Mitigating Memory Safety Vulnerabilities

CS 161 Spring 2024 - Lecture 5

Next: Memory Safety Mitigations

- Memory-safe languages
- Writing memory-safe code
- Building secure software
- Exploit mitigations
  - Non-executable pages
  - Stack canaries
  - Pointer authentication
  - Address space layout randomization (ASLR)
- Combining mitigations

Today: Defending Against Memory Safety Vulnerabilities

- We’ve seen how widespread and dangerous memory safety vulnerabilities can be. Why do these vulnerabilities exist?
  - Programming languages aren’t designed well for security.
  - Programmers often aren’t security-aware.
  - Programmers write code without designing security in from the start.
  - Programmers are humans. Humans make mistakes.

Today: Defending Against Memory Safety Vulnerabilities

- What are some approaches to defending against memory safety vulnerabilities?
  - Use safer programming languages.
  - Learn to write memory-safe code.
  - Use tools for analyzing and patching insecure code.
  - Add mitigations that make it harder to exploit common vulnerabilities.

Using Memory-Safe Languages

Textbook Chapter 4.1

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Memory-Safe Languages

- **Memory-safe languages** are designed to check bounds and prevent undefined memory accesses
- By design, memory-safe languages are not vulnerable to memory safety vulnerabilities
  - Using a memory-safe language is the **only** way to stop 100% of memory safety vulnerabilities
- Examples: Java, Python, C#, Go, Rust
  - Most languages besides C, C++, and Objective C

Why Use Non-Memory-Safe Languages?

- Most commonly-cited reason: **performance**
- Comparison of memory allocation performance
  - C and C++ (not memory safe): `malloc` usually runs in (amortized) constant-time
  - Java (memory safe): The garbage collector may need to run at any arbitrary point in time, adding a 10–100 ms delay as it cleans up memory

The Cited Reason: The Myth of Performance

- For most applications, the performance difference from using a memory-safe language is insignificant
  - Possible exceptions: Operating systems, high performance games, some embedded systems
- C's improved performance is not a direct result of its security issues
  - Historically, safer languages were slower, so there was a tradeoff
  - Today, safe alternatives have comparable performance (e.g. Go and Rust)
  - Secure C code (with bounds checking) ends up running as quickly as code in a memory-safe language anyway
  - You don't need to pick between security and performance: You can have both!

The Cited Reason: The Myth of Performance

- Programmer time matters too
  - You save more time writing code in a memory-safe language than you save in performance
- “Slower” memory-safe languages often have libraries that plug into fast, secure, C libraries anyway
  - Example: NumPy in Python (memory-safe)

The Real Reason: Legacy

- Most common actual reason: inertia and **legacy**
- Huge existing code bases are written in C, and building on existing code is easier than starting from scratch
  - If old code is written in {language}, new code will be written in {language}!

Example of Legacy Code: iPhones

- When Apple created the iPhone, they modified their existing OS and environment to run on a phone
- Although there may be very little code dating back to 1989 on your iPhone, many of the programming concepts remained!
- If you want to write apps on an iPhone, you still often use Objective C
- **Takeaway**: Non-memory-safe languages are still used for legacy reasons

Writing Memory-Safe Code

Textbook Chapter 4.2

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Writing Memory-Safe Code

- Defensive programming: Always add checks in your code just in case
  - Example: Always check a pointer is not null before dereferencing it, even if you're sure the pointer is going to be valid
  - Relies on programmer discipline
- Use safe libraries
  - Use functions that check bounds
  - Example: Use **`fgets`** instead of **`gets`**
  - Example: Use **`strncpy`** or **`strlcpy`** instead of **`strcpy`**
  - Example: Use **`snprintf`** instead of **`sprintf`**
  - Relies on programmer discipline or tools that check your program

Writing Memory-Safe Code

- Structure user input
  - Constrain how untrusted sources can interact with the system
  - Example: When asking a user to input their age, only allow digits (0–9) as inputs
- Reason carefully about your code
  - When writing code, define a set of *preconditions*, *postconditions*, and *invariants* that must be satisfied for the code to be memory-safe
  - Very tedious and rarely used in practice, so it's out of scope for this class

Building Secure Software

Textbook Chapter 4.3

Today: Defending Against Memory Safety Vulnerabilities

- What are some approaches to defending against memory safety vulnerabilities?
  - Use safer programming languages.
  - Learn to write memory-safe code.
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Approaches for Building Secure Software/Systems

- Run-time checks
  - Automatic bounds-checking
  - May involve performance overhead
  - Crash if the check fails
- Monitor code for run-time misbehavior
  - Example: Look for illegal calling sequences
  - Example: Your code never calls **`execve`**, but you notice that your code is executing **`execve`**
  - Probably too late by the time you detect it
- Contain potential damage
  - Example: Run system components in sandboxes or virtual machines (VMs)
  - Think about privilege separation

Approaches for Building Secure Software/Systems

- Bug-finding tools
  - Excellent resource, as long as there aren't too many false bugs
- Code review
  - Hiring someone to look over your code for memory safety errors
  - Can be very effective… but also expensive
- Vulnerability scanning
  - Probe your systems for known flaws
- Penetration testing ("pen-testing")
  - Pay someone to break into your system

Testing for Software Security Issues

- How can we test programs for memory safety vulnerabilities?
  - Fuzz testing: Random inputs
  - Use tools like Valgrind (tool for detecting memory leaks)
  - Test corner cases
- How do we tell if we've found a problem?
  - Look for a crash or other unexpected behavior
- How do we know that we've tested enough?
  - Hard to know, but code-coverage tools can help

Working Towards Secure Systems

- Modern software often imports lots of different libraries
  - Libraries are often updated with security patches
  - It's not enough to keep your own code secure: You also need to keep libraries updated with the latest security patches!
- What's hard about patching?
  - Can require restarting production systems
  - Can break crucial functionality

Exploit Mitigations

Textbook Chapter 4.4

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Exploit Mitigations

- Scenario
  - Someone has just handed you a large, existing codebase
  - It's not written in a memory-safe language, and it wasn't written with memory safety in mind
  - How can you protect this code from exploits without having to completely rewrite it?
- **Exploit mitigations (code hardening)**: Compiler and runtime defenses that make common exploits harder
  - Find ways to turn attempted exploits into program crashes
  - Crashing is safer than exploitation: The attacker can crash our system, but at least they can't execute arbitrary code
  - Mitigations are cheap (low overhead) but not free (some costs associated with them)

Recall: Putting Together an Attack

1. Find a memory safety (e.g. buffer overflow) vulnerability
2. Write malicious shellcode at a known memory address
3. Overwrite the RIP with the address of the shellcode
4. Return from the function
5. Begin executing malicious shellcode

Recall: Putting Together an Attack

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We can defend against memory safety vulnerabilities by making each of these steps more difficult (or impossible)!

Mitigation: Non-Executable Pages

Textbook Chapter 4.5 & 4.6 & 4.7

Recall: Putting Together an Attack

1. Find a memory safety (e.g. buffer overflow) vulnerability
2. Write malicious shellcode at a known memory address
3. Overwrite the RIP with the address of the shellcode
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5. Begin executing malicious shellcode
    - Mitigation: Non-executable pages

We can defend against memory safety vulnerabilities by making each of these steps more difficult (or impossible)!

Non-Executable Pages

- Idea: Most programs don't need memory that is both written to and executed, so make portions of memory **either** executable **or** writable but not both
  - Stack, heap, and static data: Writable but not executable
  - Code: Executable but not writable
- Page table entries have a writable bit and an executable bit that can be set to achieve this behavior
  - Recall page tables from 61C: Converts virtual addresses to physical addresses
  - Implemented in hardware, so effectively 0 overhead!
- Also known as
  - **W^X** (write XOR execute)
  - **DEP** (Data Execution Prevention, name used by Windows)
  - **No-execute bit** (the name of the bit itself)

Subverting Non-Executable Pages

- Issue: Non-executable pages doesn't prevent an attacker from leveraging **existing** code in memory as part of the exploit
- Most programs have many functions loaded into memory that can be used for malicious behavior
  - **Return-to-libc**: An exploit technique that overwrites the RIP to jump to a functions in the standard C library (libc) or a common operating system function
  - **Return-oriented programming (ROP)**: Constructing custom shellcode using pieces of code that already exist in memory

Subverting Non-Executable Pages: Return-to-libc

- Recall: Per the x86 calling convention, each program expects arguments to be placed directly above the RIP
- Consider the **`system`** function, which executes a shell command. We want to execute it like this:

```
char cmd[] = "rm -rf /";
system(cmd);
```

Subverting Non-Executable Pages: Return-to-libc

Exploit:

```
'A' * 24
    + [address of system]
    + 'B' * 4
    + [address of "rm -rf /"]
    + "rm -rf /"
```

```
int system(char *command);

void vulnerable(void) {
    char name[20];
    gets(name);
}

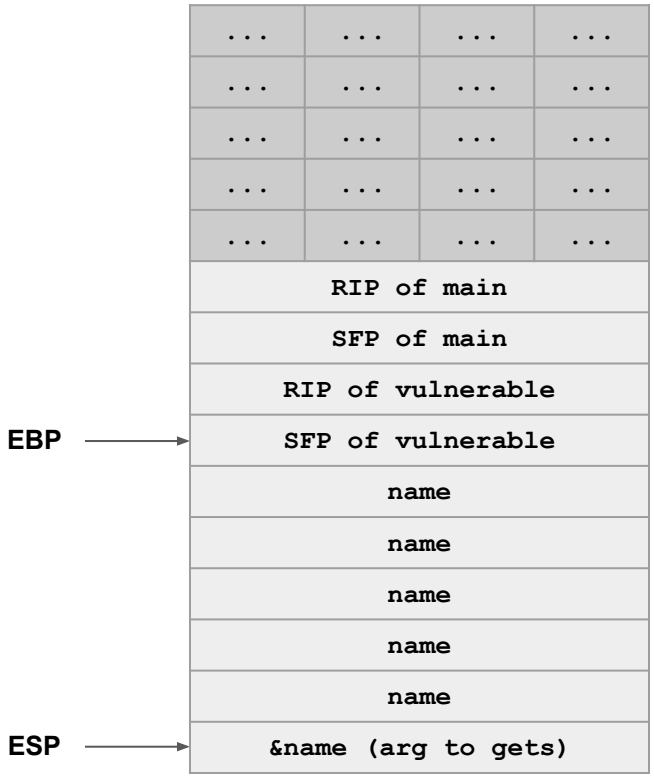
int main(void) {
    vulnerable();
    return 0;
}
```

EIP →

```
system:
    ...

vulnerable:
    ...
    call gets
    addl $4, %esp
    movl %ebp, %esp
    popl %ebp
    ret

main:
    ...
    call vulnerable
    ...
```



Subverting Non-Executable Pages: Return-to-libc

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    addl $4, %esp
    movl %ebp, %esp
    popl %ebp
    ret

main:
    ...
    call vulnerable
    ...
```

...	...	...	...
...	...	...	...
'\0'	...	...	...
'r'	'f'	' '	'/'
'r'	'm'	' '	'-'
[address of "rm -rf /"]			
'B'	'B'	'B'	'B'
[address of system]			
'A'	'A'	'A'	'A'
'A'	'A'	'A'	'A'
'A'	'A'	'A'	'A'
'A'	'A'	'A'	'A'
'A'	'A'	'A'	'A'
'A'	'A'	'A'	'A'
&name (arg to gets)			

EBP →

ESP →

Subverting Non-Executable Pages: Return-to-libc


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int system(char *command);

void vulnerable(void) {
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```

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    ...

vulnerable:
    ...
    call gets
    addl $4, %esp
    movl %ebp, %esp
    popl %ebp
    ret

main:
    ...
    call vulnerable
    ...
```

EIP →

EBP →

ESP →

...	...	...	...
...	...	...	...
'\0'	...	...	...
'r'	'f'	' '	'/'
'r'	'm'	' '	'-'
[address of "rm -rf /"]			
'B'	'B'	'B'	'B'
[address of system]			
'A'	'A'	'A'	'A'
'A'	'A'	'A'	'A'
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Subverting Non-Executable Pages: Return-to-libc


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    gets(name);
}

int main(void) {
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    return 0;
}
```

```
system:
    ...

vulnerable:
    ...
    call gets
    addl $4, %esp
    movl %ebp, %esp
    popl %ebp
    ret

main:
    ...
    call vulnerable
    ...
```

EIP → popl %ebp

ESP → EBP

...	...	...	...
...	...	...	...
'\0'	...	...	...
'r'	'f'	' '	'/'
'r'	'm'	' '	'-'
[address of "rm -rf /"]			
'B'	'B'	'B'	'B'
[address of system]			
'A'	'A'	'A'	'A'
'A'	'A'	'A'	'A'
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EIP

ESP

EBP

...	...	...	...
...	...	...	...
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'A'	'A'	'A'	'A'
'A'	'A'	'A'	'A'
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Subverting Non-Executable Pages: Return-to-libc

We jumped into the **`system`** function, and it expects the first argument to be 4 bytes above the ESP: **`"rm -rf /"`**!

```
int system(char *command);

void vulnerable(void) {
    char name[20];
    gets(name);
}

int main(void) {
    vulnerable();
    return 0;
}
```

```
system:
    ...

vulnerable:
    ...
    call gets
    addl $4, %esp
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EIP →

EBP →

ESP →

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[address of "rm -rf /"]			
'B'	'B'	'B'	'B'
[address of system]			
'A'	'A'	'A'	'A'
'A'	'A'	'A'	'A'
'A'	'A'	'A'	'A'
'A'	'A'	'A'	'A'
'A'	'A'	'A'	'A'
'A'	'A'	'A'	'A'
&name (arg to gets)			

Subverting Non-Executable Pages: ROP

- Instead of executing an existing function, execute your own code by executing different pieces of different code!
  - We don’t need to jump to the beginning of a function: We can jump into the middle of it to just take the code chunks that we need
- **Gadget**: A small set of assembly instructions that already exist in memory
  - Gadgets usually end in a `ret` instruction
  - Gadgets are usually **not** full functions
- ROP strategy: We write a chain of return addresses starting at the RIP to achieve the behavior we want
  - Each return address points to a gadget
  - The gadget executes its instructions and ends with a `ret` instruction
  - The `ret` instruction jumps to the address of the next gadget on the stack

Subverting Non-Executable Pages: ROP

Example: Let's say our shellcode involves the following sequence:

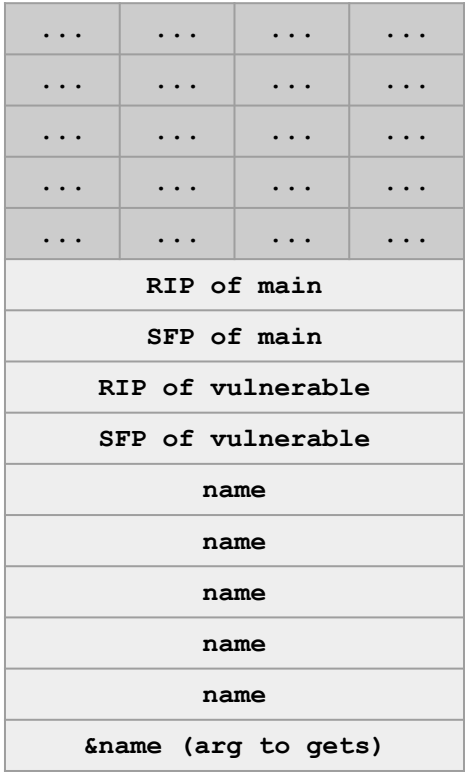
```
movl $1, %eax
xorl %eax, %ebx
```

The following is present in memory:

```
foo:
          ...
<foo+7>   addl $4, %esp
<foo+10>  xorl %eax, %ebx
<foo+12>  ret

bar:
          ...
<bar+22>  andl $1, %edx
<bar+25>  movl $1, %eax
<bar+30>  ret
```

How can we chain returns to run the code sequence we want?



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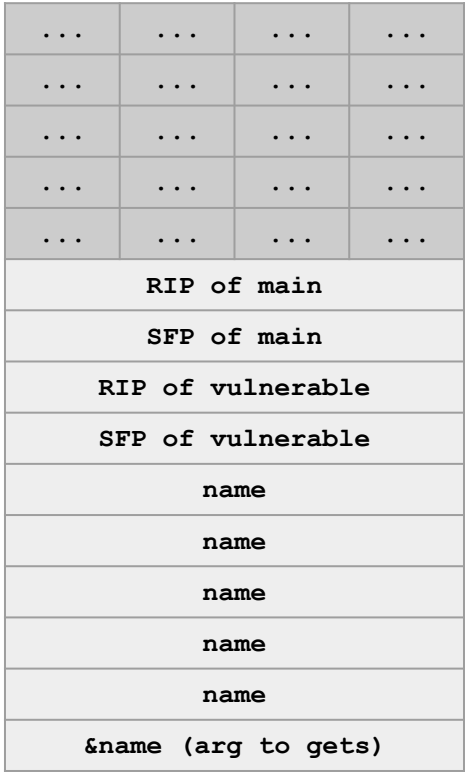
```

If we jump 25 bytes after the start of **bar** then 10 bytes after the start of **foo**, we get the result we want!

How can we chain returns to run the code sequence we want?



Subverting Non-Executable Pages: ROP

Exploit:

```
'A' * 24
    + [address of <bar+25>]
    + [address of <foo+10>]
    + ... (more chains)
```

```
void vulnerable(void) {
    char name[20];
    gets(name);
}

int main(void) {
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EIP →

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vulnerable:
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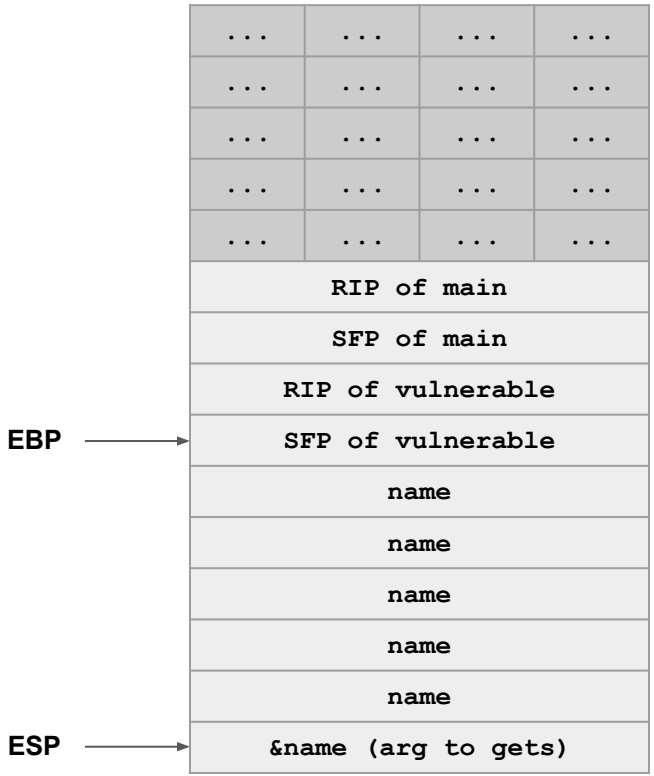

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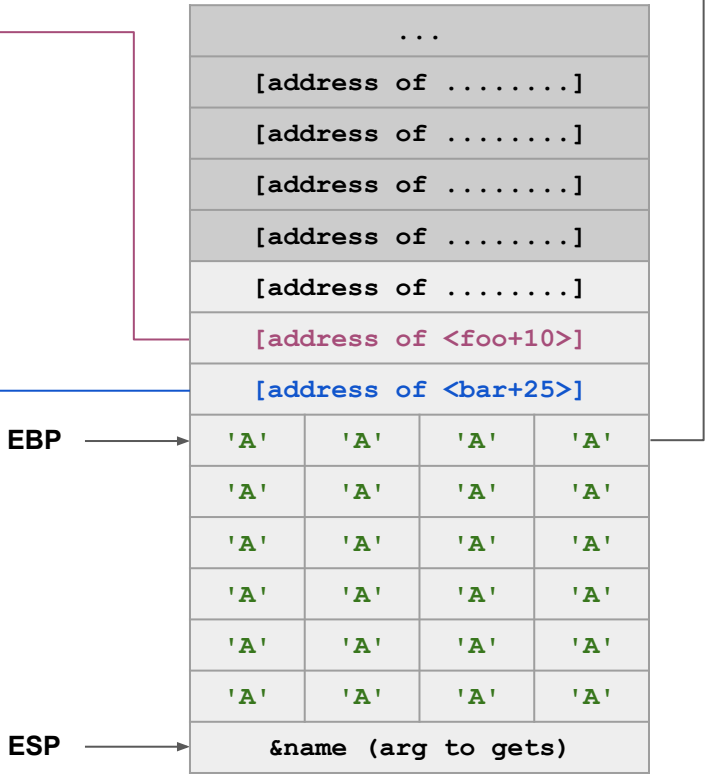
EIP →



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    ret

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```

EIP →

...
[address of ....]
[address of ....]
[address of ....]
[address of ....]
[address of ....]
[address of <foo+10>]
[address of <bar+25>]
'A' 'A' 'A' 'A' ← EBP
'A' 'A' 'A' 'A'
'A' 'A' 'A' 'A'
'A' 'A' 'A' 'A'
'A' 'A' 'A' 'A'
'A' 'A' 'A' 'A' ← ESP
&name (arg to gets)

Subverting Non-Executable Pages: ROP


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EIP →

EBP →

ESP →

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'A' 'A' 'A' 'A'
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    call gets
    addl $4, %esp
    movl %ebp, %esp
    popl %ebp
    ret

main:
    ...
    call vulnerable
    ...
```

EIP →

EBP →

ESP →

...
[address of ....]
[address of ....]
[address of ....]
[address of ....]
[address of ....]
[address of <foo+10>]
[address of <bar+25>]
'A' 'A' 'A' 'A'
'A' 'A' 'A' 'A'
'A' 'A' 'A' 'A'
'A' 'A' 'A' 'A'
'A' 'A' 'A' 'A'
'A' 'A' 'A' 'A'
&name (arg to gets)

Subverting Non-Executable Pages: ROP


```
void vulnerable(void) {
    char name[20];
    gets(name);
}

int main(void) {
    vulnerable();
    return 0;
}
```

```
foo:
    addl $4, %esp
    xorl %eax, %ebx
    ret

bar:
    ...
    andl $1, %edx
    movl $1, %eax
    ret

vulnerable:
    ...
    call gets
    addl $4, %esp
    movl %ebp, %esp
    popl %ebp
    ret

main:
    ...
    call vulnerable
    ...
```

EIP →

EBP →

ESP →

...
[address of ....]
[address of ....]
[address of ....]
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Subverting Non-Executable Pages: ROP


```
void vulnerable(void) {
    char name[20];
    gets(name);
}

int main(void) {
    vulnerable();
    return 0;
}
```

```
foo:
    addl $4, %esp
    xorl %eax, %ebx
    ret

bar:
    ...
    andl $1, %edx
    movl $1, %eax
    ret

vulnerable:
    ...
    call gets
    addl $4, %esp
    movl %ebp, %esp
    popl %ebp
    ret

main:
    ...
    call vulnerable
    ...
```

EIP

EBP

ESP

...			
[address of ....]			
[address of ....]			
[address of ....]			
[address of ....]			
[address of ....]			
[address of <foo+10>]			
[address of <bar+25>]			
'A'	'A'	'A'	'A'
'A'	'A'	'A'	'A'
'A'	'A'	'A'	'A'
'A'	'A'	'A'	'A'
'A'	'A'	'A'	'A'
'A'	'A'	'A'	'A'
&name (arg to gets)			

Subverting Non-Executable Pages: ROP

The **ret** instruction always pops off the bottom of the stack, so execution continues based on the chain of addresses!

```
void vulnerable(void) {
    char name[20];
    gets(name);
}

int main(void) {
    vulnerable();
    return 0;
}
```

```
foo:
    addl $4, %esp
    xorl %eax, %ebx
    ret

bar:
    ...
    andl $1, %edx
    movl $1, %eax
    ret

vulnerable:
    ...
    call gets
    addl $4, %esp
    movl %ebp, %esp
    popl %ebp
    ret

main:
    ...
    call vulnerable
    ...
```

EIP →

EBP →

ESP →

...
[address of ....]
[address of ....]
[address of ....]
[address of ....]
[address of ....]
[address of <foo+10>]
[address of <bar+25>]
'A' 'A' 'A' 'A'
'A' 'A' 'A' 'A'
'A' 'A' 'A' 'A'
'A' 'A' 'A' 'A'
'A' 'A' 'A' 'A'
'A' 'A' 'A' 'A'
&name (arg to gets)

Subverting Non-Executable Pages: ROP

- If the code base is big enough (imports enough libraries), there are usually enough gadgets in memory for you to run any shellcode you want
- **ROP compilers** can automatically generate a ROP chain for you based on a target binary and desired malicious code!
- Non-executable pages is not a huge issue for attackers nowadays
  - Having writable and executable pages makes an attacker's life easier, but not *that* much easier

Mitigation: Stack Canaries

Textbook Chapter 4.8 & 4.9

Recall: Putting Together an Attack

1. Find a memory safety (e.g. buffer overflow) vulnerability
2. Write malicious shellcode at a known memory address
3. Overwrite the RIP with the address of the shellcode
    - Mitigation: Stack canaries
4. Return from the function
5. Begin executing malicious shellcode
    - Mitigation: Non-executable pages

We can defend against memory safety vulnerabilities by making each of these steps more difficult (or impossible)!

Analogy: Canary in a Coal Mine

- Miners protect themselves against toxic gas buildup in the mine with a canary
  - Canary: A small, noisy bird that is sensitive to toxic gas
  - If toxic gas builds up, the canary dies first
  - The miners notice that the canary has died and leave the mine
- The canary in the coal mine is a sacrificial animal
  - The miners don’t expect the canary to survive
  - However, the canary's death is a warning sign that saves the lives of the miners
- **Takeaway**: Let’s put a sacrificial value (a *canary*) on the stack
  - The value is not meaningful (we don’t care if it’s preserved)
  - The code never uses or changes this value
  - If the value changes, that's a warning sign that somebody is messing with our code!

Stack Canaries

- Idea: Add a sacrificial value on the stack, and check if it has been changed
  - When the program runs, generate a **random** secret value and save it in the canary storage
  - In the function prologue, place the canary value on the stack right below the SFP/RIP
  - In the function epilogue, check the value on the stack and compare it against the value in canary storage
- The canary value is never actually used by the function, so if it changes, somebody is probably attacking our system!

Stack Canaries: Properties

- A canary value is unique every time the program **runs** but the same for all functions **within a run**
- A canary value uses a NULL byte as the first byte to mitigate string-based attacks (since it terminates any string before it)
  - Example: A format string vulnerability with `%s` might try to print everything on the stack
    - The null byte in the canary will mitigate the damage by stopping the print earlier.

Stack Canaries


```
void vulnerable(void) {
    char name[20];
    gets(name);
}
```

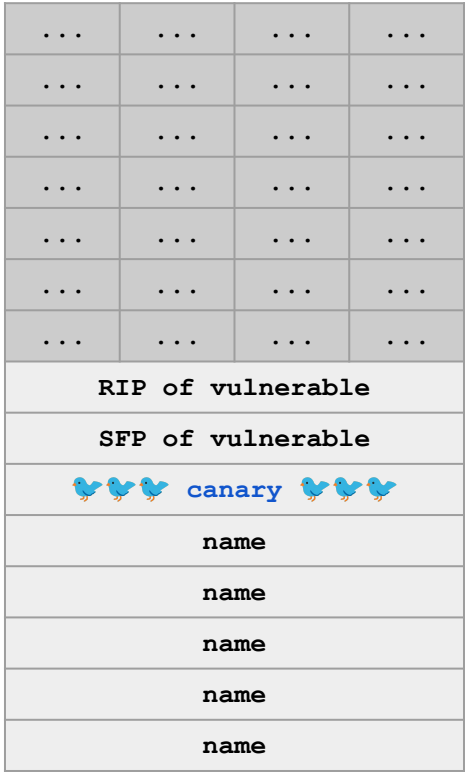
Because the write starts at name, the attacker has to overwrite the canary before the RIP or SFP!

Note: 20 bytes for **name** + 4 bytes for canary (32-bit architecture)

```
vulnerable:
    pushl %ebp
    movl %esp, %ebp
    subl $24, %esp
    movl ($CANARY_ADDR), %eax # Load canary
    movl %eax, -4(%ebp)       # Save on stack

    ...

    movl -4(%ebp), %eax       # Load stack value
    cmpl %eax, ($CANARY_ADDR) # Compare to canary and...
    jne canary_failed         # ... crash if not equal
    movl %ebp, %esp
    popl %ebp
    ret
```



Stack Canaries: Efficiency

- Compiler inserts a few extra instructions, so there is more overhead
- In almost all applications, the performance impact is insignificant
  - Very cheap way to stop lots of common attacks!

Subverting Stack Canaries

- **Leak** the value of the canary: Overwrite the canary with itself
- **Bypass** the value of the canary: Use a random write, not a sequential write
- **Guess** the value of the canary: Brute-force

Subverting Stack Canaries: Leaking the Canary

- Any vulnerability that leaks stack memory could be used to leak the canary's value
  - Example: Format string vulnerabilities let you print out values on the stack
- Once you learn the value of the stack canary, place it in the exploit such that the canary is overwritten with itself, so the value is unchanged!

Subverting Stack Canaries: Bypassing the Canary

- Stack canaries stop attacks that write to *increasing*, *consecutive* addresses *on the stack*
  - On the stack diagram: Writing upwards, with no gaps
  - Many common functions only write this way, e.g. **`gets`**, **`fgets`**, **`fread`**, etc.
- Stack canaries do not stop attacks that write to memory in other ways
  - An attacker can write *around* the canary
  - Example: Format string vulnerabilities let an attacker write to any location in memory
  - Example: Heap overflows never overwrite a stack canary (they write to the heap)
  - Example: C++ vtable exploits overwrite the vtable pointer without overwriting the canary

Subverting Stack Canaries: Guessing the Canary

- On 32-bit systems: 24 bits to guess
  - Remember that the first byte (8 bits) is always a NULL byte: 32 - 8 = 24
- On 64-bit systems: 56 bits to guess
  - 64 - 8 = 56
- Stack canaries are less effective on 32-bit systems since there are only 2^{24} possibilities (~16 million), which can feasibly be brute-forced

Subverting Stack Canaries: Guessing the Canary

- How feasible is guessing the canary?
  - It depends on your threat model
- How are you running the program?
  - If the program is running on your own computer, you can keep trying with nobody to stop you
  - If the program is running on a remote server, the server might see you sending the exploit over and over and reject your requests
- Does the program have a timeout?
  - Timeout: A mandatory waiting period after a failed request
  - No timeout: 10,000 tries per second = 2^{24} tries in around 30 minutes
  - 0.1 second timeout: 10 tries per second = 2^{24} tries in around 3 weeks
- More complicated timeouts are possible
  - 10 consecutive failures causes a 10-minute timeout: 1 try per minute = 2^{24} tries in ~32 years!
  - Exponentially growing timeout (the timeout doubles for each failure): 2^{24} tries is not happening

Mitigation: Pointer Authentication

Textbook Chapter 4.10

Recall: Putting Together an Attack

1. Find a memory safety (e.g. buffer overflow) vulnerability
2. Write malicious shellcode at a known memory address
3. Overwrite the RIP with the address of the shellcode
    - Mitigation: Stack canaries
    - Mitigation: Pointer authentication
4. Return from the function
5. Begin executing malicious shellcode
    - Mitigation: Non-executable pages

We can defend against memory safety vulnerabilities by making each of these steps more difficult (or impossible)!

Reminder: 32-Bit and 64-Bit Processors

- 32-bit processor: integers and pointers are 32 bits long
  - Can address 2^{32} bytes ≈ 4 GB of memory
- 64-bit processor: integers and pointers are 64 bits long
  - Can address 2^{64} bytes ≈ 18 exabytes ≈ 18 billion GB of memory
  - No modern computer can support this much memory
  - Even the best most modern computers only need 2^{42} bytes ≈ 4 terabytes ≈ 4000 GB of memory
  - At most 42 bits are needed to address all of memory
  - 22 bits are left unused (the top 22 bits in the address are always 0)

Pointer Authentication

- Recall stack canaries: A secret value stored in memory
  - If the secret value changes, detect an attack
  - One canary per function on the stack
- Idea: Instead of placing the secret value below the pointer, store a value in the pointer itself!
  - Use the unused bits in a 64-bit address to store a secret value
  - When storing a pointer in memory, replace the unused bits with a **pointer authentication code (PAC)**
  - Before using the pointer in memory, check if the PAC is still valid
    - If the PAC is invalid, crash the program
    - If the PAC is valid, restore the unused bits and use the address normally
  - Includes the RIP, SFP, any other pointers on the stack, and any other pointers outside of the stack (e.g. on the heap)

Pointer Authentication: Properties of the PAC

- Each possible address has its own PAC
  - Example: The PAC for the address `0x000000007ffffec0` is different from the PAC for `0x000000007ffffec4`
  - If an attacker changes the address without changing the PAC, the PAC will no longer be valid
- Only someone who knows the CPU's master secret can generate a PAC for an address
  - An attacker cannot generate a PAC for their malicious pointer without the master secret
  - An attacker cannot generate a PAC using a PAC for a different address
  - Later: We'll discuss how this algorithm works (MACs in the cryptography unit)
- The CPU's master secret is not accessible to the program
  - Leaking program memory will not leak the master secret
    - Contrast with canaries, which can be leaked

Subverting Pointer Authentication

- Find a vulnerability to trick the program to generating a PAC for any address
- Learn the master secret
  - The operating system has to set up the secrets: What if there is a vulnerability in the OS?
  - Workaround: Embed the master secret in the CPU, which can only be used to generate PACs, never read directly
- Guess a PAC: Brute-force
  - Most 64-bit systems use 32-52 bits (plus one extra configuration bit) for addressing, which leaves 11-31 bits for the PAC
  - Number of possible PACs is in the millions or billions, so possibly feasible depending on your threat model
- Pointer reuse
  - If the CPU already generated another PAC for another pointer, we can copy that pointer and use it elsewhere

Defenses Against Pointer Reuse

- In practice, there are usually multiple master secrets for different types of pointers
  - ARM uses 5 master secrets: 2 instruction pointer secrets (IA and IB), 2 data pointer secrets (DA and DB), and 1 general-purpose secret (GA)
  - Instruction pointer secrets are used for pointers to machine instructions (e.g. RIP)
  - Data pointer secrets are used for pointers to data (e.g. local variables)
  - Data pointers can’t be reused as instruction pointers, and vice-versa
- The CPU can generate a unique PAC for each pointer and “context”
  - Context: usually the address where the pointer is located
  - The same pointer will have a different PAC depending on where in memory it's located
  - If an attacker copies a pointer and PAC to a different location, the PAC is no longer valid!

Pointer Authentication on ARM

- Pointer authentication is supported by:
  - ARM 8.3 (a new architecture, like x86 or RISC-V)
  - The latest Apple chips (starting with the A12 and including the new M1), which use ARM
  - macOS on ARM (operating system)
- Probably the biggest benefit for Apple going to ARM
  - Can take advantage of the more efficient instructions instead of backwards-compatible ones
  - Usable in both standard user programs and kernel programs (privileged code run by the OS)
- x86 has not developed a similar defense

Mitigation: Address Space Layout Randomization (ASLR)

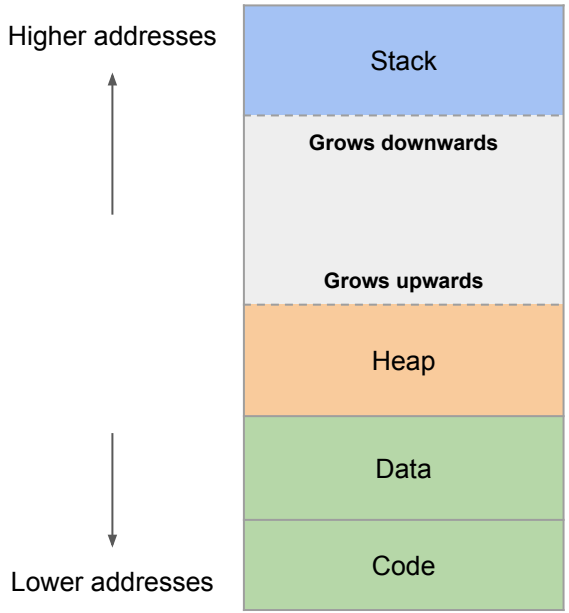
Textbook Chapter 4.11 & 4.12

Recall: Putting Together an Attack

1. Find a memory safety (e.g. buffer overflow) vulnerability
2. Write malicious shellcode at a known memory address
    - Mitigation: Address-space layout randomization
3. Overwrite the RIP with the address of the shellcode
    - Mitigation: Stack canaries
    - Mitigation: Pointer authentication
4. Return from the function
5. Begin executing malicious shellcode
    - Mitigation: Non-executable pages

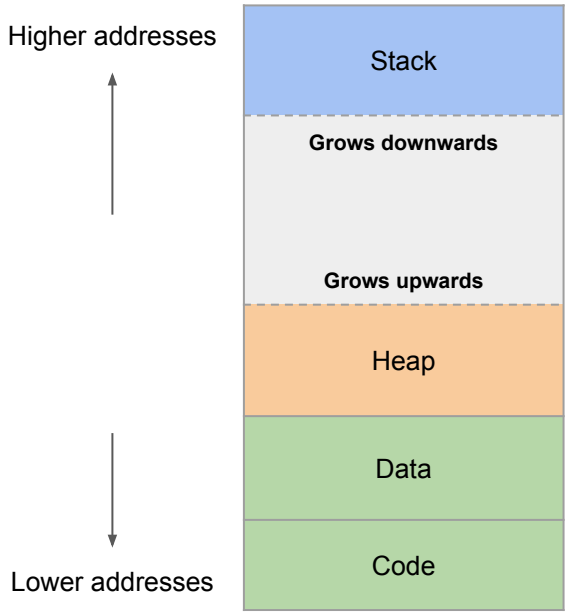
We can defend against memory safety vulnerabilities by making each of these steps more difficult (or impossible)!

Recall: x86 Memory Layout

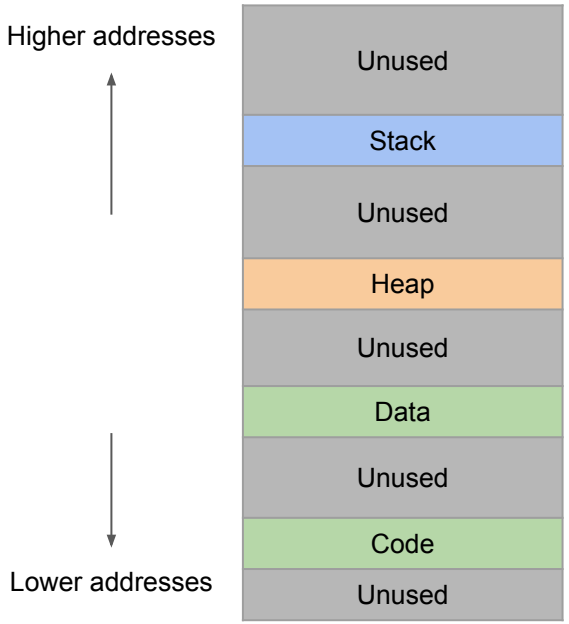


In theory, x86 memory layout looks like this...

Recall: x86 Memory Layout

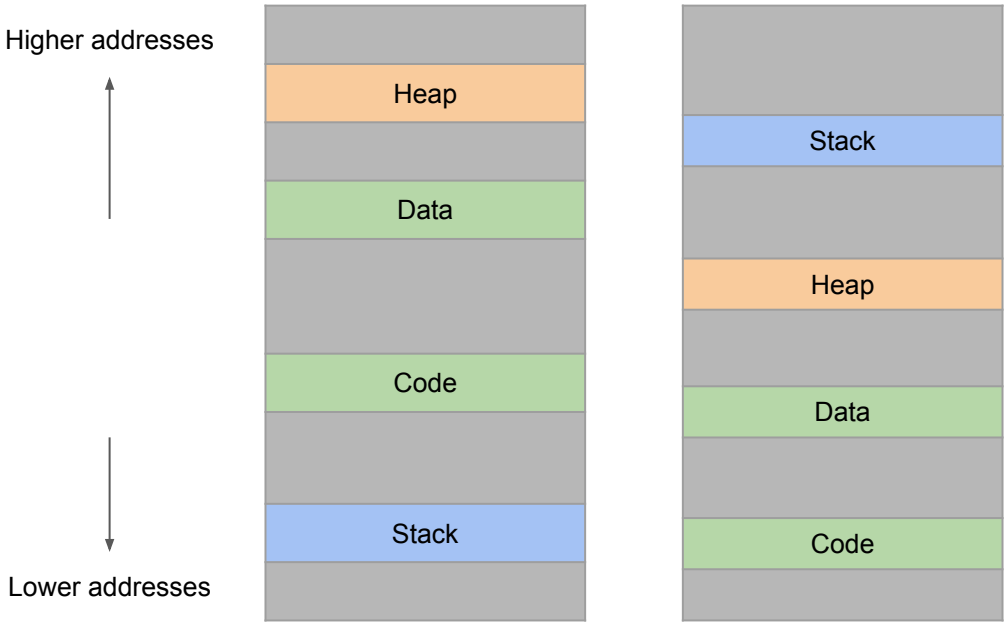


In theory, x86 memory layout looks like this...



...but in practice, it usually looks like this (mostly empty)!

Recall: x86 Memory Layout



Idea: Put each segment of memory in a different location each time the program is run

Address Space Layout Randomization

- **Address space layout randomization (ASLR)**: Put each segment of memory in a different location each time the program is run
  - The attacker can't know where their shellcode will be because its address changes every time you run the program
- ASLR can shuffle all four segments of memory
  - Randomize the stack: Can't place shellcode on the stack without knowing the address of the stack
  - Randomize the heap: Can't place shellcode on the heap without knowing the address of the heap
  - Randomize the code: Can't construct a ROP chain or return-to-libc attack without knowing the address of code
  - Within each segment of memory, relative addresses are the same (e.g. the RIP is always 4 bytes above the SFP)

ASLR: Efficiency

- Recall from 61C
  - Programs are dynamically linked at runtime
  - We already have to do the work of going through the executable and rewriting code to contain known addresses before executing it
- ASLR has effectively no overhead, since we have to do relocation anyway!

Subverting ASLR

- Leak the address of a pointer, whose address relative to your shellcode is known
  - Relative addresses are usually fixed, so this is sufficient to undo randomization!
  - Leak a stack pointer: Leak the location of the stack
  - Leak an RIP: Leak the location of the caller
- Guess the address of your shellcode: Brute-force
  - Randomization usually happens on page boundaries (usually 12 bits for 4 KiB pages)
  - 32-bit: 32 - 12 = 20 bits, 2^{20} possible pages, which is feasibly brute-forced
  - 64-bit (usually 48-bit addressing): 48 - 12 = 36 bits, 2^{36} possible pages

Relative Addresses


```
void vulnerable(char *dest) {
    // Format string vulnerability
    printf(dest);
}

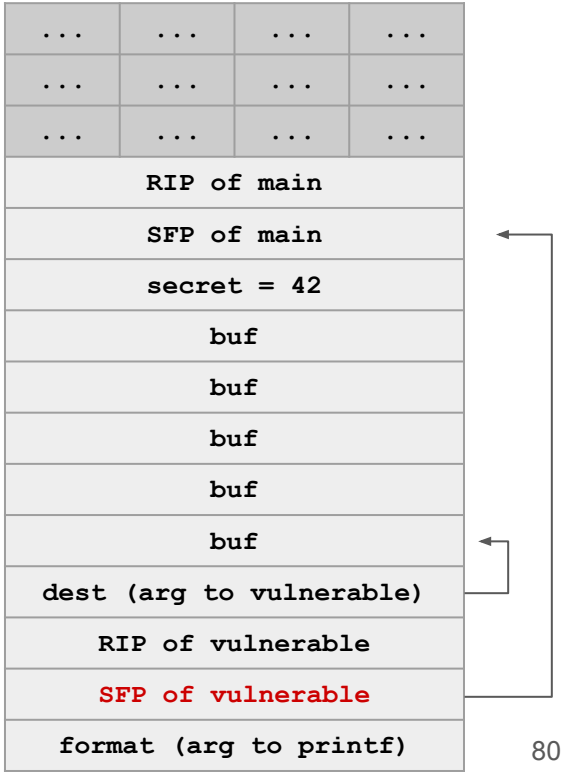
int main(void) {
    int secret = 42;
    char buf[20];
    fgets(buf, 20, stdin);
    vulnerable(buf);
}
```

We know that the SFP is a pointer to the stack. How would you print the value of the SFP?

Input:
`'%x'`

If the output is **bfff0408** what is the address of **secret**?

secret is 4 bytes below where the SFP points, so its address is **0xbfff0404**!



Combining Mitigations

Textbook Chapter 4.13

Combining Mitigations

- Recall: We can use multiple mitigations together
  - Synergistic protection: one mitigation helps strengthen another mitigation
  - Force the attacker to find multiple vulnerabilities to exploit the program
  - Defense in depth
- Example: Combining ASLR and non-executable pages
  - An attacker can't write their own shellcode, because of non-executable pages
  - An attacker can't use existing code in memory, because they don't know the addresses of those code (ASLR)
- To defeat ASLR *and* non-executable pages, the attacker needs to find two vulnerabilities
  - First, find a way to leak memory and reveal the address randomization (defeat ASLR)
  - Second, find a way to write to memory and write a ROP chain (defeat non-executable pages)

Combining Mitigations

- Memory safety defenses used by Apple iOS
  - ASLR is used for user programs (apps) and kernel programs (operating system programs)
  - Non-executable pages are used whenever possible
  - Applications are sandboxed to limit the damage of an exploit (TCB is the operating system)
- Trident exploit
  - Developed by the NSO group, a spyware vendor, to exploit iPhones
  - Exploit Safari with a memory corruption vulnerability → execute arbitrary code in the sandbox
  - Exploit another vulnerability to read the kernel stack (operating system memory in the sandbox)
  - Exploit another vulnerability in the kernel (operating system) to execute arbitrary code
- **Takeaway**: Combining mitigations forces the attacker to find multiple vulnerabilities to take over your program. The attacker's job is harder, but not impossible!

Enabling Mitigations

- Many mitigations (stack canaries, non-executable pages, ASLR) are effectively free today (insignificant performance impact)
- The programmer sometimes has to manually enable mitigations
  - Example: Enable ASLR and non-executable pages when running a program
  - Example: Setting a flag to compile a program with stack canaries
- If the default is disabling the mitigation, the default will be chosen
  - Recall: Consider human factors!
  - Recall: Use fail-safe defaults!

Enabling Mitigations: CISCO

- Cisco's Adaptive Security Appliance (ASA)
  - Cisco: A major vendor of technology products (one of 30 giant companies in the Dow Jones stock index)
  - ASA: A network security device that can be installed to protect an entire network (e.g. AirBears2)
- Mitigations used by the ASA
  - No stack canaries
  - No non-executable pages
  - No ASLR
  - Easy for the NSA (or other attackers) to exploit!
- **Takeaway**: Even major companies can forget to enable mitigations. Always enable memory safety mitigations!

Enabling Mitigations: Internet of Things

Qualys Security Blog

Link

CVE-2021-3156: Heap-Based Buffer Overflow in Sudo (Baron Samedit)

Animesh Jain *January 26, 2021*

The Qualys Research Team has discovered a heap overflow vulnerability in sudo, a near-ubiquitous utility available on major Unix-like operating systems. Any unprivileged user can gain root privileges on a vulnerable host using a default sudo configuration by exploiting this vulnerability.

Takeaway: Many (most?) IoT devices don't enable basic mitigations

Summary: Memory Safety Mitigations

- Memory-safe languages
  - Using a memory-safe language (e.g. Python, Java) stops all memory safety vulnerabilities.
  - Why use a non-memory-safe language?
    - Commonly-cited reason, but mostly a myth: Performance
    - Real reason: Legacy, existing code
- Writing memory-safe code
  - Carefully write and reason about your code to ensure memory safety in a non-memory-safe language
  - Requires programmer discipline, and can be tedious sometimes
- Building secure software
  - Use tools for analyzing and patching insecure code
  - Test your code for memory safety vulnerabilities
  - Keep any external libraries updated for security patches

Summary: Memory Safety Mitigations

- Mitigation: **Non-executable pages**
  - Make portions of memory either executable or writable, but not both
  - Defeats attacker writing shellcode to memory and executing it
  - Subversions
    - **Return-to-libc**: Execute an existing function in the C library
    - **Return-oriented programming** (**ROP**): Create your own code by chaining together small gadgets in existing library code
- Mitigation: **Stack canaries**
  - Add a sacrificial value on the stack. If the canary has been changed, someone's probably attacking our system
  - Defeats attacker overwriting the RIP with address of shellcode
  - Subversions
    - An attacker can write around the canary
    - The canary can be leaked by another vulnerability (e.g. format string vulnerability)
    - The canary can be brute-forced by the attacker

Summary: Memory Safety Mitigations

- Mitigation: **Pointer authentication**
  - When storing a pointer in memory, replace the unused bits with a pointer authentication code (PAC). Before using the pointer in memory, check if the PAC is still valid
  - Defeats attacker overwriting the RIP (or any pointer) with address of shellcode
- Mitigation: **Address space layout randomization** (**ASLR**)
  - Put each segment of memory in a different location each time the program is run
  - Defeats attacker knowing the address of shellcode
  - Subversions
    - Leak addresses with another vulnerability
    - Brute-force attack to guess the addresses
- Combining mitigations
  - Using multiple mitigations usually forces the attacker to find multiple vulnerabilities to exploit the program (defense-in-depth)