CS323 Operating Systems

Mitigations

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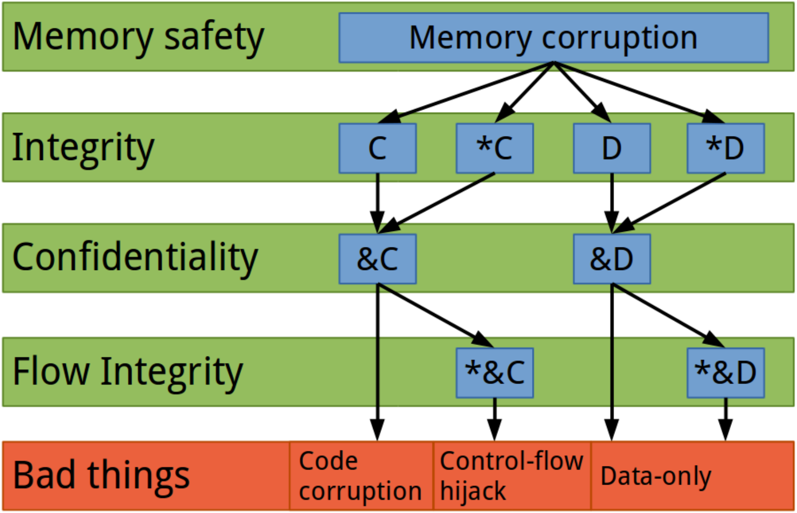
Topics covered in this lecture

- Data Execution Prevention
- Address Space Layout Randomization
- Stack canaries
- Control-Flow Integrity (CFI)

This slide deck covers chapter 6.4 in SS3P.

Model for Control-Flow Hijack Attacks



Widely-adopted defense mechanisms

- Hundreds of defense mechanisms were proposed
- Only few mitigations were adopted
- Factors that increase chances of adoption:
  - Mitigation of the most imminent problem
  - (Very) low performance overhead
  - Fits into the development cycle

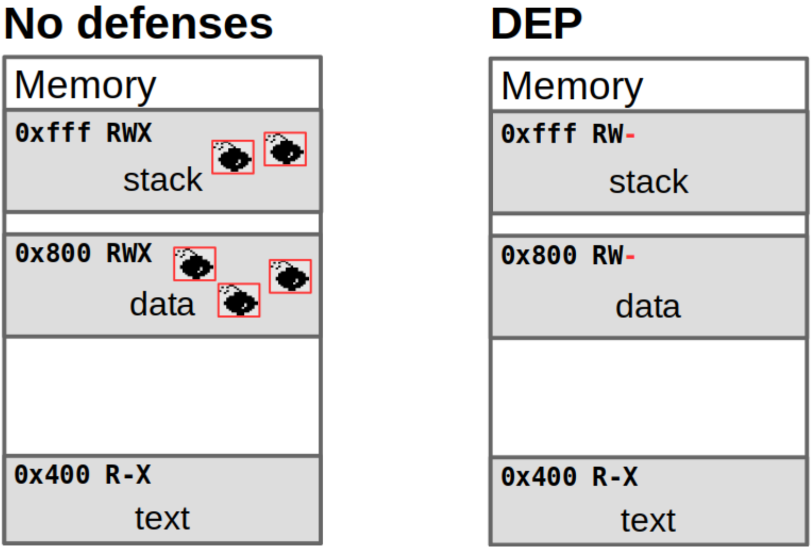
Attack vector: code injection

- Simplest form of code execution
- Generally consists of two steps:
  - Inject `code` somewhere into the process
  - Redirect control-flow to injected code

Data Execution Prevention (DEP)

- No distinction between code and data (e.g., x86, ARM)
- Any data in the process could be interpreted as code (code injection: an attacker redirects control-flow to a buffer that contains attacker-controlled data as shellcode)
- ***Defense assumption:*** if an attacker cannot inject code (as data), then a code execution attack is not possible.

DEP: process layout



DEP implementation

- HW extension, add NX-bit (No eXecute) to page table entry
  - Intel calls this per-page bit XD (eXecute Disable)
  - AMD calls it Enhanced Virus Protection
  - ARM calls it XN (eXecute Never)
- This is an additional bit for every mapped virtual page. If the bit is set, then data on that page cannot be interpreted as code and the processor will trap if control flow reaches that page.

DEP summary

- DEP is now enabled widely by default (whenever a hardware support is available such as for x86 and ARM)
- Stops all code injection
- Check for DEP with checksec.sh
- DEP may be disabled through gcc flags: `-z execstack`

- Did DEP solve all code execution attacks?

Attacks evolve: from code injection to reuse

- Did DEP solve all code execution attacks?
- Unfortunately not! But attacks got (much?) harder
- A code injection attack consists of two stages:
  a) redirecting control flow
  b) to injected code
- DEP prohibits execution of injected code
  - DEP does not stop the redirection of control flow
  - Attackers can still hijack control flow to ***existing*** code

Code reuse

- The attacker can overwrite a code pointer (e.g., a function pointer, or a return pointer on the stack)
- Prepare the right parameters on the stack, reuse a full function (or part of a function)

From Code Reuse to full ROP

Instead of targeting a simple function, we can target a gadget

- Gadgets are a sequence of instructions ending in an indirect control-flow transfer (e.g., return, indirect call, indirect jump)
- Prepare data and environment so that, e.g., pop instructions load data into registers
- A gadget invocation frame consists of a sequence of 0 to n data values and an pointer to the next gadget. The gadget uses the data values and transfers control to the next gadget

Link to simple ROP tutorial

Address Space Randomization (ASR)

The security improvement of ASR depends on (i) the available entropy for randomized locations, (ii) the completeness of randomization (i.e., are all objects randomized), and (iii) the absence of information leaks.

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The security improvement of ASR depends on (i) the available entropy for randomized locations, (ii) the completeness of randomization (i.e., are all objects randomized), and (iii) the absence of information leaks.

- Successful control-flow hijack attacks depend on the attacker overwriting a code pointer with a known alternate target
- ASR changes (randomizes) the process memory layout
- If the attacker does not know where a piece of code (or data) is, then it cannot be reused in an attack
- Attacker must first ***learn*** or recover the address layout

Candidates for randomization

- Trade-off between overhead, complexity, and security benefit.
- Randomize start of heap
- Randomize start of stack
- Randomize start of code (PIE for executable, PIC each library)
- Randomize mmap allocated regions
- Randomize individual allocations (malloc)
- Randomize the code itself, e.g., gap between functions, order of functions, basic blocks, ...
- Randomize members of structs, e.g., padding, order.

Different forms of fine-grained randomization exist. Software diversity is a related concept.

Address Space *Layout* Randomization (ASLR)

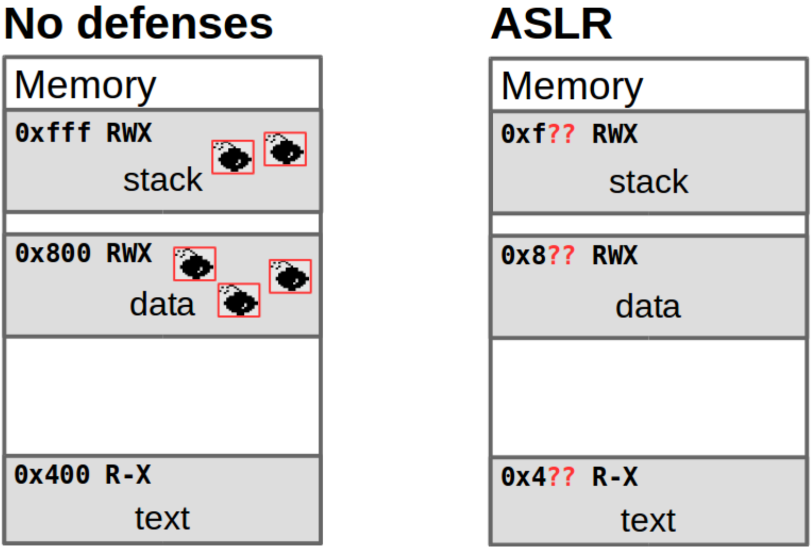
ASLR is a practical form of ASR.

- ASLR focuses on blocks of memory
- Heap, stack, code, executable, mmap regions
- ASLR is inherently page-based

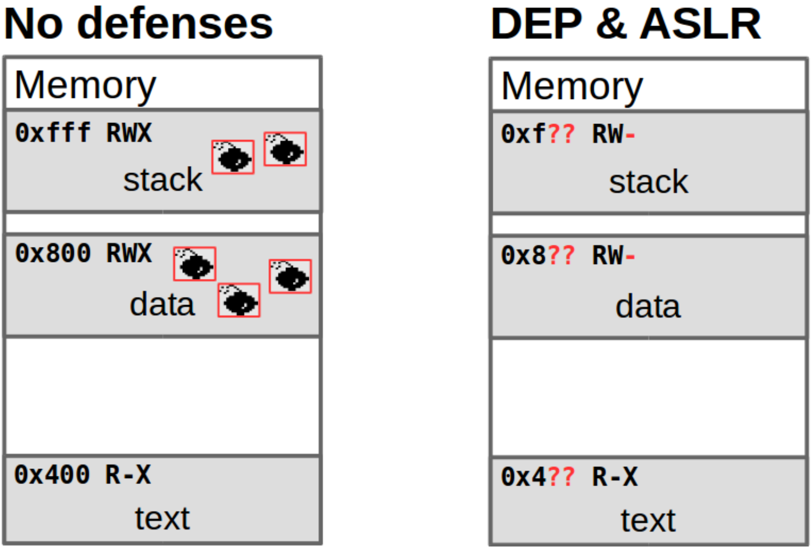
ASLR entropy

- Assume start addresses of all sections are randomized
- Entropy of each section is key to security
- Attacker targets section with lowest entropy
- Early ASLR implementations had low entropy on the stack and no entropy on x86 for the executable (non-PIE executables)
- Linux (through Exec Shield) uses 19 bits of entropy for the stack (on 16 byte period) and 8 bits of mmap entropy (on 4096 byte period).

ASLR changes to the address space



ASLR and DEP changes to the address space



Stack canaries

- Attacks relied on a stack-based buffer overflow to inject code
- Memory safety would mitigate this problem but adding full safety checks is not feasible due to high performance overhead
- Key insight: buffer overflows require pointer arithmetic
  - Instead of checking each memory dereference during function execution, we check the integrity of a variable once
- ***Assumption:*** we only prevent RIP control-flow hijack attacks
- We therefore only need to protect the integrity of the return instruction pointer

Stack canaries

- Place a canary after a potentially vulnerable buffer
- Check the integrity of the canary before the function returns
- The compiler may place all buffers at the end of the stack frame and the canary just before the first buffer. This way, all non-buffer local variables are protected as well.
- Limitation: the stack canary only protects against ***continuous overwrites*** iff the attacker does ***not know*** the canary
- An alternative is to encrypt the return instruction pointer by xoring it with a secret

Stack protector: code

```
char unsafe(char *vuln) {
  char foo[12];
  strcpy(foo, vuln);
  return foo[1];
}

int main(int ac,
    char* av[]) {
  unsafe(argv[0]);
  return 0;
}
```

Stack protector: assembly

```
push   %rbp
mov %rsp,%rbp
sub    $0x30,%rsp
mov    %rdi,-0x28(%rbp)
mov    %fs:0x28,%rax           ; load secret canary
mov    %rax,-0x8(%rbp)         ; store canary on stack
xor    %eax,%eax               ; clear register
mov    -0x28(%rbp),%rsi
lea    -0x20(%rbp),%rdi
callq  <strcpy@plt>
movzbl -0x1f(%rbp),%eax
mov    -0x8(%rbp),%rcx         ; load canary from stack
xor    %fs:0x28,%rcx           ; check canary
je     <out>
callq <__stack_chk_fail@plt> ; terminate if check failed
out: leaveq, retq
```

Other mitigations

- Fortify source: protect against format string attacks
- Safe exception handling: protect against popping exception frames

CFI is a defense mechanism that protects applications against control-flow hijack attacks. A successful CFI mechanism ensures that the control-flow of the application never leaves the predetermined, valid control-flow that is defined at the source code/application level. This means that an attacker cannot redirect control-flow to alternate or new locations.

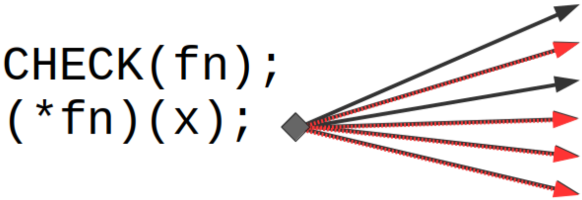


Figure 1: CFI target restriction

Basics of a CFI mechanism

Core idea: restrict the dynamic control flow of the application to the control-flow graph of the application.

- Target set construction
- Dynamic enforcement mechanism to execute runtime checks

CFI: target set construction

How do we infer the control-flow graph (for C/C++ programs)? A static analysis (on source code or binary) can recover an approximation of the control-flow graph. Precision of the analysis is crucial!

- Valid functions
- Arity
- Function prototypes
- Class hierarchy analysis

CFI: target set construction

- Trade-off between precision and compatibility.
- A single set of ***valid functions*** is highly compatible with other software but results in imprecision due to the large set size
- ***Class hierarchy analysis*** results in small sets but may be incompatible with other source code and some programmer patterns (e.g., casting to void or not passing all parameters)

CFI: limitations

- CFI allows the underlying bug to fire and the memory corruption can be controlled by the attacker. The defense only detects the deviation after the fact, i.e., when a corrupted pointer is used in the program
- Over-approximation in the static analysis reduces security guarantees
- Some attacks remain possible
  - An attacker is free to modify the outcome of any conditional jump (e.g., `if` clauses depend on unprotected data values)
  - An attacker can choose any allowed target at each indirect control-flow transfer location
  - For return instructions: one set of return targets is too broad and even localized return sets are too broad for most cases
  - For indirect calls and jumps, attacks like COOP (Counterfeit Object Oriented Programming) have shown that full functions serve as gadgets

OS support for mitigation and sanitization

- Fault or trap signal: a segmentation fault serves as a fast and efficient way to interrupt and stop execution. Instead of adding `if (x)` to each instruction, an illegal access quickly and efficiently stops program execution.
- Virtual address space: the OS controls this important abstraction and during program instantiation the OS can introduce randomness and diversity to make exploitation more costly (and requires the attacker to first recover information).
- Segments: the OS enables thread-local data by repurposing segment registers, stack canaries are stored in thread-local data
- Virtual address space: not all memory needs to be mapped to physical memory, enabling shadow data structures as used for sanitization
- Access to new architecture features such as Intel MPK (memory protection keys), ARM PAC (pointer authentication codes), shadow stacks, ...

Summary and conclusion

- Deployed mitigations do not stop all attacks
- ***Data Execution Prevention*** stops code injection attacks, but does not stop code reuse attacks
- ***Address Space Layout Randomization*** is probabilistic, shuffles memory space, prone to information leaks
- ***Stack Canaries*** are probabilistic, do not protect against direct overwrites, prone to information leaks
- ***CFI*** restricts control-flow hijack attacks, does not protect against data-only attacks

Don't forget the Moodle quiz!