System Security fiche

Pierre Colson

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Contents

Markdown version on *github*
Compiled using *pandoc* and *`gpdf` script*

Side Channels & Tempest

- **Compromising Emanations**: Physical signals related to digital activity; break the assumption of higher-level abstractions; Root cause of many attacks
- **Tempest**: Passive leakage of plaintext information (E.g., video on screen)
  - Video Signal
    - Signal in wire/connector/etc. not well shielded
    - Current in wires generates EM waves
    - Modulated with the pixel values
- **Soft Tempest**: Active version of *Tempest*; leakage used to exfiltrate data
  - Vide Signal
    - Signal in wire/connector/etc. not well shielded
    - Current in wires generates EM waves
    - Modulated witht the pixel values
    - Use to transmit data
    - Or to add noise Tempest leakage
    - Possible with many other sources of leakage (e.g. memory access)
- **Side Channels**: Use leakage to attack cryptographic implementation (Only in proximity, with few exceptions)
- Type of *pysical leakage*: Execution time, Power, Magnetic and electromagnetic, optical, thermal, acoustic and vibrational, reflection of injected signals
- Type of *attack*: Passively recover plaintext, Actively exfiltrate data; attack cyrptographic implementation
- **Symmetric encryption** for *confidentiality*
  - *Stream cypher*

        - Process a message bit by bit (byte by byte)
        - $KeyStream = PseudoRandomBitStreamGenerator(seed)$
        - $CyphertextStream = KeyStream + PlaintextStream$
    - *Block cypher*
        - Process a message block by block (EAS, DES)
        - Plaintext might need *padding*
        - $Plaintext + Key = BlockCipher$
        - All block cipher leads to the cipher text
        - There is different way to concatenate block cipher
        - **Electronic CodeBlock** (ECB, *insecure*) $C_1 = P_1 \bigoplus K$, $C_2 = P_2 \bigoplus K$, ...
        - **Cipher Block Chaining** (CBC) $C_1 = (P_1 \bigoplus IV) \bigoplus K$, $C_2 = (P_2 \bigoplus C_1) \bigoplus K$, ...
- **Symmetric crypto for authentication**
    - **Message Authentication Code (MAC)**
    - Shared key between A and B
    - A sends to B message $M + MAC$ where $MAC = MACFunction(M, K)$
- **Asymmetric crypto for confidentiality**
    - A and B exchange a key pair via a trusted channel
    - A wants to send M to B, she sends: $C = \mathit{Encryption}(Pu_B, M)$ where Pu_B is B's public key
    - B decrypts the message as follow: $M' = \mathit{Decryption}(Pr_B, C)$ where Pr_B is B's private key
- **Asymmetric crypto for authentication**
    - A send to B message M and Signature S, where $S = \mathit{Encryption}(Pr_A, M)$ where (A's private key)
    - B verifies the signature by checking: $\mathit{Decryption}(Pu_A, S) = M$ where (Pu_A is A's public key)
- Combine the best of two: Asymmetric key exchange + Symmetric encryption
- **Security** of cryptographic algoritms
    - We *model* system and possible attackers
    - Security properties are valid under certain *assumptions*
- Side Channel concrete example
    - **Timing**: Measure execution time
        - Classic timign attack against RSA
        - Remote attack are possible
        - Modern example of remote attack onc cryptocurrencies
    - **Power** Measure some physical quantity influenced by execution
        - Simple Power Analysis (SPA)
        - Differential Power Analysis (DPA)
        - Correlation Power Analysis (CPA)
- Reminder on **RSA**
    - *Key generation*
        1. Chose numbers p, q such that p and q are prime and $p \neq q$
        2. Compute $n = pq$
        3. Compute $\Phi(n) = (p-1)(q-1)$
        4. Chose e such that e and $\Phi(n)$ are relative prime and $1 < e < \Phi(n)$
        5. Compute d as such that $de \mod \Phi(n) = 1$
        6. Public key $PU = \{e, n\}$
        7. Private key $PR = \{d, n\}$
    - *Encryption*
        - Plaintext $m < n$
        - Ciphertext $C = m^e \mod n$
    - *Decryption*
        - Ciphertext C
        - Plaintext $m = C^d \mod n$
    - *Signature*
        - Plaintext $m < n$
        - Signature $s = m^d \mod n$
    - The *security* of RSA is based on two hard problems

    * The RSA problem, i.e., computing the e^{th} root of m modulo n from $C = m^e \mod n$
    * FActoring large numbers into smaller primes
- Exponentiation is implemented using *Square and multiply*
  - Problem 1
    * Key dependant branching
    * Execution time depends on the key d, if bit i of d is 0 is will be faster than if bit i of d is 1
  - Problem 2
    * Montgomery used for modular multiplication because it is more efficient
    * Montgomery execution time T_{mont} depends on the plaintext m; there is a reduction step done only if necessary
- **Countermeasures**
- **Constant time**
  - Relatively easy for specific cases
    * E.g., modular multiplication without conditional reduction
  - Generic protection is hard
    * Identify and elininate all dependencies of time with plaintext and key
    * Can have performance issues
- **What if we artificially add noise**
  - An attacker jus tneed more measurements to dig the signal out of the noise
- **Masking**: Can we make it impossible fot the attacker to guess
  - Mask with random number C different for each message:
    * $md \mod n \rightarrow [(m.X)d \mod n].[(X^{-1})d \mod n] \mod n$
  - Intuitively, given m and d_i the attacker cannot guess slow/fast any more
- A **logic gate**
  - Electronic component that implements a logic operator (not, and, nand, or, xor)
  - Stateless (Combinatorial)
  - Together with memory elements it is used to implement finit state machines
- *MOS transistor*: electronic switch
- Logical gate can be implemented with MOS
- **Data dependency**: There are physical phenomena that create a data dependency between logic values and their transitions and the power consumption of the circuit
- **Measure**
  - We can measure the power consumption and observe these phenomena
  - Signals are small, many measurements and statistical analysis are often needed
- **Model**: we know how it works: given some logic data manipulated by the software/hardware, we can predict the corresponding power consumption
- **Countermeasures**
  - *Problem*: There is a data dependency (of some order) between plaintext,key and the power
  - Add noise
    * Desyncronize ther traces
    * Inject random noise
    * Defeated with better signal processing and more measurements
  - Try to balance the hardware
    * Filtering shielding (Filtering is not perfect, expensive, can be tempered)
    * Make a processor where every instruction/operands consumes the same power (Not easy and expensive)
  - N^{th} order masking
    * Multiply each data with a random variable
    * This algorithmically breaks the dependecy making it impossible to guess the intermediate value
- **EM side channel**
  - Currents flowing in cables produce EM signals
  - Clock might act as a carrier
  - Emissions from localized areas, are not all overall power consumption
- **Sound side channel**

  - Currents in certain capacitors make them vibrate and produce sounds
- We don't always need a physical access
- **Tamper resistant** systems take the bank vault approach
  - Prevention of break in
- **Tamper responding** systems use the burglar alarm approach
  - Real-time detection of intrusion and prevention of access to sensitive data
- **Tamper evident** system are designed to ensure that is a break-in occurs, evidence of the break in is left behind
  - Detection of intrusion

Architectural Support for Security

- **Application security**: Requirements
  - **Launch-time integrity**: correct application was started or loaded
  - **Run-time isolation**: no interference from malicious software, peripherals
  - **Secure persistent storage**
- **OS Security**: Privilege rings
  - Ring 3: applications
  - Ring 2: Device drivers
  - Ring 1: Device drivers
  - Ring 0: Kernel
  - Currently, only *ring 0* and *ring 3* are used
  - CPU tracks the current privilege level CPL using two register bits
  - Main uses: limiting access to privileged instructions, I/O-ports
  - Legacy use: kernel memory protection
  - Privilege in Modern OS (only two levels)
    * Level 0 for the kernel
    * Level 3 for users
- Calls across Privilege Rings
  1. Before **syscall**, put argument into registers
  2. Issue **syscall** → CPU changes privilege level and calls *Hook*
  3. *Hook* performs access policy checks and validates arguments
  4. Kernel performs the requests action
  5. Return to the application
- **Discretionary Access Control** (Linux Security Model)
  - A means of restricting access to objects based on the identity of subjects and/or groups to which they belong. The controls are discretionary in the sense that a subject with a certain access permission is capable of passing that permission to any other subject
- **Users and Groups**
  - A *user-account* (user, uid)
    * Represents someone capable of using files
    * Associated both with human and processes
  - A *group-account* (group, gid)
    * Is a list of user-accounts
    * Users have a main group
    * May also belong to other groups
- **Permissions**
  - A file has owner and group id
  - A process has owner and group id
  - Kernel verifies permissions before executing system calls
    * If owner uid = 0(root), everything in allowed
    * Otherwise the uid and gid of the process and object are compared in this order and permission for the operation is searched based on owner, group, and other rights
- A **basic transaction**, wherein a *subject* (user or process) attemps some action (read, write, execute)

against some *object* (file, directory, special file)

- `setuid` bit means program run with same privileges as owner
  - No matter who executes it
- `setgid` bit means run with same privileges as a member of the group which owns it
  - Again regardless of who executes it
- Password are changed using the program `/bin/passwd`
- Real UID (RUID): UID of the user running the program
- Effective UID (EUID): UID of uer with whose privileges the program runs
- `getuid()` returns RUID
- `geteuid()` returns EUID
- `setuid(uid)` set UID
  - If EUID == root, set EUID and RUID
  - If not root, sets EUID if certain conditions are met
- `setruid(uid)` set RUID
- `seteuid(uid)` set EUID
- `fork()` functions shall create a new process. The new process (child process) shall be an extact copy of the calling process (parent process)
- Linux uses a DAC security model but **Mandatory Access Control (MAC)** imposes a global security policy on all users
  - User may not set controls weaker than policy
  - Normal admin done with accounts without authority to change the global security policy
  - but MAC systems have been hard to manage
- **SE linux**
  - In SELinux, all access must be explicitely granted
  - Allows no acces by default, regardless of the linux user/groups ids
  - There is no default superuser in SELinux unlike the `root` in standard linux
  - Each individual subject and object in SELinux is governed by a **security context** being a:
    * User - individual user (human or daemon)
    * Role - like a group, assumed by user
    * Domain (type) - a sandbox being a combination of subjects and objects that may interact with each other
    * this model is called **Type enforcement (TE)**
  - Decision making
    * **Access** decisions: when subject do things to objects that already exist, create new things in expected domain
    * **Transition** decisions: invocation of processes in different domains than the one in which the subject process is running; creation of objects in defferent types (domains) than their parents domain; transitions must be authorized by SELinux policy
  - Access in granted by specifying access from a subject type (that is, a damain) and an object type using an allow rule
  - A domain transition is allowed only when the following three conditions are tue
    * The process' new domain type has *entrypoint* access to executable file type
    * The process' current domain type has *execute* access to the entry point file type
    * The process' current domain type has *transition* access to the new domain type
- **Paging-based Security**
  - Security-relevant data in page table entries
  - *Supervisor bit*: if set, this page is accessible only in ring 0 (isolates OS from applications)
  - *RW bits*: to distinguish between read-only and writeable pages
  - *Non executable (NX) bit*: if set, the page is not executable (prevents run-time code injection)
- **Virtual address space**
  - Every process has its own virtual address space
  - Kernel address space is protected with the supervisor bit
- **Firewire DMA**
  - Key idea: Access RAM is tightly controlled by the CPU, but this can be circumvented through

DMA (Direct Memory Access)
  - Firewire technology allow for fast communication speeds between devices, use DMA
  - The attacker uses a Firewire cable to connect to a (locked) PC and issue a DMA request to fetch the contents of RAM
  - Later on, can look in the collected data and leak keys and other passwords
- **BadUSB**
  - Key idea: change a USB device controller to mimic another device class
- **DMA remapping**
  - Setup by the OS, similar to MMU
  - Control DMA access to physical memory
- *OS trust assumptions*
  - Intel Managment Engine
  - BIOS/UEFI
  - Periferical firmware
  - etc.
- **Physical access Attacks** are harder to defend for the OS
  - Remove the hard drive from a machine left unattended
  - Boot from a USB key and copy the data out/change the password
  - Trivial (and possibly broken) solutions:
    * Prevent booting from an external source from the BIOS (Broken; we can reset the bios by removing the battery)
    * Protect the BIOS with a password (Broken; we can reset the bios by removing the battery)
    * Partial/Full disk encryption
    * Data hiding
- **Disk encryption**
  - *Simple approach*: use password only
    * The disk is encrypted with a key that is protected using a user-privided password
    * Problem: password can be brute-forced
  - *Better approach*: leverage a secure element
    * The disk key encryption is stored in a secure element
    * Example: Trusted Platform Module (TPM) chip on motherboard
- **Cold Boot Attack Process**
  - *Normal operation*
    * The user logs with a password
    * The disk encryption key is kept in RAM when the computer is locked
  - *Attack process*
    * Attacker opens the machine to expose the RAM chips
    * Remove power
    * Cool down RAM (dust-sprayer upside down (-50 degree), LN2 (-192 degree))
    * Plug RAM module to another (acquisition) platform
    * Recover key
- Cold Boot Attack: *Countermeasures*
  - Erase key from memory on every (controlled) suspend
    * User needs to type in password often
    * Does not help sudden power loss
  - Prevent booting from external media
    * Does not prevent DRAM component transfers
  - Physical protection
    * Components that respond to enclosure opening or low temperatures
    * Expensive for commodity systems
  - Avoid placing the key in memory
    * Performs encryption in disk controller
    * Requires architectural changes
- **TPM Support**

  - **Secure boot**: OS boots only if the chain of trust is valid
  - **Authenticated boot**: System records chain of trust but the OS boots even if the chain of trust in invalid
- **UEFI** instead of BIOS
- Hardware-supported OS-based - Application Security

.	Hardware support for OS-based Security
CPU	Privilege rings
	Memory Management Unit
Chipset	DMA Remapping tables
Periferals	Trusted Platform Module
	Normal HDD with OS-enforced access control

- Runtime Attacks: Typical Attacks
  - Buffer overflows
  - Format string
  - Double free
  - Use-after-free
- Runtime Attacks: Mitigation Techniques
  - **Non-executable pages (NX)**
    * Attackers used to place shell code in normal data pages/stack
    * Stack should not be executable
    * Mark all pages that do not contain code as Non-executable (NX)
    * Hardware support required
    * Mark all pages with executable code as read-only
    * Not always possible
  - **Stack canaries**
    * Add random stack canaries
    * To overwrite the return pointer, the stack canary must also be overwritten
    * Check the value before jumping to return address
    * Can prevent some attacks
    * Assumes the attacker cannot read memory
  - **Address space layout randomization (ASLR)**
    * Return to libc: overwrite return pointer with address of `exec(/bin/sh)`
    * What if we move the binary by a few MB in its virtual address space?
    * The location of `exec` will be unknown to the attacker
    * Implemented in all major operating systems
    * KASLR (linux) also defends against Meltdown
    * Broken if the attacker can read memory (separate info leak exploit)
  - **Control flow integrity**
    * Generate all legal control flow transfers
    * Verify every transfer at runtime
    * Straight forward for direct-control transfers
    * Static destination addresses
    * Forward edges: switch statements, indirect calls, etc.
    * Backward edges: returns

Trusted Execution Environment

- **Defense in depth**:
  - Small Trusted Computing Base (TCB)
  - Even if the OS/Hypervisor are comprised, code/data can be protected
- **Confidential computing**:

  - Client can verify what is running on remote system; operator cannot violate the integrity of the execution
  - Operator cannot see the code/data of the client
- Enforced in Hardware (typically via special CPU instructions or co-processor)
- We need to trust the HW manufacturers: Intel, AMD
- Vulnerable to some side channel attack
- **Computing Systems Trust Model**
  - The **Trusting Computing Base** (TCB) is the set of software and hardware components that need to be trusted for an application to execute securely
  - For instance, the TCB of a banking application includes the Operating System, the CPU, the DRAM chips, the disk ...
    - If any of these are malicious the execution integrity and confidentiality cannot be guaranteed
  - Other applications are not in the TCB
  - In principle, they can be malicious and the OS (with hardware support) still provides isolation to other benign apps
    - However some exploit can lead to privilege escalation
  - **Trusted Execution Environment (TTEs)** usuallly aim to reduce the TCB needed to execute applications
- *Primitives*: Isolation, Bootstrapping trust, Sealing storage
- **Isolation** (defense in depth and confidential computing)
  - CPUs traditionally enforce isolation berween permission levels
  - More privileged levels control and can modify less privileged levels
- **Intel SGX** *Isolate 'small' Apps into enclaves*
  - Design choice
    - Create isolated environments at the application level, called **enclaves**
    - Enclaves are isolated from all the other software in the system OS/Hypervisor
  - Resists a physical attacker (cold boot attack, bus tapping, etc)
    - Everything outside the CPU die is untrusted
    - The CPU die is assumed to be secure
  - The OS and the Hypervisor are still in charge of managing virtual memory and interrupts
  - The CPU keeps track of whether it is currently executing in enclave-mode and which enclave is executing
  - Memory reads to enclave memory when not in enclave mode always return `0xff`
  - Trying to read another enclave memory returns `0xff`
  - Similarly, not authorized memory writes fail silently
  - Enclaves can read/write the memory to their untrusted app
  - New component on the CPU takes care of securing memory, the **Memory Encryption Engine (MEE)**
  - The CPU is trusted, so data resides in the cache in plain text
  - While the content of memory pages is protected by SGX and the MEE, page metadata is not, metadata includes:
    - Access permissions of a page
    - Accessed bit: whether a memory page was recently accessed
    - Dirty bit: whether a memory page was recently written
  - **Controlled Channel attacks**
    - The os can remove execute or read/write access to memory page
    - This trigger an exception which contains the address of the memory page that was being accessed
    - This reveals enough information
    - Information from the accessed/dirty bits are also enough to leak information
  - **Side Channel attacks**
    - Enclaves share resources with other applications in the system: cache, core execution units, branch prediction structure
    - Monitoring utilization of these resources from another application leaks information

- **AMD SEV**: *Isolate entire VMS*
  - Design choices:
    * Isolate Virtual Machine from Hypervisor. VMs can execute code on ring 3,2 and 1
  - Resists low skilled physical attacker (cold boot, but not bus tampering)
    * Everything outside the CPU die is untrusted
  - Comparison with SGX
    * SEV encrypts data that leaves the CPU die
    * However, it does not store a MAC tag together with the data (data in memory is not authenticated)
    * Like SGX, SEV keeps track of the different isolated environments with HW prinitives
    * While unauthorized writes cannot happen from the CPU, if memory is corrupted some other way VMs will read the wrong value from memory
  - Key management
    * SEV uses an ARM co-processor to manage the different encryption key for each VM
    * At VM creation a new key is created in the co-processor to encrypt the VM memory
    * Each new VM has a different encryption key
- **ARM TrustZone**: *The tale of two world*
  - Design choices:
    * Have two separate isolated execution environments. These are referred to as the Non secure and the Secure world
  - No physical attacker
    * Communication to peripherals is assumed to be trusted
  - The memory is partition between the Secure and Non-Secure world
  - The Secure world can read/write the Non-Secure world memory, but the Non-Secure world is restricted to its own memory
  - The TrustZone Address space is controller (TZASV) is a hardware component that is used to configure which ranges of memory belong to which world
  - Only the secure world can configure the TZASV
  - Memory is separated at the physical layer. That is there are two separate physical address ranges, one for the secure world and one for the non-secure world
  - The CPU keeps track of which world in currently executing
- **AMD SEV**
  - *Advantages*:
    * Tolerate strong physical attacker, only CPU in TCB
  - *Disadvantages*:
    * Memory and interrupt management performed by OS
    * Application need to be adapted to run inside an SGX enclave
    * Only small applications possible
- **AMD SEV**
  - *Advantages*:
    * Applications do not need to specifically adapted to run in an isolated SEV environment
  - *Disadvantages*:
    * Resilience against physical attackers varies depending on the SEV version
    * Memory management perfromed by hypervisor
- **ARM TrustZone**:
  - *Advantages*:
    * No page/interrupt management by untrusted code, infrastruture (partially) supports secure state
    * Availability guarantees for sedure world possible
  - *Disadvantages*:
    * No physical attacker
    * Only one protected state
    * All software runnin before and under software in secure world need to be trusted
    * Secure state is often locked for use by device vendors and not generally open for application

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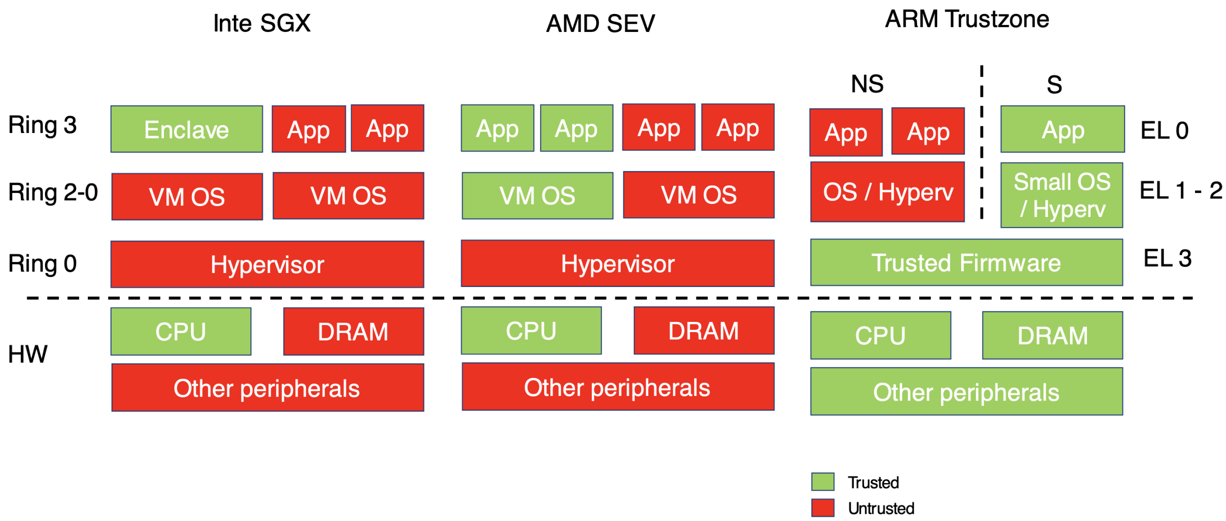
- **Trusted Isoltation Environments** Trust Model summary



- **Bootstrapping trust** (Attestation/Secure boot) (confidential computing)
  - The isolation provided by TEEs is a useful primitive
  - However secret need to get into the TEE somehow
  - How do we make sure that we are sending secret to the right TEE and not the malicious OS
  - The main way to prove the authenticity of a TEE:
    * **Secure boot** check that at each boot stage, only trusted software is loaded
    * **Remote attestation**
- **Remote Attestation**
  - Different Enclaves and keys involved
  - CPU measures the enclave and signs it hash
  - Enclave invokes measurement, OS is suspended, CPU measures and returns the the signed hash
  - This can be done so that client creates a secure channel into the enclave
- **Sealing storage** (defense in depth and confidential computing)
  - Enclave has no direct access to disk or IO / no access to persistent storage
  - No access to trusted clock, limited support for counters
  - Can do **sealing** - store encrypted confidential data on disk
    * This data is encrypted and MACed with enclave and processor specific keys
- **Remote Attestation**
  - During manufacturing, two keys are burned into the CPU
    * **Fused Seal key** is used as Processor's secret
    * **Provisionning key** serve as a proof for remote platform
    * Remote platform issues an **Attestation key** which is encrypted and stored for future use
- To prevent attestation key from leaking the platform's identity, Intel introduces the **EPID** scheme
  - **EPID**: digital signature scheme with anonymity properties
    * One group public key corresponds to multiple private keys
    * Each unique private key can be used to generate a signature
    * Signature can be verified using the group public key
    * A signature cannot be linked to a private key

Memory vulnerabilities and Exploits

- **x86 Machine Model**
  - Both code and data are represented as numbers

  - **Little endian**: least significant bytes is put at lower addresses
  - **Stack** grows down, other memory accesses move up
- **OS Model**
  - Ring-0,runs on behalf of every process
  - Context switches
    - On an interrupt, CPU switches control to ring-0
    - Ring-0 (OS) sets CR3 to another process, then `iret`
- Stack organization:
  - Function parameters
  - Return address
  - Saved Frame Pointer
  - Function's data
- **Integer Overflow**
- **Use after free**
- **Double free**
- **Format string vulnerabilities**
- **Upcasting**: From a derived class to its parent class
- **Downcasting**: From a parent class to one of its derived classes
- Upcasting is always safe, but downcasting is not
- Hardware does *not give memory and type safety*
- **Control oriented Exploits**
  - Goals: Divert or Hijack Control Flow
  - Main tricks:
    - Corrupt code pointers
    - Corrupt non-code pointer
  - Outcome:
    - Code injection
    - Code reuse
- **Data oriented Exploits**
  - Goal: Hijack Data flow
  - Outcomes: Privilege escalation, Data leakage
- **Code injection**: A memory exploit that hijacks control to jump to attacker's data payload
  - *Requirements*
    - Write attack payload in memory
    - Have Attack Payload Be Executable
    - Divert control-flow to payload
- **Code pointers**: A memory address, the value of which is deirectly used as a control-flow transfer (in machine code) under benign inputs
  - **Code pointer injection**: Forging the runtime value of a code pointer to an invalid one
- **Type safety for Code Pointers**
  - Enforce that code pointers point to code-segment only
  - Enforce that control transfers use code pointers
  - Defeats code injection
- **Code reuse**: A memory exploit that hijack contro to jump to attacker's controlled code address
  - *Requirements*
    - Have attack payload be excutable
    - Divert control flow to payload
  - Type safety of code pointers in not enough
  - The idea:
    - Attacker hijacks control flow
    - Jumps back to the code segment
- **Control flow integrity**: Each control transfer jumps to a statically known set of locations
- **Data flow switching**
  - Manipulate data flows for exploits

- Goal:
    - Information leakage
    - Privilege escalation
- Constraints:
    - Keep the control flow same
    - Prevent abrupt termination

- **Defense goals**
  - Complete memory safety
  - Prevent memory writes
  - Protect all pointers
  - Protect code pointers
  - Prevent bad control flow transfers
  - Protect arbitrary parts/region of memory
  - Protect data-flow patterns
  - Complete Type safety
  - Don't protext, simple randomize

Memory Defenses

- Complete **Memory Safety**: Access memory in an intended way
- **Fault isolation**: Each module only accesses pre-determined data/code
- **No foreign code**: Execute only predetermined code
- **Control flow integrity**: Control transfers are to legitimate points only
- **System call sandboxing**: Access only a subset of system calls
- **(Code) pointers/Data integrity**: Ensure (code) pointers/date have valid values
- **Data flow integrity**
- **Non-executable Data/DEP**
  - Setting regions of memory non-executable
  - Use NX bit
  - *Defense goal*: Prevents Foreign code injection
- **Software Fault Isolation**
  - *Goal*: Fault isolation
    - Confine read/write to certain region M
    - This goal is also called *address sandboxing* (Access memory segments statically verified)
  - Attacker controls all memory values in M
  - Mechanism: Inline instrumentation of D
  - Limit all memeory acces to region M
  - **Trusted Computing Base (TCB)**: The trusted codebase for ensuring security properties
  - Smaller the TCB, the better the design
- **Inline Reference Monitors**: Control flow integrity
  - Follow the statically determine CFG at runtime
  - CFI blocks all control flow hijacking exploits
- **Randomized tags**: Control flow integrity; Each code block must start with a tag
  - The tag should be a random, secure value
  - If `f` can jump to block `g`, `h`, ... then these blocks, should have the same tag
- **Address Space Layout Randomization (ASLR)**
  - *Assumption*: The attacker can write arbitrary places
  - *Defense goal*: Attacker can't predict location accessed in attack
  - *Mechanism*:
    - At load time, randomize stack, code, bss, etc.
    - Randomize heap location at runtime
- **Instruction Set Randomization (ISR)**
  - *Goal*: Randomize machine instruction encoding, to defeat foreingn code injection
- **Stack Canaries**

- Secret Data values, to protect corruption of nearby data
  - Check: the random canary value is OK at ret
- **Guard Pages**
  - *Defense*: Guard Pages
    * Certain pages with NR, NW, NX inserted
  - *Assumption*:
    * Attacker can only write linearly
    * All written values are not used in dereferences
- **Code Checking Tools**
  - Tools checking for vulnerabilities using static source code analysis
- **Safe Language and Coding**
  - Use bug-finding techniques
  - Safe code techniques
  - Use safe libraries

Detection and Prevention

- **Information Flow Policies** Non interference
  - Differentiate programs with good information flows
  - Non interference: 'A program is non interfering iff any executions, started with the same L-Inputs, generate the same L-Outputs'
- **Bell-LaPadula**: No read up, no write down
- **Kinds of Information flow**
  - **Direct**: use legitimate channels for data transfer
  - **Indirect**: use channels not intended for data transfer
  - **Explicit**: created by the occurence of an event/action
  - **Implicit**: created by the absence of a specific event/action
- Application of **Taint-tracking**
  - A kind of Information Flow Technique
  - Runtime Detection/Prevention
    * Controle flow hijacking
    * Non control data corruption
    * XSS, SQL, Command injection
    * User Kernel Pointer Bugs
  - Off line Analysis
    * Malware Analysis
    * Privacy-leaking Android apps
  - $f : X \to Y$
    * X has some bits in which are private
  - Aims to detect: Does an output Y reveal some private X
- **Soundness & Completeness**
  - *Goal*: Given P prove that P satisfies C
  - **Complete**: Identifies all safe Ps
  - **Sound**: If P is claimed safe, it does not satisfy P (?)
- In practice choose 3 between **Sound**, **Complete** and **Termination**
- **Static tracking**
  - Relies on CFG/DFG
  - *Advantages*
    * No false negative
- **Dynamic tracking**
  - Dataflow at runtime
  - *Advantages*
    * Can have FPs
    * But lower FP

- **Uncertity and Entropy**
  - **Shanon Entropy**

$$H(X \mid Y = y) = \sum_{x \in \mathcal{X}} P[X = x \mid Y = y] \log \frac{1}{P[X = x \mid Y = y]}$$

- Initial uncertity = Information leaked + Remaining uncertity ($H[X] = I[X;Y] + H[X \mid Y]$)
- **Symbolic Execution**
  - Check Safety Properties (Model)
- **Dynamic Symbolic Execution**
  - *The main idea*: Analyze One Execution Path
    - Run the program under one concrete input
    - Collect the values of all variables at each executed statement. This information often called an 'execution trace'
    - Mark certain inputs as symbolic
    - Track the relationship between variables in the execution trace and symbolic inputs as a formula
    - At symbolic branch conditions, assert that the condition evaluates to the value in the execution trace
    - Calculate Symbolic Formula for path constraints: The logically comjunction of all the symbolic constraints
  - **Symbolic input**: Values captured with symbolic formula
  - **Branch constraints**: A symbolic formula capturing the values that make the branch condition evaluate a specific value
  - **Path constraints**: A formula over the symbolic inputs that encodes all branch decisions taken up to a certain program point
  - **Execution path space**: All paths in the program, each captured by its path constraints
  - **Feasible path** A path which has a satisfiable symbolic formula, there exists one assignement of values to its symbolic variables that make formula 'True'
- Testing software for bugs
  - **Blackbox testing**: no analysis
  - **Greybox testing**:
    - Lightweight analysis
    - Coverage
  - **Whitebox testing**:
    - Heavyweight analysis
    - Path conditions
- **Fuzzing**
  - Automatically generate test cases
  - Random
  - Grab & mutate
  - Grammar based
- **Greybox fuzzing**
  - Guide input generation toward a goal
    - Guidance bsaed on lightweight program analysis
  - Three main steps:
    - Randomly generate inputs
    - get feedback from previous executions
  - What code is covered? Mutate inputs that have covered new code
- **American Fuzzy Lop**
  - Simple yet effective fuzzing tool
  - Targets C/C++ programs
  - Inputs are, e.g., files read by the program
  - Widely used in industry, in particular, to find security-related bugs

- **Measuring Coverage**
  - Different coverage metrics
    - Line/statement/branch/path coverage
  - Here: Branch coverage
  - Branches between basic blocks
  - Rationale: Reaching a code location not enough to trigger a bug, but state also matters
  - Compromise between
    - Effort spent on measuring coverage
    - Guidance it provides to the fuzzer
- **Detecting new Behaviours**
  - Inputs that trigger a new edge in the CFG: Considered as new behaviour
  - Alternative: Consider new paths
    - More expensive to track
    - Path explosion problem
- **Evolving queue of inputs**
  - Maintain queue of inputs
    - Initially: Seed inputs provided by user
    - Once used, keep input if covers new edges
    - Add new inputs by mutating existing input
- **Mutation operators**
  - *Goal*: Create new inputs from existing inputs
  - Random transformation of bytes in an existing input
  - Bit flips with varying lengths and stepovers
  - Additions and substraction of small integers
  - Insertion of known interesting integers
- More tricks for fast fuzzing
  - Time and memory limits
    - Discard input when execution is too expensive
  - Prunning the queue
    - Periodically select subset of inputs that still cover every edge seen so far
  - Prioritize how many mutants to generate from an input in the queue
- In-application Isolation Techniques
  - Page table protection
  - Software bounds checks
- **Pointer authentication**: Ensure pointers in memory remain unchanged
  - General purpose hardware primitive approximation pointer integrity
  - Adds pointer authentication Code into unused bits of pointer
  - Keyed, tweakable MAC from pointer address and 64-bits modifier
  - PA keys protected by hardware, modifier decided where pointer created and used
  - *Prevent arbirtrary pointer injection*
    - Modifiers do not need to be confidential
    - Visible or inferable from the code section/binary
    - Keys are protected by hardware and set by kernel
    - Attacker cannot generate PACs