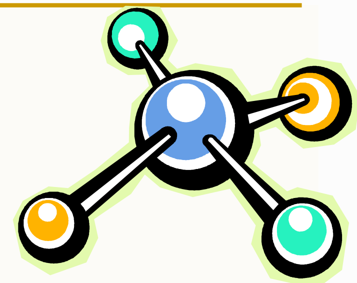


- Bare-metal virtualization
  - The hypervisor runs on top of the host hardware

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)

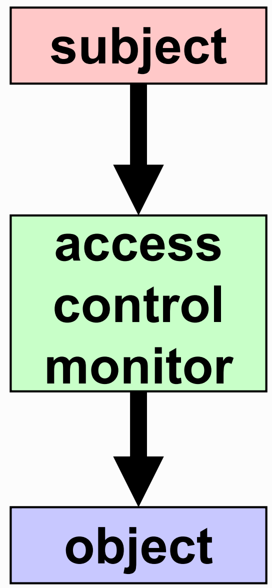
- Security-related context
  - Identity (UID and GIDs)
    - Fundamental for enforcing access control
  - Resources being used
    - Open files
      - Including communication channels
    - Reserved virtual memory areas
    - CPU time used

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

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

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

- Set-GID bit

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

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

- Sticky bit

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

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

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

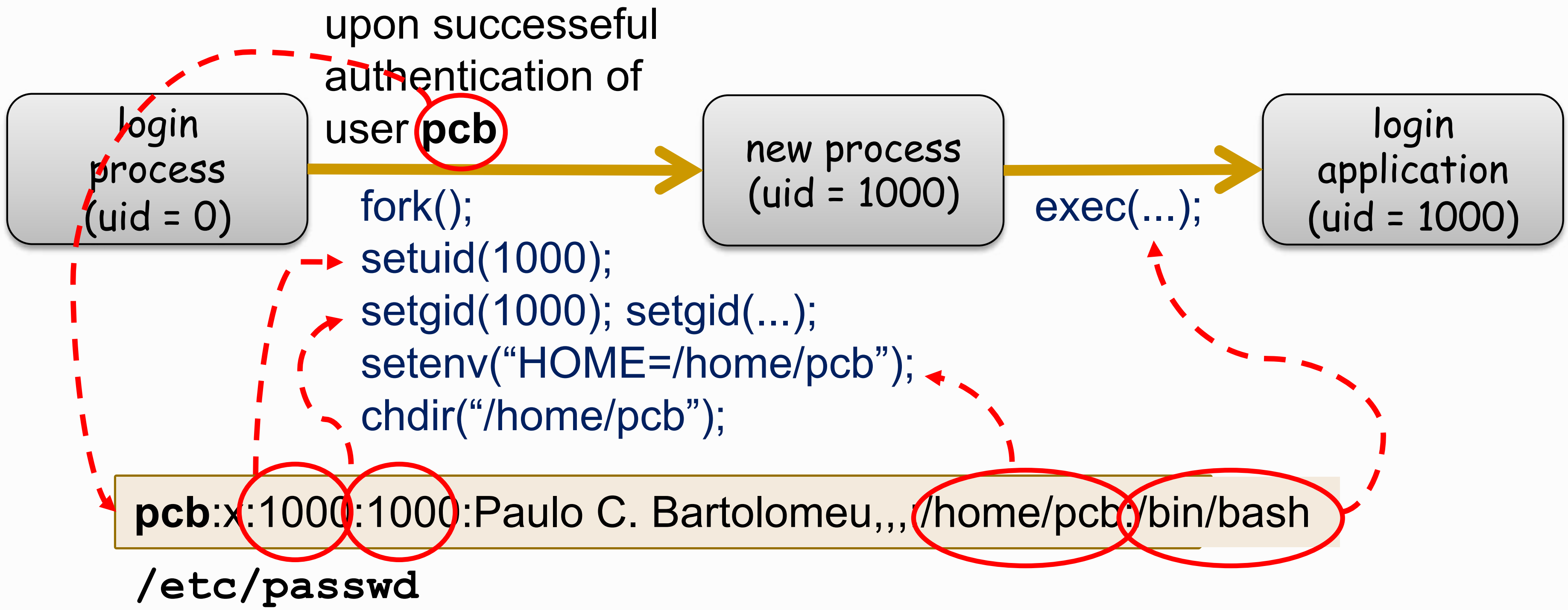
- A privileged login application presents an interface for getting users' credentials
  - A username/password pair
  - Biometric data
  - Smartcard and activation PIN

- 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)

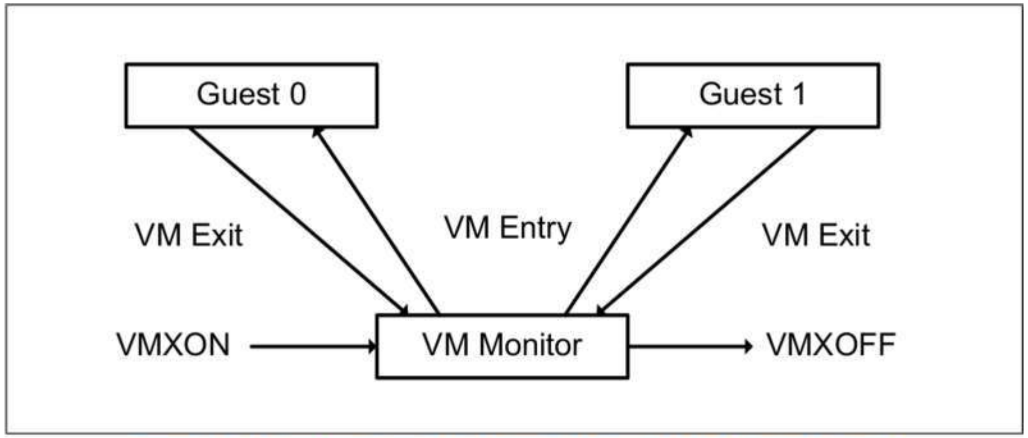


Figure 23-1. Interaction of a Virtual-Machine Monitor and Guests

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

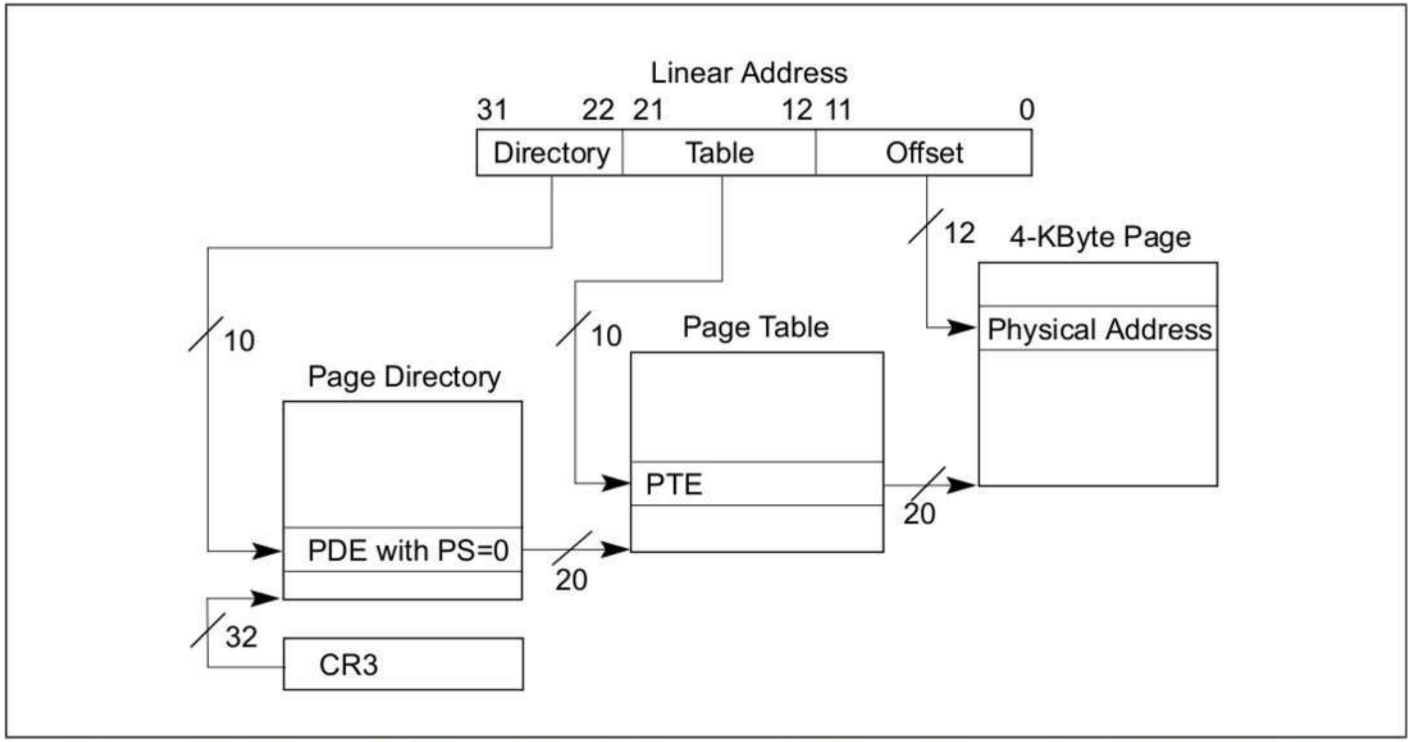


Figure 4-2. Linear-Address Translation to a 4-KByte Page using 32-Bit Paging

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

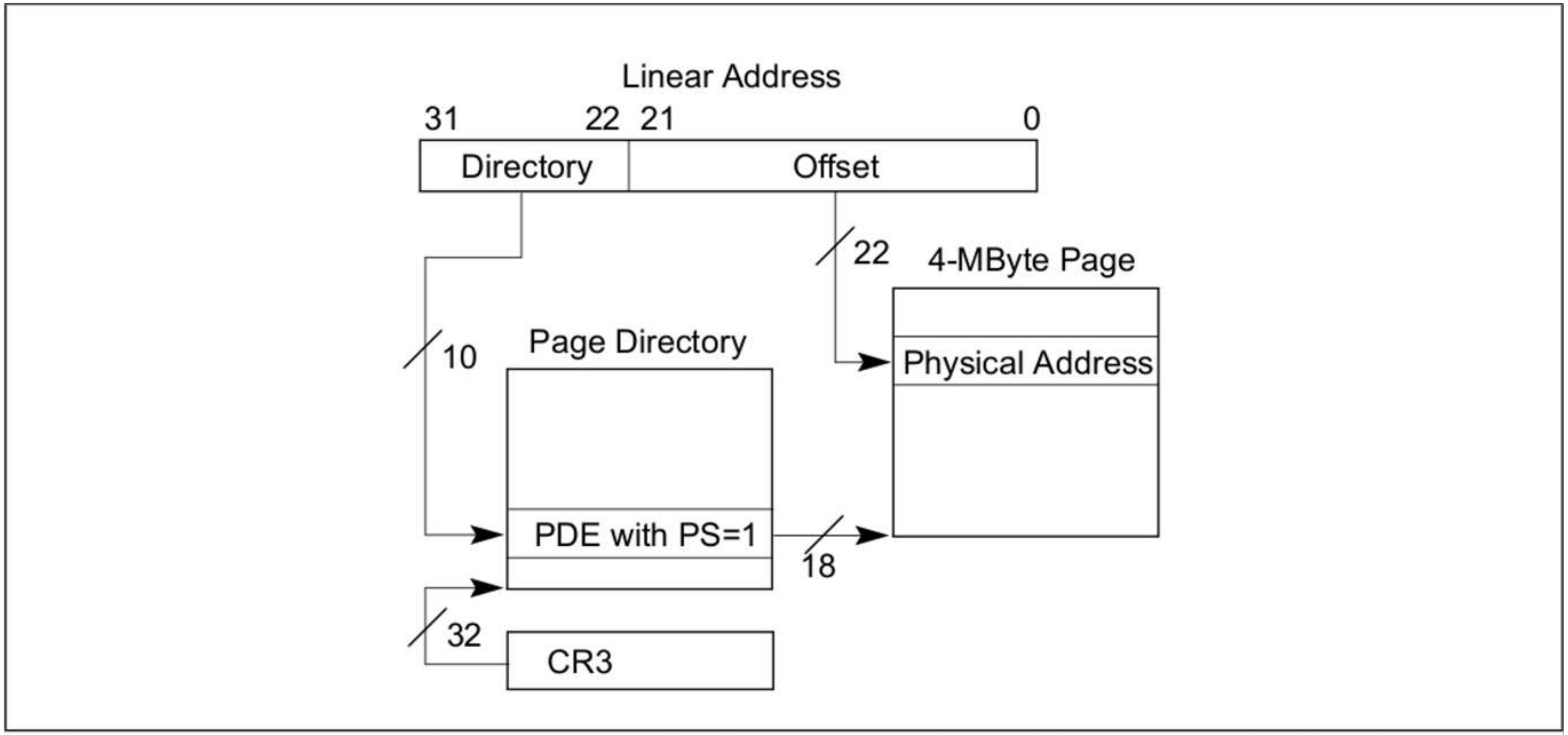


Figure 4-3. Linear-Address Translation to a 4-MByte Page using 32-Bit Paging

Virtual memory (4 levels, 4KiB pages)

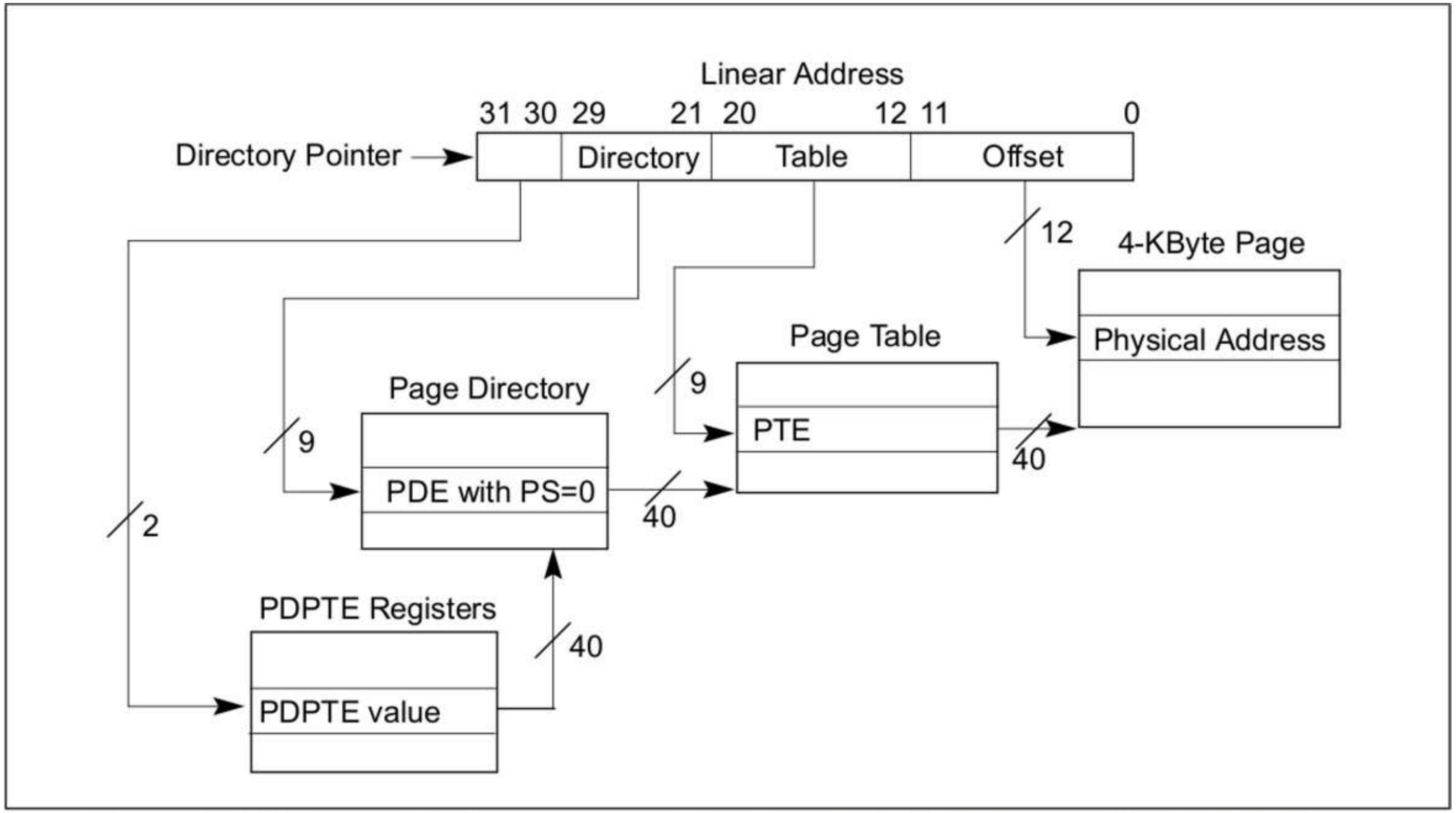


Figure 4-5. Linear-Address Translation to a 4-KByte Page using PAE Paging

Virtual memory (3 levels, 2MiB pages)

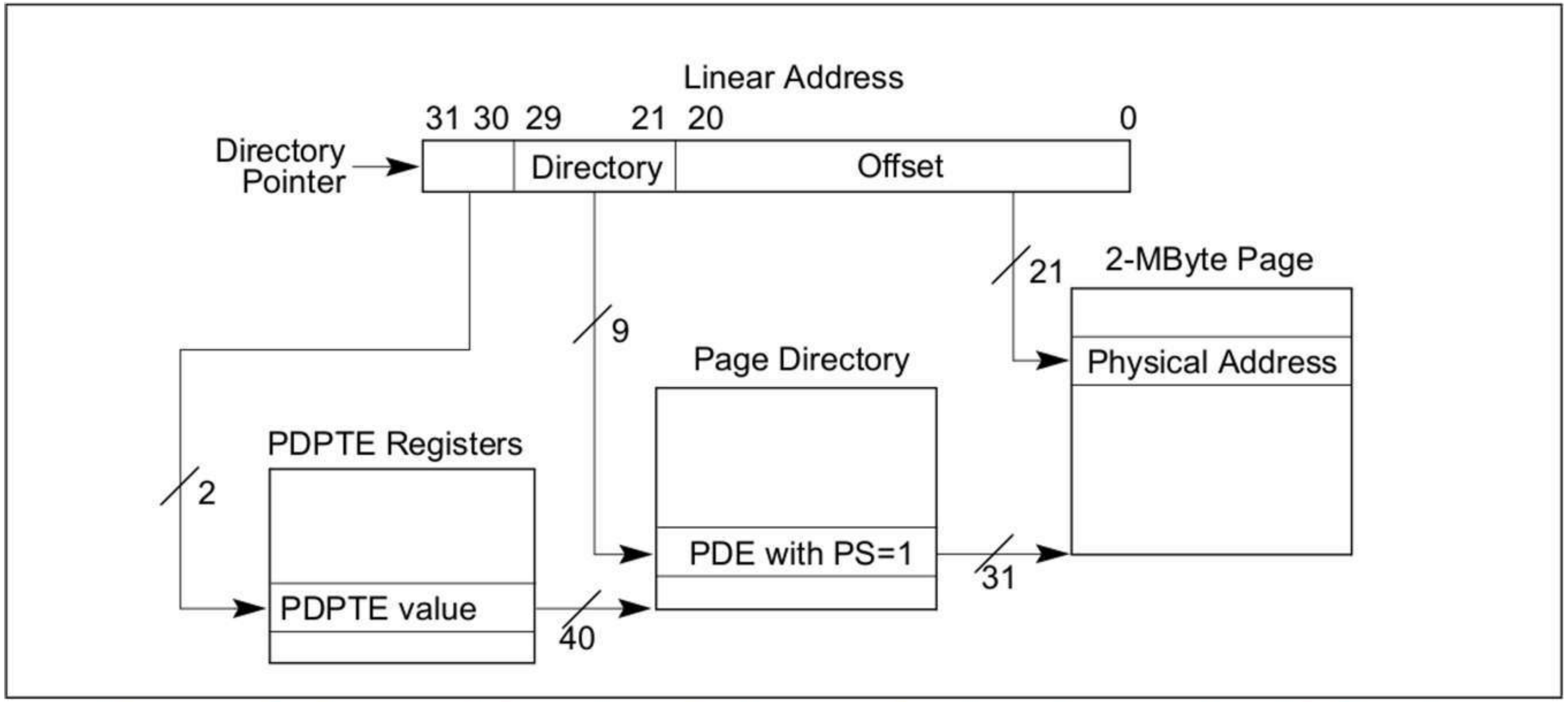


Figure 4-6. Linear-Address Translation to a 2-MByte Page using PAE Paging

Virtual memory (4 level, 4KiB pages)

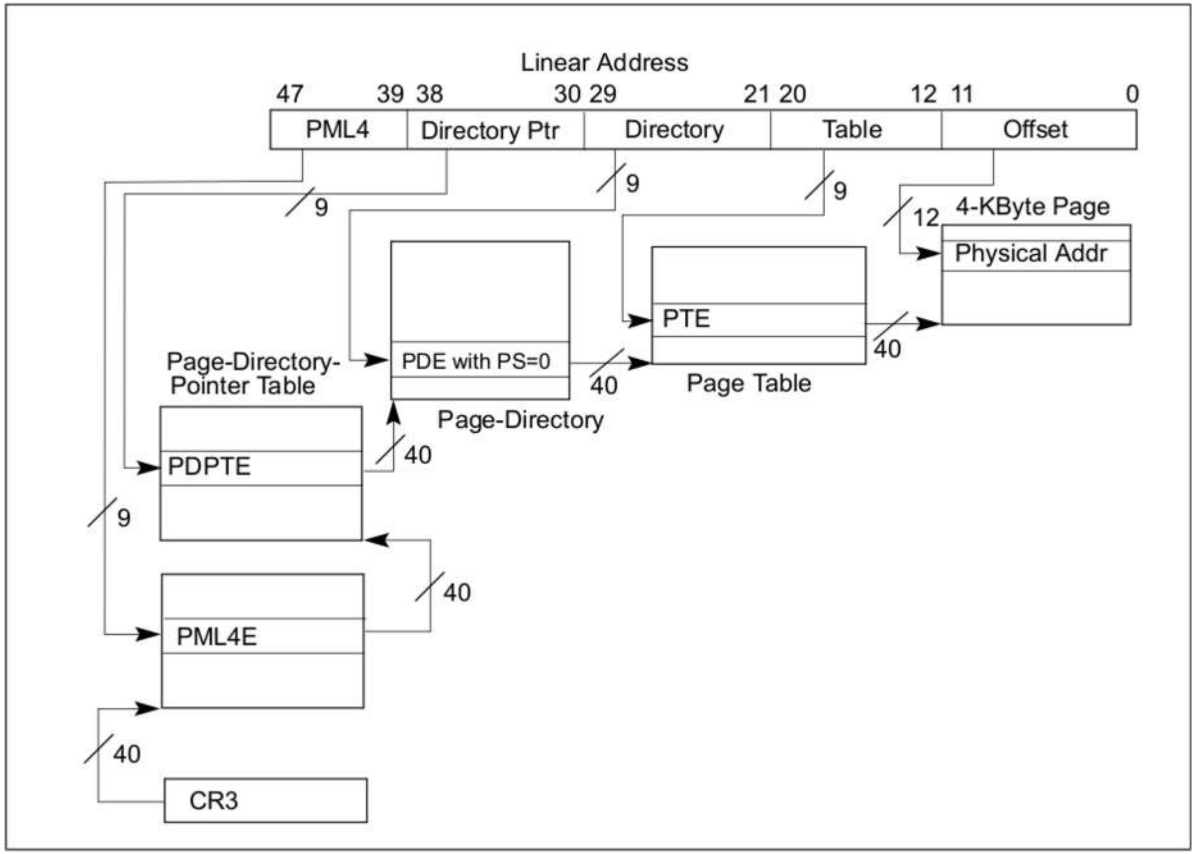


Figure 4-8. Linear-Address Translation to a 4-KByte Page using 4-Level Paging

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 <u>and</u> 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)

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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.

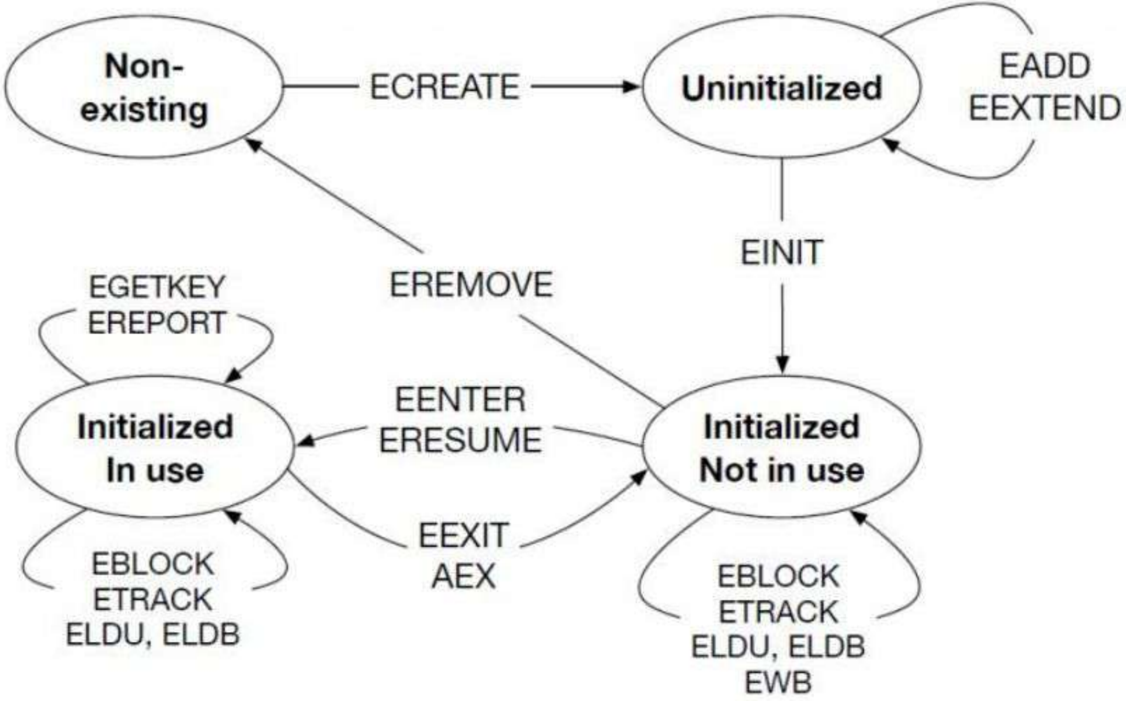
Instructions related to enclaves

- 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

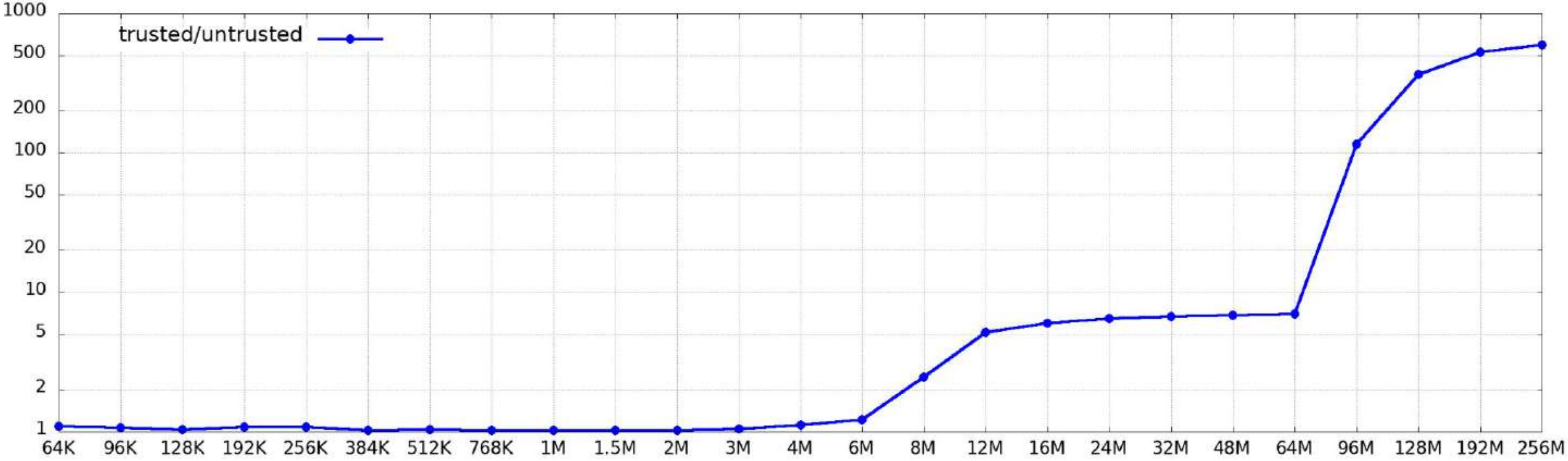
```
Checksum(0x0x7ffeac1ee4f0, 100) = 0xfffd4143
Info: executing thread synchronization, please wait...
Info: SampleEnclave successfully returned.
Enter a character before exit ...
```

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

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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

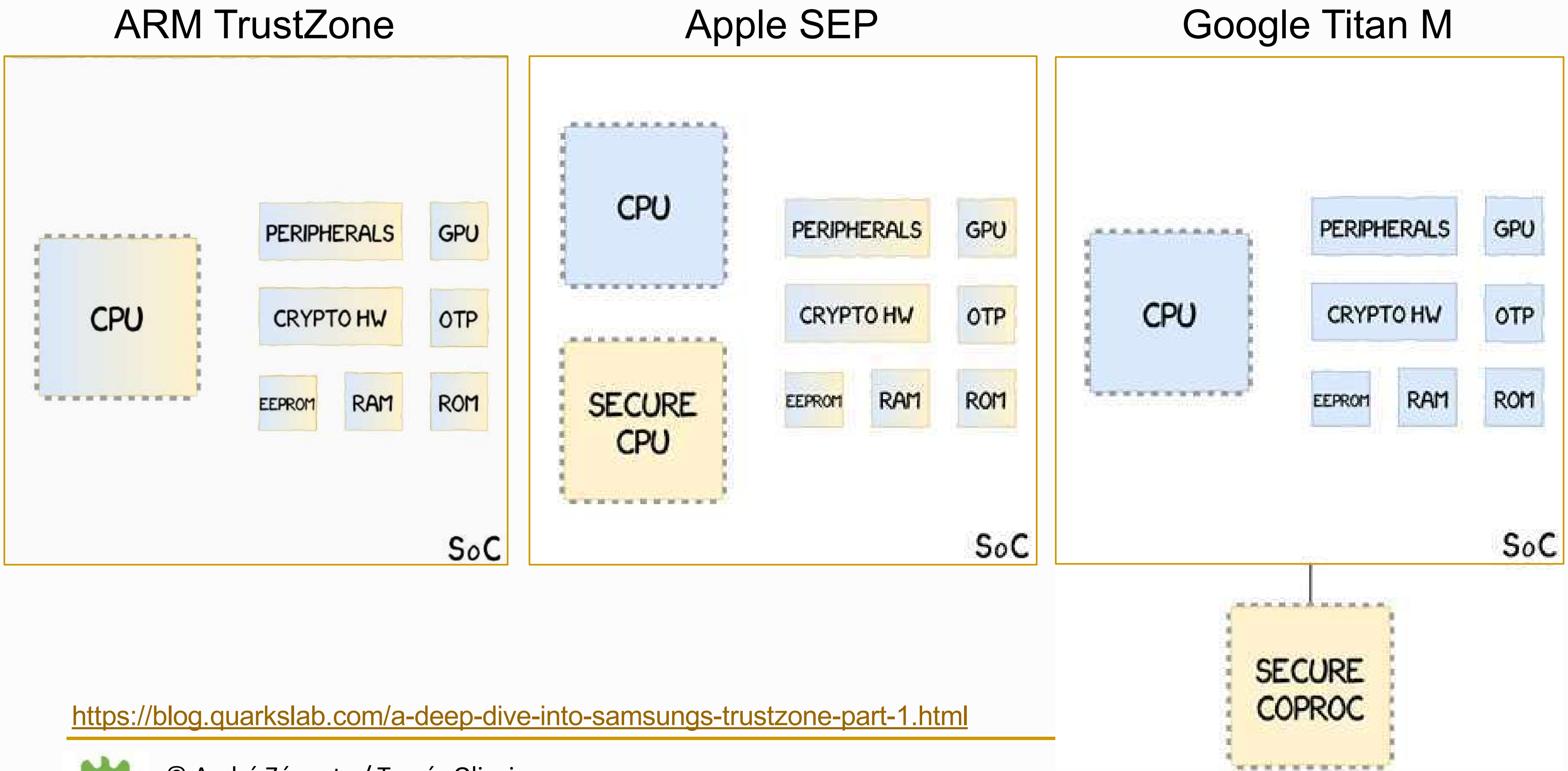
- Set of technologies for packing special security features into a SoC
  - Extra security-related features on processor cores
    - Instructions
    - Bus lines
    - Execution levels
    - Extra logic for dealing with interruptions
  - Security-related IPs

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



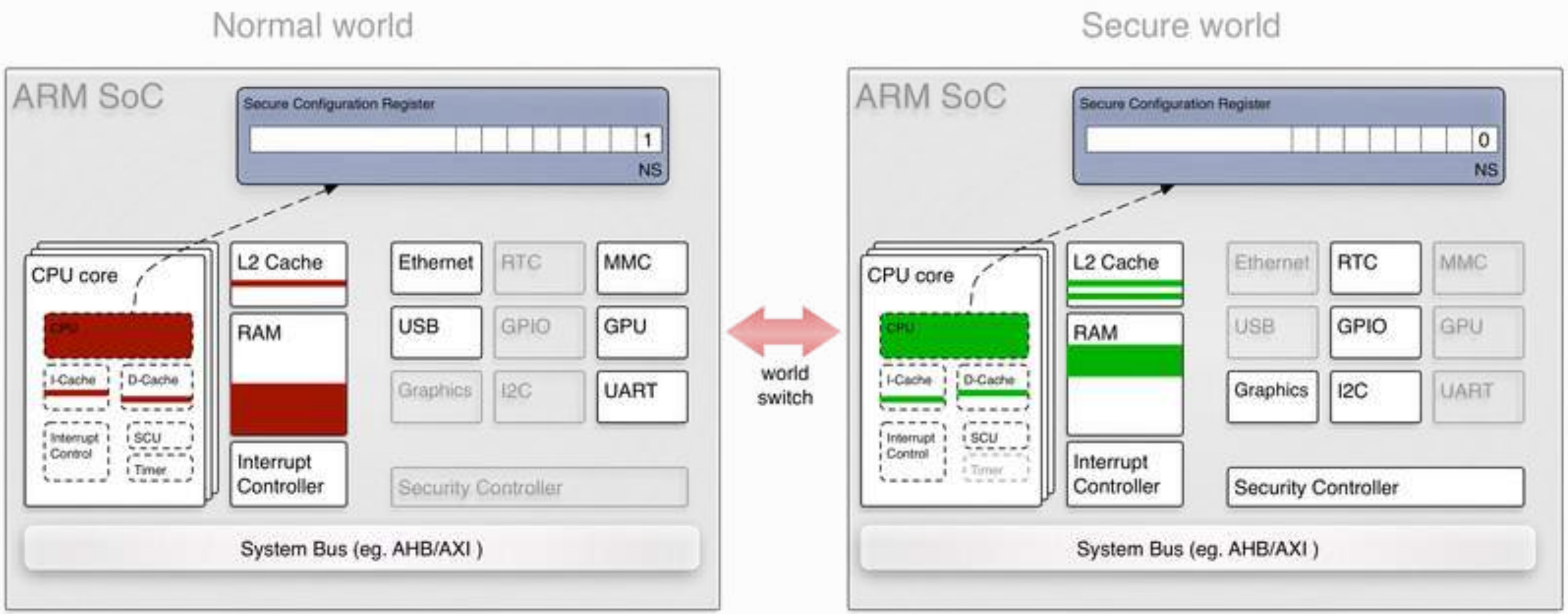
https://blog.quarkslab.com/a-deep-dive-into-samsungs-trustzone-part-1.html

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

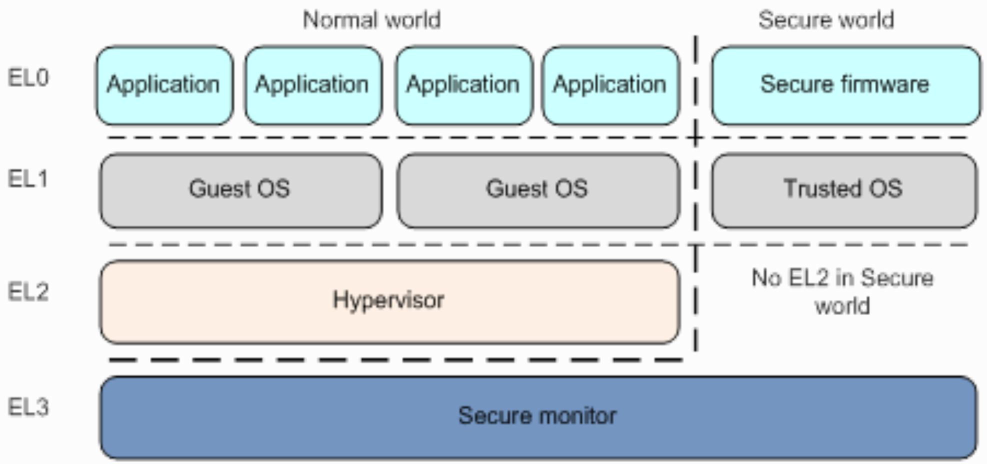
▷ Resources accessible only to the Secure OS



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

ARM (v8) exception levels

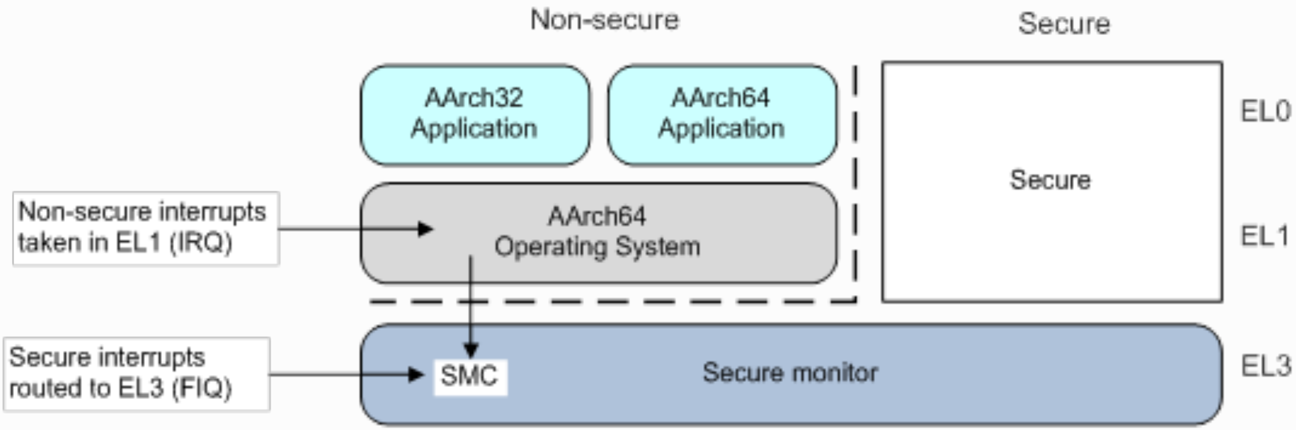
- Similar to run levels
- TrustZone introduces one EL more
  - Secure monitor (EL3)
- Combination of exception levels



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

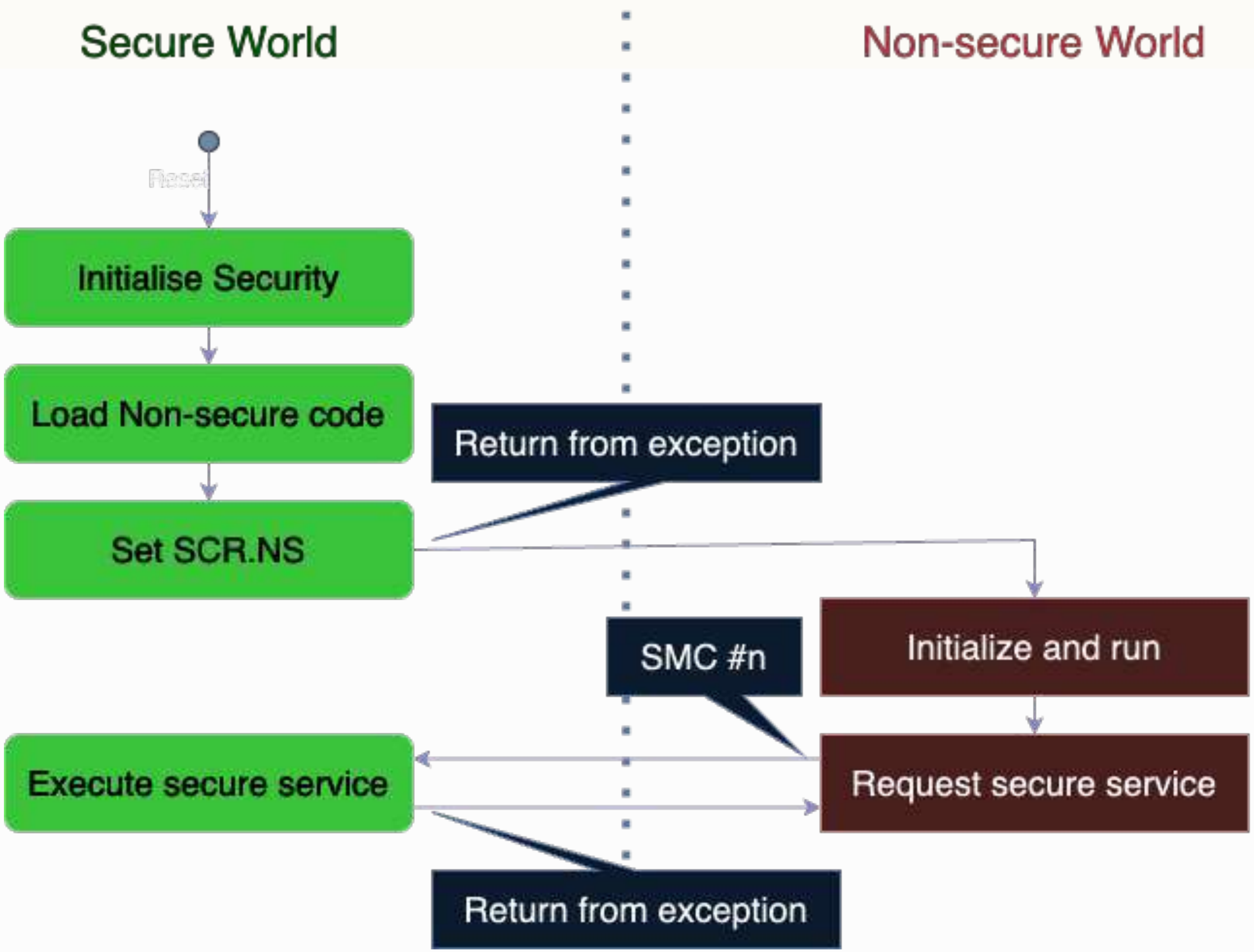
Access to the Secure world

- 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

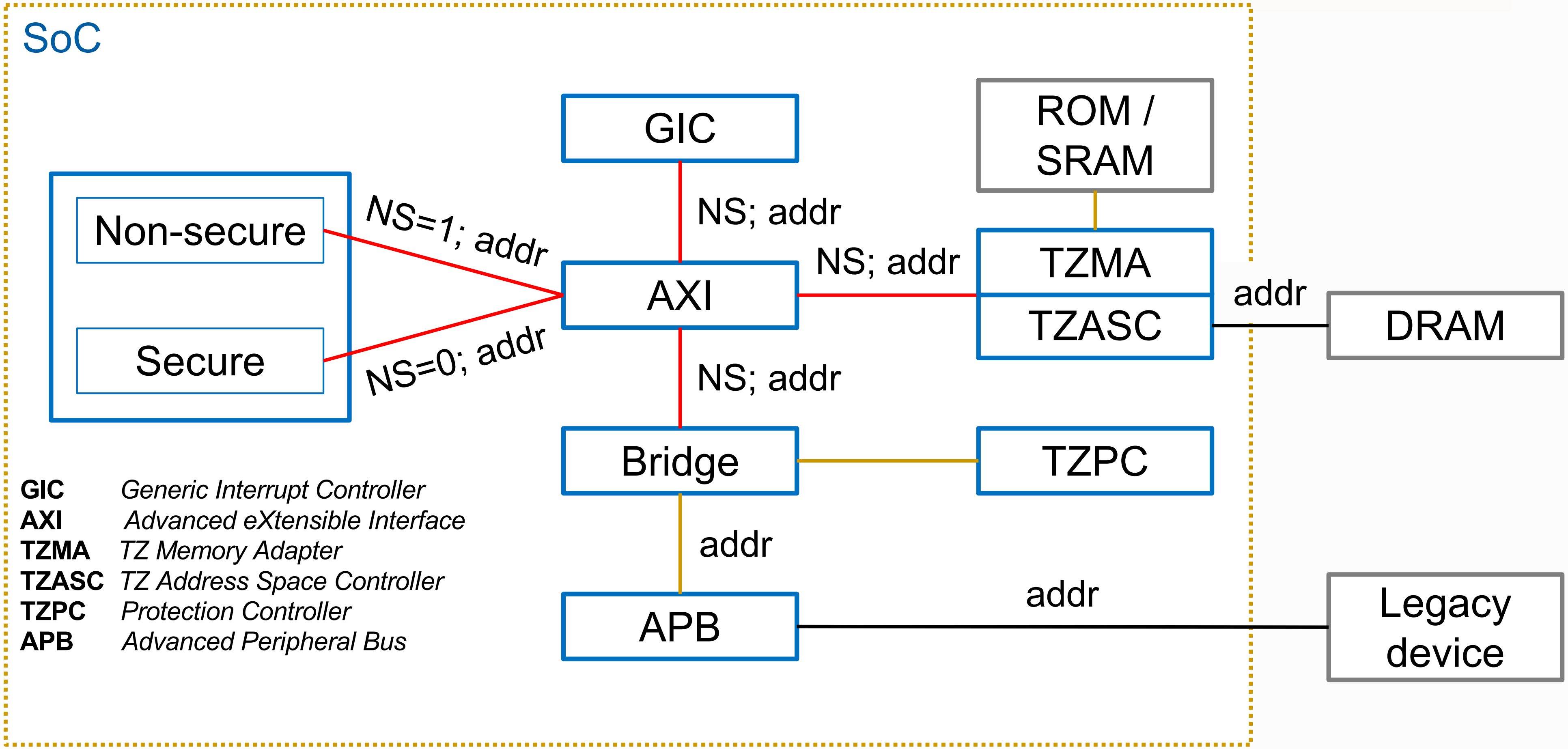


https://sergioprado.blog/introduction-to-trusted-execution-environment-tee-arm-trustzone/

Access to the Secure world

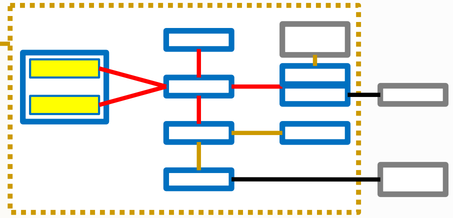


Architecture overview



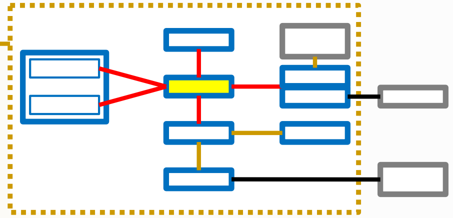
GIC *Generic Interrupt Controller*
AXI *Advanced eXtensible Interface*
TZMA *TZ Memory Adapter*
TZASC *TZ Address Space Controller*
TZPC *Protection Controller*
APB *Advanced Peripheral Bus*

Architectural details: MMU / TLB / Cache Controllers

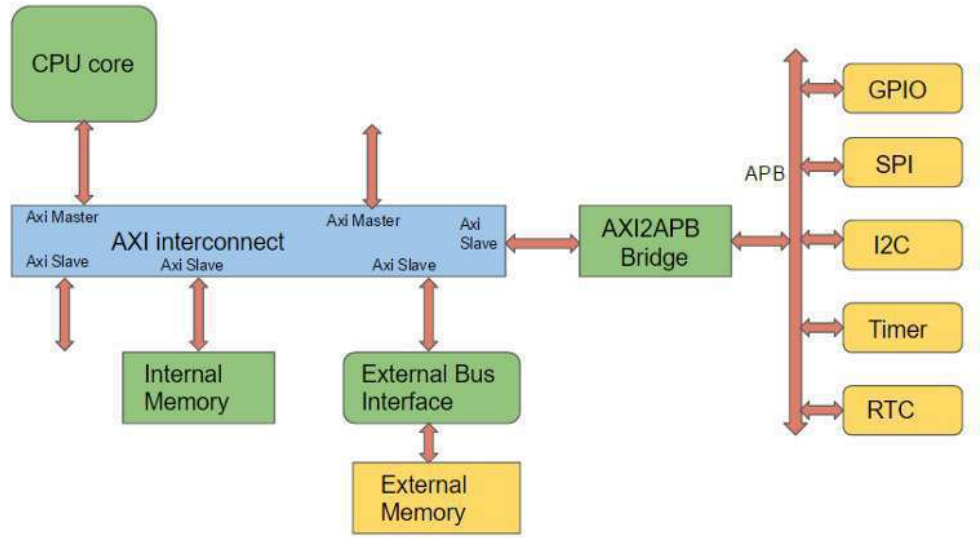


- 2 separate, virtual MMUs
  - Indexed by NS
- Single TLB
  - But entries keep the value of NS that created them
  - No need to invalidate them when switching between worlds
- The Secure world can still access non-secure memory
  - Extra bit on each entry in the secure translation table
- Single cache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

Architectural details: AXI (Advanced eXtensible Interface)



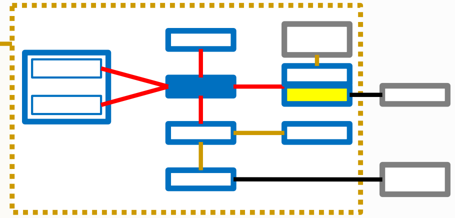
- ▷ SoC internal bus



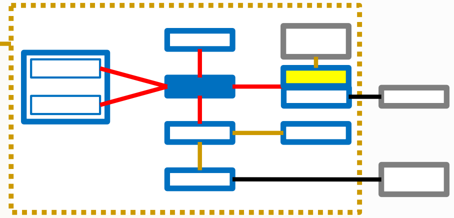
- ▷ Extra NS line for secure read/write operations
  - Non-secure master cannot access a resource marked as secure

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

Architectural details:
TZASC (TZ Address Space Controller)

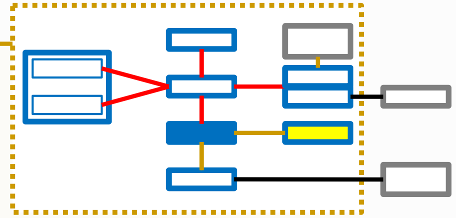


- Allows a dynamic classification of AXI slave memory-mapped devices as secure or non-secure
  - Partitioning of single memory units
- Controlled by the Secure world



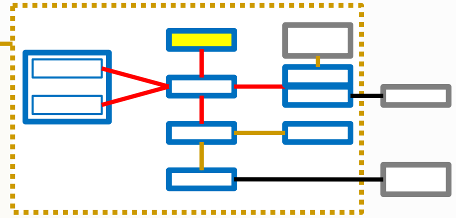
Architectural details: TZMA (TZ Memory Adapter)

- 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



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

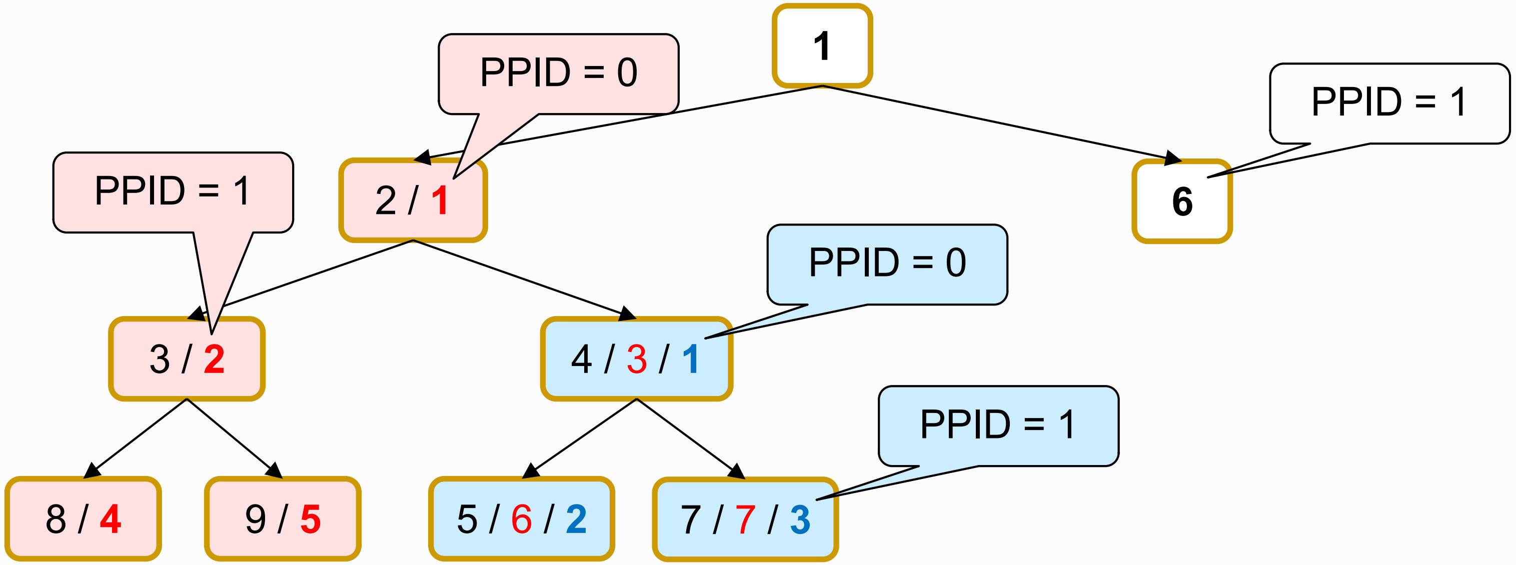
- Process namespaces **isolate the process ID number space**, meaning that processes in different PID namespaces can have the same PID;
- Process namespaces allow containers to provide functionality such as **suspending/resuming the set of processes** in the container and migrating the container to a 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

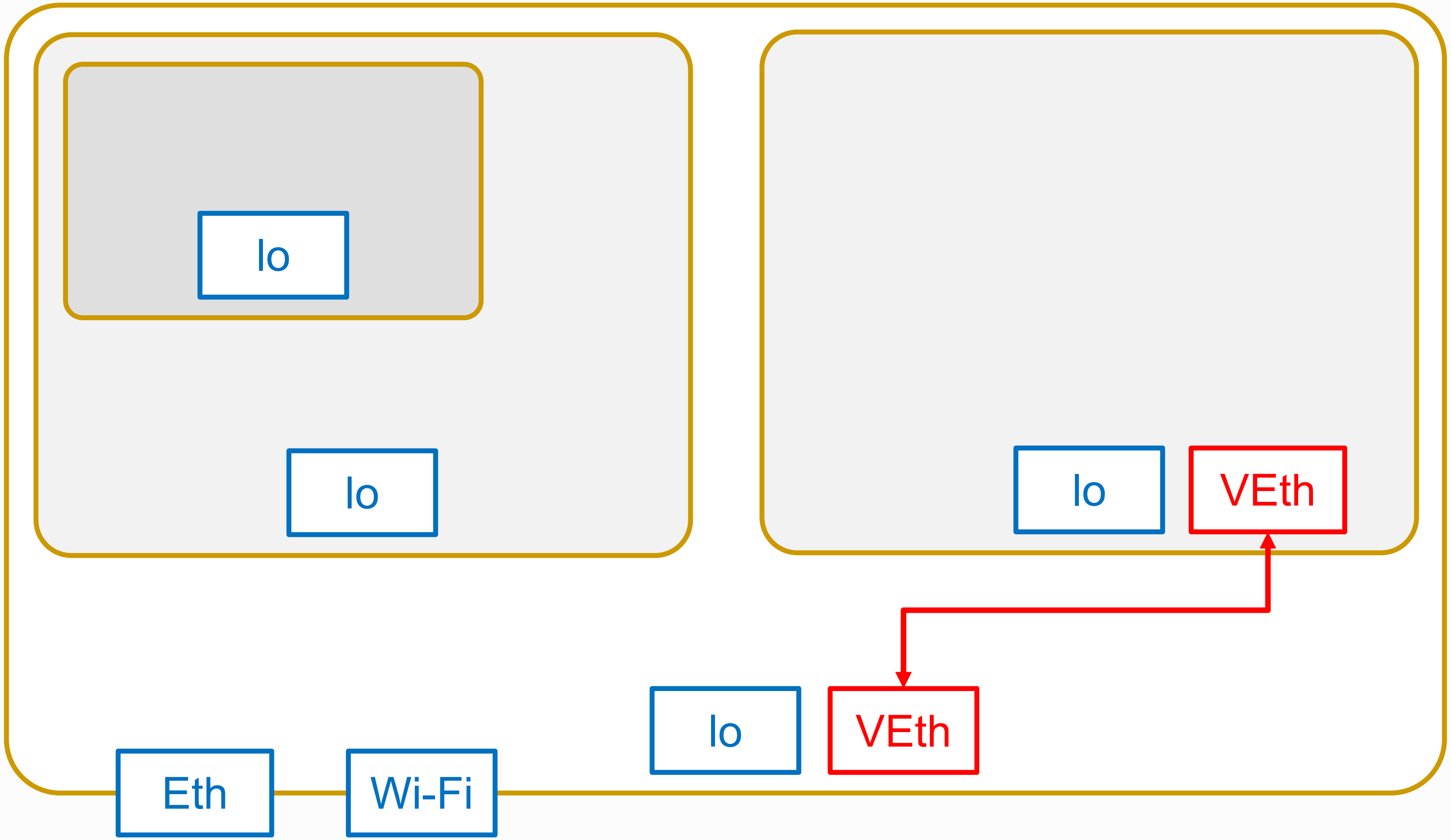
- **Network namespaces provide isolation of the system resources associated with networking**: network devices, Ipv* protocol stacks, IP routing tables, firewall rules, port numbers, etc;
- A physical network device can live in exactly one network namespace. When a network namespace is freed, its physical 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

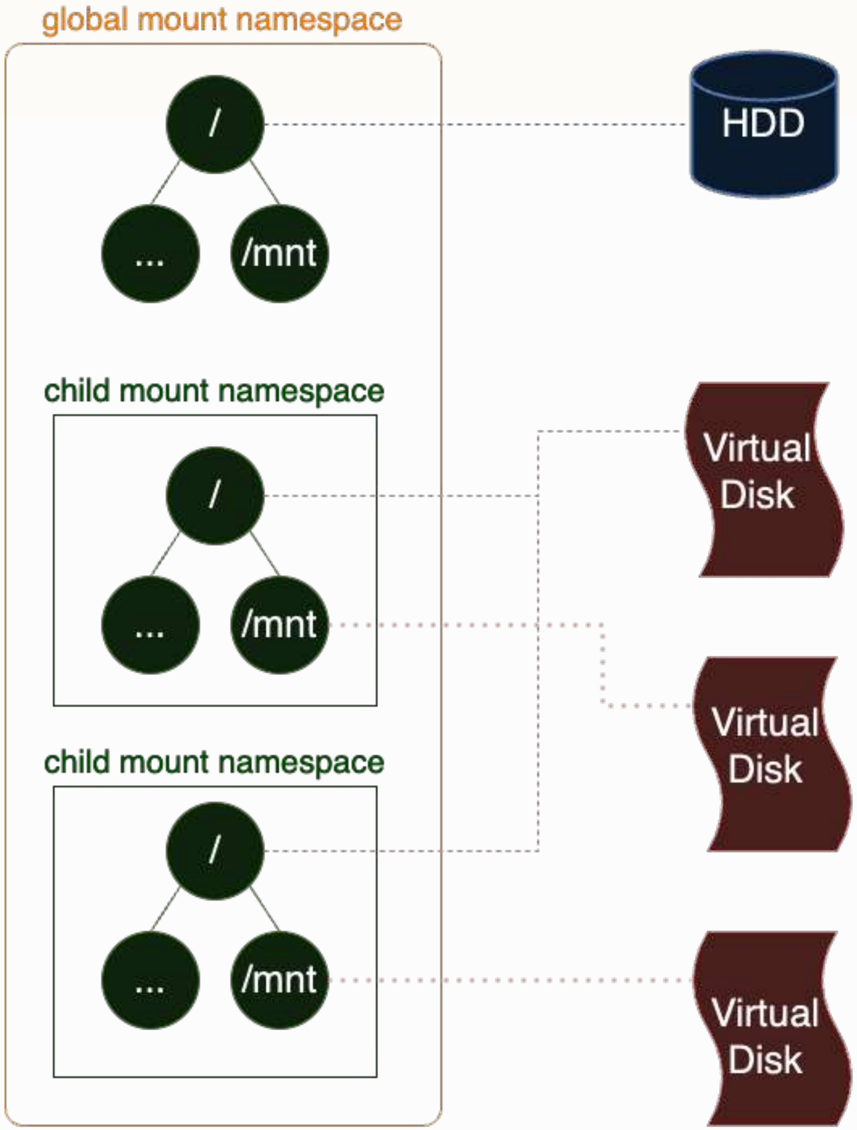
- **Mount namespaces provide isolation of the list of mount points seen by the processes in each namespace instance**. The processes in each of the mount namespace instances will see distinct single-directory hierarchies;
- The views provided by the (/proc/[pid])/mounts, mountinfo, and mountstats files 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