Memory Safety Mitigations

CMPSC 403 Fall 2021

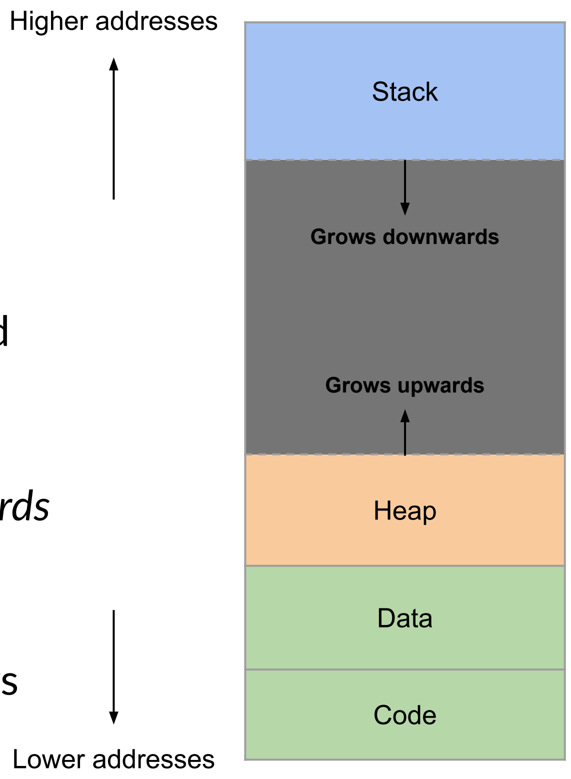
September 28 - 30, 2021

Review: x86 Function Call, Buffer Overflows

- Calling convention
  - At the start of the function, the callee saves the register values on the stack
  - During the function, the callee can now change those registers
  - At the end of the function, the callee will put the saved values on the stack back into the registers
- Important saved registers on the stack
  - When the callee saves the value of EBP on the stack, we call it the **SFP** (**saved frame pointer**)
  - When the callee saves the value of EIP on the stack, we call it the **RIP** (**return instruction pointer**)
- Buffer overflows: An attacker overwrites unintended parts of memory
- Stack smashing: An attacker overwrites saved registers on the stack
  - Overwriting the RIP lets the attacker redirect program execution to shellcode

Reminder:x86 Memory Layout

- Code
  - The program code itself (also called “text”)
- Data
  - Static variables, allocated when the program is started
- Heap
  - Dynamically allocated memory using **malloc** and **free**
  - As more and more memory is allocated, it grows *upwards*
- Stack
  - Local variables and stack frames
  - As you make deeper and deeper function calls, it grows *downwards*



Memory-Safe Code

Still Vulnerable Code?

```
void vulnerable?(void) {
    char *name = malloc(20);
    ...
    gets(name);
    ...
}
```

Heap overflows are also vulnerable!

Solution: Specify the Size

```
void safe(void) {
    char name[20];
    ...
    fgets(name, 20, stdin);
    ...
}
```

The length parameter specifies the size of the buffer and won't write any more bytes—no more buffer overflows!

Warning: Different functions take slightly different parameters

Solution: Specify the Size

```
void safer(void) {
    char name[20];
    ...
    fgets(name, sizeof(name), stdin);
    ...
}
```

`sizeof` returns the size of the variable (does *not* work for pointers)

Vulnerable C Library Functions

- **`gets`** - Read a string from stdin
  - Use **`fgets`** instead
- **`strcpy`** - Copy a string
  - Use **`strncpy`** (more compatible, less safe) or **`strlcpy`** (less compatible, more safe) instead
- **`strlen`** - Get the length of a string
  - Use **`strnlen`** instead (or **`memchr`** if you really need compatible code)
- … and more (look up C functions before you use them!)

Integer Memory Safety Vulnerabilities

Signed/Unsigned Vulnerabilities

Is this safe?

```
void func(int len, char *data) {
    char buf[64];
    if (len > 64)
        return;
    memcpy(buf, data, len);
}
```

`int` is a **signed** type, but **`size_t`** is an **unsigned** type. What happens if **`len == -1`**?

This is a **signed** comparison, so **`len > 64`** will be false, but casting **-1** to an unsigned type yields **`0xffffffff`**: another buffer overflow!

```
void *memcpy(void *dest, const void *src, size_t n);
```

Signed/Unsigned Vulnerabilities

Now this is an **unsigned** comparison, and no casting is necessary!

```
void safe(size_t len, char *data) {
    char buf[64];
    if (len > 64)
        return;
    memcpy(buf, data, len);
}
```

Integer Overflow Vulnerabilities

Is this safe?

What happens if **`len == 0xffffffff`**?

```
void func(size_t len, char *data) {
    char *buf = malloc(len + 2);
    if (!buf)
        return;
    memcpy(buf, data, len);
    buf[len] = '\n';
    buf[len + 1] = '\0';
}
```

`len + 2 == 1`, enabling a heap overflow!

Integer Overflow Vulnerabilities

```
void safe(size_t len, char *data) {
    if (len > SIZE_MAX - 2)
        return;
    char *buf = malloc(len + 2);
    if (!buf)
        return;
    memcpy(buf, data, len);
    buf[len] = '\n';
    buf[len + 1] = '\0';
}
```

It's clunky, but you need to check bounds whenever you add to integers!

Think Along: Integer Overflows in the Wild

WJXT Jacksonville [Link]

Broward Vote-Counting Blunder Changes Amendment Result *November 4, 2004*

The Broward County Elections Department has egg on its face today after a computer glitch misreported a key amendment race, according to WPLG-TV in Miami.

Amendment 4, which would allow Miami-Dade and Broward counties to hold a future election to decide if slot machines should be allowed at racetracks, was thought to be tied. But now that a computer glitch for machines counting absentee ballots has been exposed, it turns out the amendment passed.

"The software is not geared to count more than 32,000 votes in a precinct. So what happens when it gets to 32,000 is the software starts counting backward," said Broward County Mayor Ilene Lieberman.

That means that Amendment 4 passed in Broward County by more than 240,000 votes rather than the 166,000-vote margin reported Wednesday night. That increase changes the overall statewide results in what had been a neck-and-neck race, one for which recounts had been going on today. But with news of Broward's error, it's clear amendment 4 passed.

Think Along: Integer Overflows in the Wild

<u>How could this have been prevented?</u>

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Format String Vulnerabilities

`printf` behavior

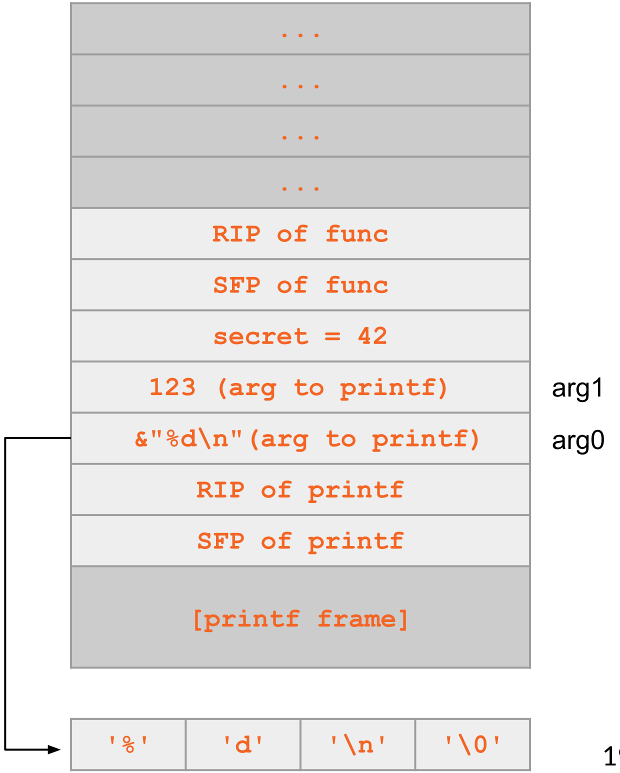
- `printf` takes in a variable number of arguments
  - How does it know how many arguments that it received?
  - It infers it from the first argument: the format string!
  - Example: `printf("One %s costs %d", fruit, price)`
  - What happens if the arguments are mismatched?

`printf` behavior

```
void func(void) {
    int secret = 42;
    printf("%d\n", 123);
}
```

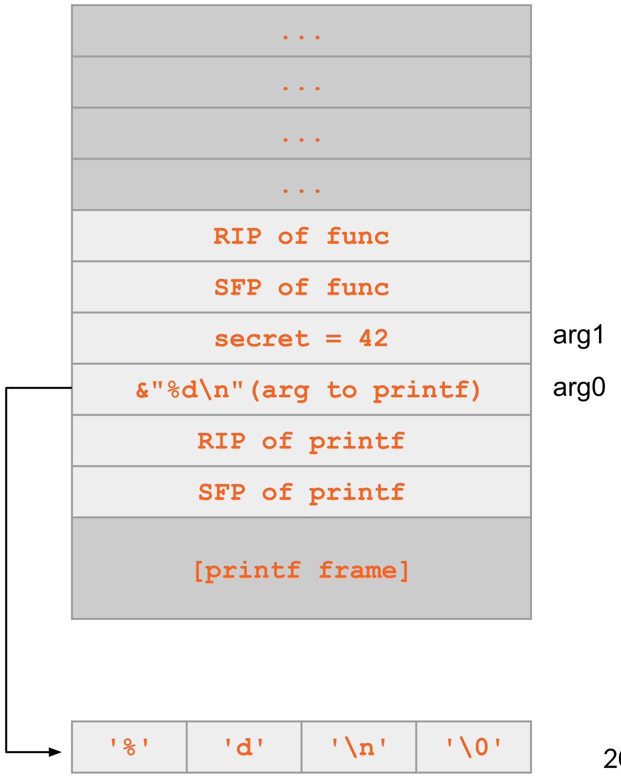
`printf` *assumes* that there is 1 more argument because there is one format sequence and will look 4 bytes up the stack for the argument

What if there is no argument?



`printf` behavior

```
void func(void) {
    int secret = 42;
    printf("%d\n");
}
```



Because the format string contains the `%d`, it will still look 4 bytes up and print the value of `secret`!

Format String Vulnerabilities

What is the issue here?

```
char buf[64];

void vulnerable(void) {
    if (fgets(buf, 64, stdin) == NULL)
        return;
    printf(buf);
}
```

Format String Vulnerabilities

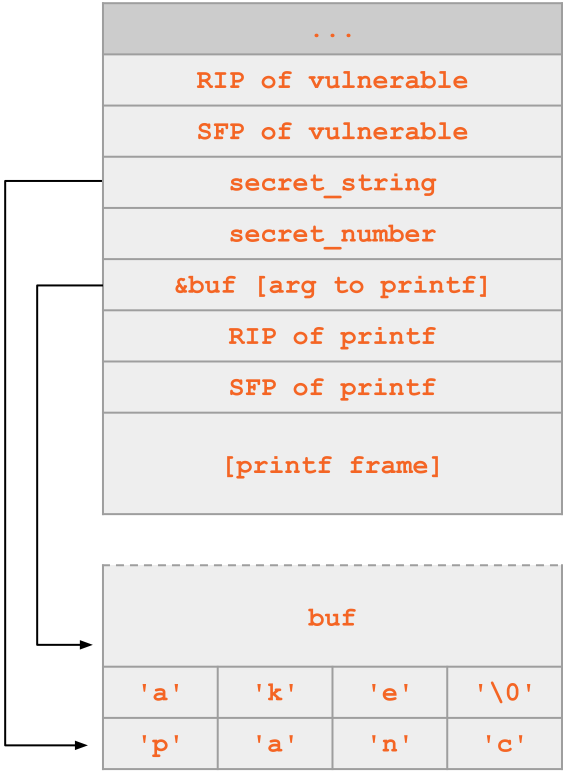
- Now, the attacker can specify any format string they want:
  - `printf("100% done!")`
    - Prints 4 bytes on the stack, 8 bytes above the RIP of `printf`
  - `printf("100% stopped.")`
    - Print the bytes **pointed to** by the address located 8 bytes above the RIP of `printf`, until the first NULL byte
  - `printf("%x %x %x %x ...")`
    - Print a series of values on the stack in hex

```
char buf[64];

void vulnerable(void) {
    if (fgets(buf, 64, stdin) == NULL)
        return;
    printf(buf);
}
```

Format String Vulnerability Walkthrough

```
char buf[64];

void vulnerable(void) {
    char *secret_string = "pancake";
    int secret_number = 42;
    if (fgets(buf, 64, stdin) == NULL)
        return;
    printf(buf);
}
```

Note that strings are passed by reference in C, so the argument to **`printf`** is actually a pointer to **`buf`**, which is in static memory.

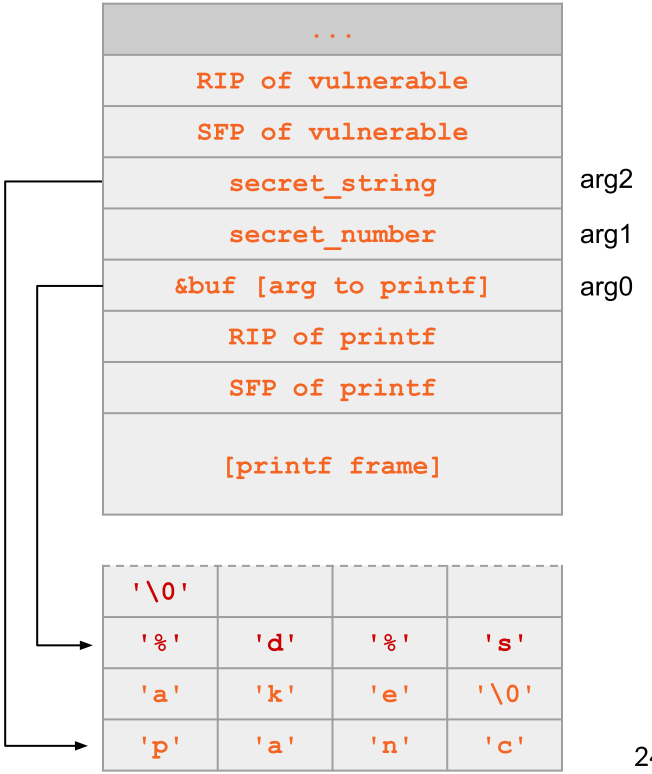


Format String Vulnerability Walkthrough

Input: **%d%s**

Output:

```
char buf[64];

void vulnerable(void) {
    char *secret_string = "pancake";
    int secret_number = 42;
    if (fgets(buf, 64, stdin) == NULL)
        return;
    printf(buf);
}
```



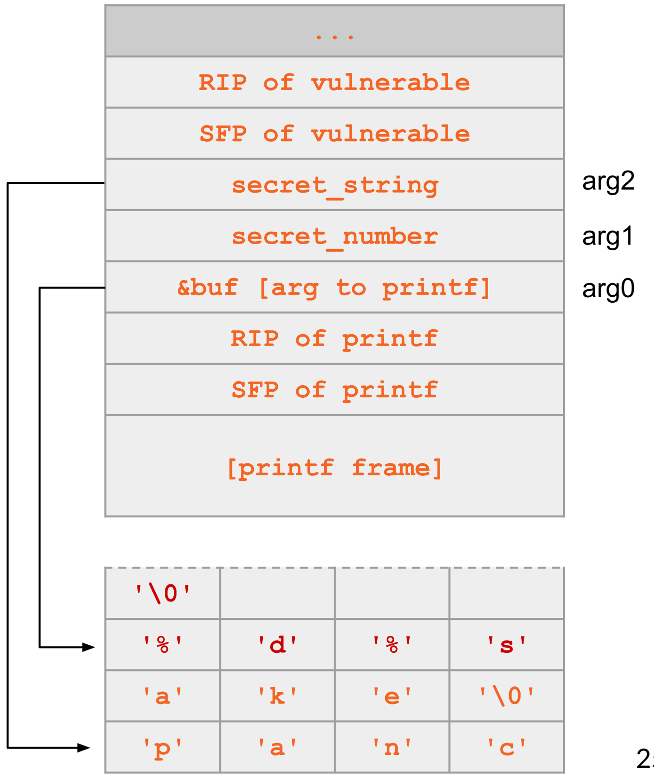
We're calling **printf("%d%s")**. **printf** reads its first argument (arg0), sees two format specifiers, and expects two more arguments (arg1 and arg2).

Format String Vulnerability Walkthrough

Input: `%d%s`

Output:
`42`

```
char buf[64];

void vulnerable(void) {
    char *secret_string = "pancake";
    int secret_number = 42;
    if (fgets(buf, 64, stdin) == NULL)
        return;
    printf(buf);
}
```



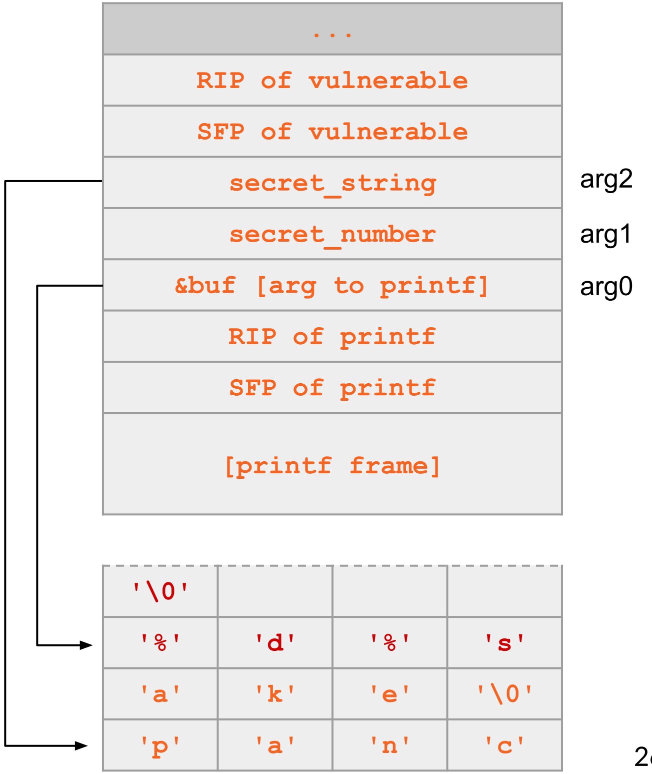
The first format specifier `%d` says to treat the next argument (arg1) as an integer and print it out.

Format String Vulnerability Walkthrough

Input: `%d%s`

Output: **42pancake**

```
char buf[64];

void vulnerable(void) {
    char *secret_string = "pancake";
    int secret_number = 42;
    if (fgets(buf, 64, stdin) == NULL)
        return;
    printf(buf);
}
```



The second format specifier `%s` says to treat the next argument (arg2) as an string and print it out.

`%s` will dereference the pointer at arg2 and print until it sees a null byte (`'\0'`)

Format String Vulnerabilities

- They can also write values using the `%n` specifier
    - `%n` treats the next argument as a **pointer** and writes the number of bytes printed so far to that address (usually used to calculate output spacing)
        - `printf("item %d:%n", 3, &val)` stores 7 in `val`
        - `printf("item %d:%n", 987, &val)` stores 9 in `val`
    - `printf("000%n")`
        - **Writes** the value 3 to the integer **pointed to** by address located 8 bytes above the RIP of `printf`

```
void vulnerable(void) {
    char buf[64];
    if (fgets(buf, 64, stdin) == NULL)
        return;
    printf(buf);
}
```

Format String Vulnerabilities: Defense

```
void vulnerable(void) {
    char buf[64];
    if (fgets(buf, 64, stdin) == NULL)
        return;
    printf("%s", buf);
}
```

Never use untrusted input in the first argument to **`printf`**.

Now the attacker can't make the number of arguments mismatched!

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

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
- 2014: Swift, a new memory-safe language, introduced
- **Takeaway**: Non-memory-safe languages are still used for legacy reasons

Writing Memory-Safe Code

Defending Against Memory Safety Vulnerabilities

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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
  - Implement a reference monitor
  - 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

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.

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
  - Too many false bugs = wasted programmer time
- 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
  - Take notes on how they did it

Testing for Software Security Issues

- What makes testing a program for security problems difficult?
  - We're testing for the *absence* of vulnerabilities
  - Normal inputs rarely reveal security vulnerabilities
- 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
  - Management burden (the "patch treadmill" never stops)

Exploit Mitigations

Defending Against Memory Safety Vulnerabilities

- What are some approaches to defending against memory safety vulnerabilities?
  - Use safer programming languages.
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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)

Exploit Mitigations

- Mitigations involve a large back-and-forth arms race
  - Security researchers find a new mitigation to make an exploit harder
  - Attackers find a way to defeat the mitigation
- Mitigations make attacks harder, but not impossible
  - The only way to prevent all buffer overflow attacks is to use a memory-safe language

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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2. Write malicious shellcode at a known memory address
3. Overwrite the RIP with the address of the shellcode
4. Return from the function
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We can defend against memory safety vulnerabilities by making each of these steps more difficult (or impossible)!