

Modern C++ Memory Safety

**Safer Systems Software
Without a Full Rewrite**



**Modern C++ features, practical tools and
proven techniques to reduce memory safety
risks in existing systems no full rewrite needed.**

FABIAN KRÜGER

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Safer Systems Software Without a Full Rewrite

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Safer Systems Software Without a Full Rewrite

This book is a practical engineering guide for reducing memory safety vulnerabilities in existing C++ systems through incremental modernization. It covers the root causes of common vulnerabilities, modern C++ features that eliminate them, compiler diagnostics and sanitizers, static analysis, fuzzing, runtime mitigations and real-world strategies for assessment, refactoring and continuous improvement. The code examples are complete, fully working and designed to translate directly into production systems.

Introduction: The Memory Safety Problem in C++

The Scale of the Problem

In October 2017, a Windows update rolled out a patch that inadvertently broke printers across thousands of organizations. The flaw that caused it was a heap-based buffer overflow in a memory manager, triggered by malformed print spooler data. It was not the first memory corruption bug to make headlines, and it would not be the last. That same year, NotPetya exploited Windows vulnerabilities, including memory corruption flaws, to infect networks worldwide, ultimately inflicting more than ten billion dollars in damage.

These are not isolated incidents. The numbers behind them tell a sobering story. Microsoft analyzed a decade of their security bulletins and found that roughly seventy percent of critical vulnerabilities were memory safety bugs. Google found a similar distribution in Android and Chromium. Roughly seventy percent of the CVEs both organizations assign each year trace to memory-unsafe C and C++ code. In memory-unsafe languages, the compiler will happily let you write past a buffer, free memory twice, or keep using a pointer after it is gone. None of it will stop your program from compiling, or often from running, until an attacker notices first.

Google Project Zero reports that memory safety vulnerabilities accounted for about two-thirds of zero-day exploits tracked in the wild. Spatial memory safety vulnerabilities alone accounted for forty percent of in-the-wild exploits. The NSA and CISA have published advisory documents explicitly calling for the adoption of memory-safe languages. The White House issued “Back to the Building Blocks: A Path Toward Secure and Measurable Software,” which named memory safety as a critical priority for federal IT modernization.

The common refrain has become familiar: memory safety bugs are the single largest category of exploitable vulnerabilities in C and C++ software. They are responsible for buffer overflows, use-after-free exploits, out-of-bounds access, double free attacks, uninitialized memory reads, type confusion and

numerous other vulnerability classes. If your organization runs C++ code that handles untrusted data, manages memory manually, or exposes any externally reachable interface, your system is almost certainly vulnerable to one or more of these classes of bugs.

Why C++ Gets Memory Safety Wrong

C++ was designed with three competing goals: performance, expressiveness and compatibility with C. Memory safety was not among them. The language gives you direct access to raw memory through pointers, no garbage collection to manage object lifetimes and no built-in bounds checking for arrays. It trusts you to get it right.

This trust comes at a cost. Modern C++ offers powerful abstractions for safe programming, but they are opt-in. A developer writing legacy-style C++ can still write a buffer overflow, use-after-free, or dangling pointer bug, and the compiler will not raise an objection. The language provides no mandatory runtime checks and no compile-time guarantees about object lifetimes or buffer bounds.

Undefined behavior (UB) compounds the problem. When you perform certain illegal operations in C++, the standard says the program's behavior is undefined. This means the compiler is free to assume such operations never happen, and can optimize your code under that assumption. An optimizing compiler may remove null pointer checks, reorder memory accesses, or eliminate loop guards. What looks like a simple bug in your code may become a security vulnerability through compiler optimization.

Data races are also undefined behavior in C++. If two threads access the same memory location and at least one writes without proper synchronization, anything can happen. This includes silent data corruption that is only visible under specific timing conditions, making data races notoriously difficult to diagnose and reproduce.

The Full Rewrite Fallacy

When faced with a legacy C++ codebase full of memory safety vulnerabilities, the obvious answer seems to be: rewrite it in a memory-safe language. Rust,

Java, Go, and others provide language-level guarantees that C++ cannot match. The logic is straightforward: if C++ is inherently unsafe, switch to something safe.

But this answer is incomplete for real-world systems. Consider a production storage engine, a network server, or an embedded device driver that has accumulated millions of lines of C++ code over decades of development. These systems have architectural commitments, ABI contracts with downstream consumers, performance requirements, deployment constraints and teams of engineers who know the code. Rewriting any of these systems wholesale is expensive, risky and often impractical.

Even at organizations that advocate strongly for memory-safe languages, a wholesale rewrite is rarely the chosen path. Google, for example, sees “no realistic path for an evolution of C++ into a language with rigorous memory safety guarantees that include temporal safety,” yet their strategy is not to rewrite every C++ service in Rust. Instead, they retrofit spatial safety checks to hundreds of millions of lines of existing C++ code, use Rust for new security-critical components, and incrementally migrate where it makes sense. They deployed hardened libc++ across their server-side production systems, discovered over a thousand bugs, reduced segmentation faults by thirty percent and prevented an estimated one to two thousand new bugs annually. Their average performance impact was 0.30 percent.

Microsoft has followed a similar path. They use Rust in the Windows kernel and new development while modernizing existing C++ codebases through stricter compiler flags, sanitizers and safer idioms.

This book is built on a pragmatic premise: your organization does not have to choose between “rewrite everything” and “do nothing.” You can make existing C++ software measurably safer, one component at a time, while preserving architectural continuity, backward compatibility, performance and operational stability.

What This Book Will Give You

This book is a hands-on engineering guide for reducing memory safety vulnerabilities in existing C++ systems. It assumes you understand C++ at a working level, including pointers, classes, templates, and the standard library. You

do not need to be an expert in modern C++ or security, but you should be comfortable reading and modifying nontrivial C++ code.

The central thesis of this book is simple: the vast majority of memory safety bugs in C++ systems can be systematically reduced, often by orders of magnitude, through incremental adoption of modern language features, safer idioms, disciplined tooling and thoughtful refactoring. You do not need a full rewrite.

Here is what the book covers:

Chapters one through eight explain how memory safety failures happen. You will learn the mechanics of common vulnerabilities including buffer overflows, out-of-bounds access, use-after-free, dangling references, double free, memory leaks, uninitialized memory, iterator invalidation, type confusion and concurrency-related memory errors. Each chapter covers how the bug arises, how it is exploited, and why it matters in production systems.

Chapters nine through thirteen examine modern C++ language features and idioms that eliminate or reduce these risks. You will see in depth how RAII, smart pointers, move semantics, value semantics, bounds-safe interfaces, `std::span`, `std::string_view`, containers, allocators and exception safety interact to provide safety at zero runtime cost. This is where you will learn the specific patterns to use in your code.

Chapters fourteen through sixteen describe how to assess legacy code-bases, establish a measurable security baseline, identify and prioritize high-risk components, introduce safer abstractions incrementally, modernize interfaces without breaking existing consumers, isolate unsafe operations, and manage ABI compatibility, dependencies, technical debt, performance constraints, and deployment risks. These chapters focus on real-world strategy: how to get the work done in an organization with real constraints.

Chapters seventeen through twenty-two cover the tools you need to find and fix memory safety issues: compiler diagnostics and warnings, AddressSanitizer, UndefinedBehaviorSanitizer, MemorySanitizer, ThreadSanitizer, static analysis with clang-tidy and Cppcheck, fuzzing with LibFuzzer, Control Flow Integrity and automated refactoring. You will learn how to configure these tools, interpret their findings, measure their effectiveness, and incorporate them into existing development workflows.

Chapters twenty-three and twenty-four provide end-to-end case studies showing incremental modernization in realistic systems: a network server and

a storage engine. These case studies tie together the techniques from the entire book into concrete refactoring plans.

Throughout the book, code examples are complete and fully working. Each example includes the necessary headers, build configuration, compiler commands and expected output. You should be able to compile the code and run it on your own system. The examples are grounded in production-level patterns, not toy illustrations.

The C++ standard baseline for this book is C++17. This standard is widely available across all major toolchains and provides the majority of the safety features needed for incremental modernization: `std::optional`, `std::variant`, `std::string_view`, `std::filesystem`, structured bindings, fold expressions and the parallel algorithms. Where C++20 features such as `std::span`, `std::ranges`, or C++23 features such as `std::expected` materially improve safety, I call them out explicitly and provide C++17-compatible alternatives where feasible.

The book distinguishes carefully between prevention, detection, containment and mitigation. Prevention eliminates a class of bugs by making it impossible or extremely difficult to introduce them. Detection finds bugs after they are introduced but before they are exploited. Containment limits the blast radius when exploitation occurs. Mitigation reduces the probability of successful exploitation even if a vulnerability exists. Each approach has a role in a defense-in-depth strategy, but they are not interchangeable. The book makes clear which techniques fall into which category.

This book will not give you a silver bullet. C++ will not become a fully memory-safe language, and you cannot make a complex system immune to all memory errors. But you can make it substantially safer than it is today, you can measure your progress and you can keep making it safer over time. The path is clear, practical and proven in production at scale. Let us begin.

Chapter 1: How Memory Safety Failures Happen

The C++ Memory Model in Practice

Memory safety describes the property that a program only accesses memory locations it is permitted to access, in ways that do not corrupt program state. A memory-safe program never reads or writes outside the bounds of an allocated object, never accesses an object after it has been deallocated, never uses uninitialized memory in a way that affects program behavior and never performs data races between threads.

C++ does not guarantee memory safety. The C++ standard defines a memory model that specifies the observable behavior of well-formed programs, but it leaves the behavior of ill-formed programs undefined. The standard does not require bounds checking on array access, does not require objects to be freed only once and does not require the runtime to detect use-after-free or data races. It places the burden on the programmer.

In practice, C++ programs manage memory through three regions: the stack, the heap and the static data segment. Stack memory is allocated when a function is called and deallocated when it returns. Heap memory is allocated explicitly through `new` or `malloc` and must be deallocated explicitly through `delete` or `free`. Static memory is allocated for the lifetime of the program, including global and static variables.

Each region has its own failure modes. Stack-based bugs typically manifest as stack buffer overflows, where data written beyond the end of a local array corrupts adjacent stack frames. Heap-based bugs include heap buffer overflows, use-after-free and double free, which corrupt allocator metadata and adjacent heap allocations. Static memory bugs are rarer but can occur when objects in static storage duration have circular or invalid dependencies during initialization or destruction.

Consider this simple example of a stack-based buffer overflow:

```
1 // Example 1.1: Stack buffer overflow
2 #include <cstring>
3
4 void process_name(const char* input) {
5     char buffer[32];
6     strcpy(buffer, input); // No bounds checking
7     // Use buffer...
8 }
9
10 int main() {
11     const char* long_name = "This is a very long name that exceeds the buffer
12     ↪ size";
13     process_name(long_name);
14     return 0;
15 }
```

Build and run:

```
1 g++ -O0 -g -o example1.1 example1.1.cpp
2 ./example1.1
```

The `strcpy` call copies input into buffer without checking whether input fits. When input is longer than thirty-one characters plus the null terminator, `strcpy` writes past the end of buffer onto adjacent stack memory. This may corrupt local variables, the saved return address, or the stack frame of the calling function. In production code, an attacker who can control input could use this to redirect control flow or execute arbitrary code.

Pointers, References, and Their Promises

C++ provides two primary mechanisms for indirect memory access: pointers and references. Both are central to the language's expressiveness, and both are central to its memory safety problems.

A raw pointer is a variable that holds a memory address. Pointers can be reassigned, incremented, decremented, compared and converted. They can point to the null address. The type system constrains what you can do with a pointer to some extent, but pointer arithmetic and casts weaken those constraints significantly.

```

1  #include <iostream>
2
3  int main() {
4      int* p = new int(42);
5      int* q = p + 1;           // Pointer arithmetic: points past allocated object
6      void* v = p;             // Conversion to void* erases type information
7      int* r = static_cast<int*>(v); // Type restored, but no runtime check
8      (void)q;
9      (void)r;
10     delete p;
11     int x = *p;               // Use-after-free: undefined behavior
12     std::cout << x << std::endl;
13     return 0;
14 }

```

Raw pointers carry no information about ownership, lifetime, or size. When you see `int* p` in a function parameter, you cannot tell whether the caller expects the function to take ownership, borrow the object, or return a copy. You cannot tell whether `p` points to a single object, the first element of an array, or a dangling address. All of this must be inferred from context, comments, or naming conventions.

References are a safer alternative for borrowing. A reference is an alias for another object that cannot be reseated and cannot be null. References make it clear that the function will use the object but not take ownership.

```

1  void process(int& x) {
2      x *= 2;
3  }
4
5  int main() {
6      int value = 21;
7      process(value); // value is now 42
8  }

```

However, references can dangle if the object they refer to is destroyed. The compiler does not track object lifetimes, so it cannot always catch this.

```
1 // Example 1.2: Dangling reference
2 #include <iostream>
3
4 int* create() {
5     int x = 42;
6     return &x; // Returns address of local variable
7 }
8
9 int main() {
10    int* p = create();
11    std::cout << *p << std::endl; // Undefined behavior: dangling pointer
12 }
```

In this example, `create` returns a pointer to a local variable. The local variable is destroyed when `create` returns, leaving `p` pointing to invalid memory. The behavior is undefined: `p` may contain garbage, point to reused stack data, or cause a segmentation fault.

Object Lifetimes and Aliasing

Object lifetime is the period from when an object is created to when it is destroyed. In C++, objects have different lifetime categories:

Static storage duration: Objects with static storage duration are constructed before `main` begins and destroyed after `main` ends. Their lifetime spans the entire execution of the program.

Automatic storage duration: Objects with automatic storage duration are created when their scope is entered and destroyed when their scope exits. These include local variables and function parameters.

Dynamic storage duration: Objects with dynamic storage duration are created explicitly with `new` and destroyed explicitly with `delete`. Their lifetime is controlled by the programmer.

Thread storage duration: Objects with thread storage duration are created when their thread begins and destroyed when their thread ends.

Memory safety failures often occur at the boundaries between these lifetime categories. A pointer or reference created while an object has one lifetime may become invalid when that lifetime ends. The compiler does not enforce these boundaries.

Aliasing complicates lifetime tracking. Aliasing occurs when multiple names, pointers, or references refer to the same memory location. C++ is an aliasing-heavy language: pointers can alias, references can alias, and arrays naturally alias through pointer arithmetic. When aliases exist, it is difficult to determine when it is safe to destroy an object, because other code may still be using it.

```
1 // Example 1.3: Aliasing and premature deallocation
2 #include <memory>
3
4 void share_object(std::shared_ptr<int>& a, std::shared_ptr<int>& b) {
5     b = a; // Now both share ownership of the same int
6 }
7
8 int main() {
9     auto a = std::make_shared<int>(42);
10    std::shared_ptr<int> b;
11    share_object(a, b);
12    // Both a and b can be used safely
13    // The int is destroyed when the last shared_ptr is destroyed
14 }
```

Here, `std::shared_ptr` tracks how many aliases exist and only destroys the object when all aliases have been released. This is a key principle: ownership semantics must be explicit. When multiple pointers or references can point to the same object, the code must make clear which one is responsible for destruction.

Undefined Behavior as the Root Cause

Undefined behavior is at the heart of C++ memory safety problems. The C++ standard defines undefined behavior as behavior for which the standard imposes no requirements. When your program performs an undefined behavior, the compiler is free to generate any code at all: your program may crash, it may produce incorrect results, it may appear to work correctly, or it may do something entirely unexpected.

Undefined behavior is not the same as a bug. A bug is any deviation from the intended behavior. Undefined behavior is a specific category of bug where the language standard says nothing about what should happen. The compiler

can assume that undefined behavior never occurs in a well-formed program, and it optimizes under that assumption. This is where things get dangerous.

Consider signed integer overflow. In C++, signed integer overflow is undefined behavior. An optimizing compiler may assume that signed overflow never occurs and reorder or eliminate checks under that assumption.

```

1  // Example 1.4: Signed integer overflow optimization
2  #include <iostream>
3  #include <climits>
4
5  bool is_safe_addition(int a, int b) {
6      int result = a + b;
7      return result > a; // Compiler may optimize this away
8  }
9
10 int main() {
11     // With -O2 the compiler may assume the addition never overflows and
12     // return true here even though INT_MAX + 1 wraps to INT_MIN.
13     std::cout << std::boolalpha << is_safe_addition(INT_MAX, 1) << std::endl;
14     return 0;
15 }
```

The compiler knows that if *a* is positive, and *a + b* overflows, the behavior is undefined. Since undefined behavior cannot occur in a well-formed program, the compiler may assume the addition never overflows. It may then optimize the check `result > a` away entirely, because in a world where overflow never occurs, adding a positive *b* to *a* will always produce a result greater than *a*.

The compiler is correct by the standard. But your code now silently misbehaves when overflow actually occurs.

Here is a list of common sources of undefined behavior in C++:

- Dereferencing a null pointer or a dangling pointer.
- Reading uninitialized memory.
- Writing past the end of an array or buffer.
- Signed integer overflow.
- Data races: concurrent access to shared memory where at least one access is a write and neither access is atomic.
- Type punning through invalid casts or union access.
- Calling pure virtual functions during construction or destruction.
- Using a local object after its lifetime has ended.

- Deleting an object through a pointer of the wrong type.
- Modifying a const object.

Each of these is a potential security vulnerability. An attacker who can trigger undefined behavior in your program may be able to control how the compiler optimized the code around that undefined behavior, and thereby control program execution.

From Bug to Exploit

Not every memory safety bug is immediately exploitable, but every memory safety bug is a potential exploit. The path from bug to exploit follows a recognizable pattern.

First, the attacker must identify the vulnerability. This may involve reverse engineering your binary, fuzzing your input interfaces, or analyzing your source code. Memory safety vulnerabilities are particularly attractive because they can allow arbitrary code execution, not just limited information disclosure.

Second, the attacker must achieve reliable triggering. Many memory safety bugs are timing-dependent or state-dependent. A use-after-free may only manifest under specific allocation patterns. A race condition may only occur when two threads execute in a particular interleaving.

Third, the attacker must work around mitigations. Modern operating systems and compilers provide several layers of protection: address space layout randomization (ASLR), non-executable memory (NX/DEP), stack canaries, control flow integrity (CFI) and more. Each layer makes exploitation harder but not impossible. An attacker may need to combine multiple techniques: leak memory to defeat ASLR, use return-oriented programming to defeat NX, or find a reliable way to bypass CFI.

Finally, the attacker must achieve their goal: executing arbitrary code, exfiltrating data, elevating privileges, or compromising the system.

This exploitation chain is why memory safety matters. A single unchecked buffer, a single dangling pointer, a single data race can be the starting point for a complete compromise.

Consider a concrete example: a use-after-free bug in a web browser. The browser allocates an object to represent a DOM element. The object is freed

when the element is removed from the document. But due to a logic error, the browser retains a pointer to the freed object. An attacker crafts a webpage that frees the object and then allocates a malicious object in the same memory location. When the browser uses the dangling pointer, it operates on the attacker-controlled object instead. The attacker can manipulate the object's layout to overwrite function pointers or vtables and when the browser calls through those pointers, the attacker's code executes.

This is exactly the kind of attack that made use-after-free bugs the dominant class of browser exploits for over a decade. Modern browsers have largely defended against such attacks through sandboxing, type-based CFI and improved memory management. But the underlying issue remains: use-after-free bugs are still possible in C++ and they remain the most attractive targets for sophisticated attackers.

The goal of this book is to give you the tools and strategies to eliminate these vulnerabilities from your own systems, systematically and incrementally. The next chapters will examine each major class of vulnerability in detail, explain how modern C++ addresses it and provide concrete patterns for safe code.

Chapter 2: Buffer Overflows and Out-of-Bounds Access

Mechanics of Buffer Overruns

A buffer overflow occurs when a program writes more data to a buffer than it can hold. The excess data overwrites adjacent memory, corrupting program state. Buffer overflows are the oldest, most well-understood and most frequently exploited class of memory safety vulnerability. They appear in every major system: operating systems, web browsers, network services, embedded devices and libraries.

Buffer overflows arise from two sources: inadequate bounds checking and incorrect size calculations. When you read or write a buffer, you must ensure that every access is within the bounds of the allocated memory. When the buffer size is derived from input, computation, or external metadata, the size may be wrong.

Stack-based buffer overflows corrupt adjacent stack frames, including saved return addresses. An attacker who can control the overflow can overwrite the return address with an address of their choosing, causing the function to jump to arbitrary code when it returns.

Heap-based buffer overflows corrupt adjacent heap allocations or allocator metadata. The consequences are less direct but equally dangerous: corrupted metadata can cause subsequent allocations to return attacker-controlled addresses, leading to arbitrary write primitives.

```

1  // Example 2.1: Stack-based buffer overflow
2  #include <cstring>
3
4  void handle_input(const char* input) {
5      char local_buffer[64];
6      strcpy(local_buffer, input); // Vulnerable: no length check
7      // Use local_buffer...
8  }
9
10 int main() {
11     // Build oversized input: 128 'A's, far larger than local_buffer (64)
12     char payload[129];
13     memset(payload, 'A', sizeof(payload) - 1);
14     payload[sizeof(payload) - 1] = '\0';
15     handle_input(payload);
16     return 0;
17 }

```

Build with warnings:

```

1  g++ -Wall -Wextra -O0 -g -fsanitize=address -o example2.1 example2.1.cpp
2  ./example2.1

```

AddressSanitizer will report a stack-buffer-overflow at the `strcpy` call. The output shows the stack trace, the exact location of the overflow and the sizes involved.

Stack and Heap Smashing

Stack smashing attacks target stack-based buffer overflows. The classic attack overwrites the saved return address on the stack. When the vulnerable function returns, execution jumps to the attacker's code.

On modern systems, this attack faces multiple defenses. ASLR randomizes the stack address, making it difficult to predict where injected code will be located. NX bits mark the stack as non-executable, preventing execution of injected shellcode. Stack canaries are sentinel values placed between local variables and the saved return address; if the canary is corrupted, the program terminates before the return address is used.

Heap smashing attacks target heap-based buffer overflows. The heap is organized into chunks, each with metadata describing its size, allocation status

and linkage to other chunks. A heap overflow can corrupt this metadata. An attacker who controls the corrupted metadata can manipulate the heap allocator to return arbitrary addresses on subsequent malloc calls, creating an arbitrary write primitive.

Modern allocators include protections against heap corruption, including guard pages, randomized chunk layouts and integrity checks. However, these protections can be bypassed in sophisticated attacks.

```

1  // Example 2.2: Heap-based buffer overflow
2  #include <cstring>
3  #include <cstdio>
4
5  struct Message {
6      char data[32];
7      int length;
8      char padding[128]; // Simulates adjacent allocation
9  };
10
11 void process_message(const char* input) {
12     Message* msg = new Message();
13     strcpy(msg->data, input); // Vulnerable: can overflow into length and
    ↪ padding
14     printf("Message length: %d\n", msg->length);
15     delete msg;
16 }
17
18 int main() {
19     // Input longer than 32 bytes corrupts msg->length
20     char long_input[256];
21     memset(long_input, 'B', sizeof(long_input));
22     long_input[sizeof(long_input) - 1] = '\0';
23     process_message(long_input);
24     return 0;
25 }

```

Build with AddressSanitizer:

```

1  clang++ -Wall -Wextra -O0 -g -fsanitize=address -o example2.2 example2.2.cpp
2  ./example2.2

```

ASan will detect the heap-buffer-overflow and report the exact location and size. The output will show that data was written beyond the bounds of the Message object into the heap.

Off-by-One and Off-by-Many Errors

Off-by-one errors are among the most common and insidious memory safety bugs. They occur when a loop iterates one time too many or too few, or when a boundary is miscalculated by one position. An off-by-one error that writes past the end of a buffer by a single byte is still a buffer overflow and can be exploited.

Consider a common pattern: iterating through an array using a length value obtained from external input.

```

1 // Example 2.3: Off-by-one error
2 #include <cstdlib>
3
4 void copy_array(const int* src, int* dst, size_t len) {
5     for (size_t i = 0; i <= len; ++i) { // Bug: should be i < len
6         dst[i] = src[i];
7     }
8 }
9
10 int main() {
11     int src[10] = {1, 2, 3, 4, 5, 6, 7, 8, 9, 10};
12     int dst[10];
13     copy_array(src, dst, 10); // Off-by-one: writes dst[10], out of bounds
14     return 0;
15 }
```

Build and run:

```

1 g++ -Wall -Wextra -O0 -g -fsanitize=address -o example2.3 example2.3.cpp
2 ./example2.3
```

ASan will detect the out-of-bounds write on the eleventh iteration, when *i* equals ten.

Off-by-many errors are similar but involve larger miscalculations. They often arise when converting between different units or representations: bytes to words, characters to bytes in multi-byte encodings, or indices in different coordinate systems.

Another common source is incorrect understanding of C-style string functions. `strlen` returns the number of characters excluding the null terminator, but `strcpy` writes the null terminator. If you allocate `strlen(s)` bytes and copy `s` into it, you have an off-by-one overflow.

```

1 // Example 2.4: strlen off-by-one
2 #include <cstring>
3 #include <cstdio>
4 #include <stdlib>
5
6 void duplicate_string(const char* s) {
7     char* dup = static_cast<char*>(malloc(strlen(s))); // Bug: missing +1 for
    ↪ null
8     strcpy(dup, s); // Writes past allocated memory
9     printf("Duplicated: %s\n", dup);
10    free(dup);
11 }
12
13 int main() {
14     duplicate_string("hello");
15     return 0;
16 }

```

Modern C++ Bounds-Safe Patterns

C++ provides multiple mechanisms for safe buffer access. None of them are mandatory, but all of them are zero-cost or near-zero-cost when properly used.

The first and most important pattern is to prefer standard containers over raw arrays. `std::vector` provides bounds-safe access through the `at()` method, which throws `std::out_of_range` if the index is out of bounds.

```

1 // Example 2.5: Bounds-safe access with std::vector
2 #include <vector>
3 #include <iostream>
4
5 int main() {
6     std::vector<int> data = {1, 2, 3, 4, 5};
7     std::cout << data[3] << std::endl; // OK: direct access, no bounds
    ↪ check
8     std::cout << data.at(3) << std::endl; // OK: bounds-checked access
9     try {
10        std::cout << data.at(10) << std::endl; // Throws std::out_of_range
11    } catch (const std::out_of_range& e) {
12        std::cerr << "Out of range: " << e.what() << std::endl;
13    }
14    return 0;
15 }

```

Build and run:

```

1 g++ -std=c++17 -Wall -Wextra -O2 -o example2.5 example2.5.cpp
2 ./example2.5

```

Output:

```

1 4
2 4
3 Out of range: vector::_M_range_check: __n (which is 10) >= this->size() (which
  ↳ is 5)

```

The `at()` method provides a runtime bounds check with a well-defined failure behavior. The `[]` operator does not check bounds and has undefined behavior if the index is out of range. In performance-critical code, `[]` is sometimes preferred, but `at()` should be used whenever a bounds error would be a security issue.

C++20 introduced `std::span`, a non-owning view of contiguous data that provides bounds-checked access. `std::span` is particularly useful for APIs that currently take raw pointers and sizes.

```

1 // Example 2.6: std::span for safe buffer views (C++20)
2 #include <span>
3 #include <vector>
4 #include <iostream>
5
6 void print_all(std::span<const int> data) {
7     for (auto it = data.begin(); it != data.end(); ++it) {
8         std::cout << *it << " ";
9     }
10    std::cout << std::endl;
11 }
12
13 int main() {
14    std::vector<int> v = {1, 2, 3, 4, 5};
15    print_all(v); // Implicit conversion from std::vector to std::span
16
17    int raw[3] = {10, 20, 30};
18    print_all(raw); // Implicit conversion from raw array to std::span
19    return 0;
20 }

```

Build with C++20:

```

1 g++ -std=c++20 -Wall -Wextra -O2 -o example2.6 example2.6.cpp
2 ./example2.6

```

For C++17, you can use the Guidelines Support Library (GSL) `gsl::span`, which is available as a header-only library.

```

1 // Example 2.7: gsl::span for C++17
2 #include <gsl/span>
3 #include <vector>
4 #include <iostream>
5
6 void print_all(gsl::span<const int> data) {
7     for (size_t i = 0; i < data.size(); ++i) {
8         std::cout << data[i] << " ";
9     }
10    std::cout << std::endl;
11 }
12
13 int main() {
14     std::vector<int> v = {1, 2, 3, 4, 5};
15     print_all(gsl::span<const int>(v));
16     return 0;
17 }

```

Build with GSL (requires GSL installed or included in your project):

```

1 g++ -std=c++17 -Wall -Wextra -O2 -I/path/to/GSL/include -o example2.7
  ↪ example2.7.cpp
2 ./example2.7

```

`std::span` does not own the underlying data. It is a view that borrows the data, similar to a reference. If the underlying data is destroyed while a span still refers to it, the span becomes dangling. `std::span` helps with spatial safety (bounds checking) but not temporal safety (lifetime management).

Refactoring C-Style Arrays and Pointers

Legacy codebases contain many C-style arrays and raw pointer-based interfaces. Refactoring these interfaces to use bounds-safe alternatives is one of the most impactful changes you can make.

The refactoring strategy depends on the interface:

If the function takes a pointer and size, replace the pointer with `std::span` or `gsl::span`.

If the function takes a C-style array parameter, replace it with `std::span` or a reference to `std::array` if the size is known at compile time.

If the function returns a dynamically allocated array, replace it with `std::vector` or `std::unique_ptr` with a custom deleter.

If the function takes a C-style string, replace it with `std::string_view` for read-only parameters and `std::string` for owned strings.

Here is a before-and-after example:

```

1  // Example 2.8: Before: C-style array interface
2  #include <cstdint>
3  #include <vector>
4
5  // Unsafe: no bounds checking, no size validation
6  void process_buffer(int* buffer, size_t size) {
7      for (size_t i = 0; i < size; ++i) {
8          buffer[i] *= 2;
9      }
10 }
11
12 // After: std::span interface (C++20) or gsl::span (C++17)
13 #include <span> // Use gsl::span in C++17
14
15 // Safe: std::span carries its size, so the loop can only touch valid elements
16 void process_buffer_safe(std::span<int> buffer) {
17     for (size_t i = 0; i < buffer.size(); ++i) {
18         buffer[i] *= 2; // i < buffer.size() is guaranteed by the loop
19     }
20 }
21
22 int main() {
23     // C-style call
24     int raw[10] = {};
25     process_buffer(raw, 10);
26
27     // Modern call with std::vector
28     std::vector<int> v = {1, 2, 3};
29     process_buffer_safe(v);
30
31     // Fixed-size span
32     std::span<int, 10> fixed_span(raw);
33     process_buffer_safe(fixed_span);
34
35     return 0;
36 }

```

Build with C++20:

```

1 g++ -std=c++20 -Wall -Wextra -O2 -o example2.8 example2.8.cpp
2 ./example2.8

```

When refactoring, consider ABI compatibility. If the function is part of a public API compiled into a shared library, changing its signature breaks binary compatibility. In such cases, you can add new overloads with safe signatures while keeping the old ones for backward compatibility.

```

1 // Example 2.9: ABI-compatible refactoring with overloads
2 #include <cstdint>
3 #include <span>
4 #include <iostream>
5
6 class Processor {
7 public:
8     // Original C-style API: kept for ABI compatibility
9     void process(int* buffer, size_t size) {
10         process_impl(buffer, size);
11     }
12
13     // New safe API: takes std::span
14     void process(std::span<int> buffer) {
15         process_impl(buffer.data(), buffer.size());
16     }
17
18 private:
19     void process_impl(int* buffer, size_t size) {
20         for (size_t i = 0; i < size; ++i) {
21             buffer[i] *= 2;
22         }
23     }
24 };
25
26 int main() {
27     Processor proc;
28
29     // Legacy C-style call
30     int raw[4] = {1, 2, 3, 4};
31     proc.process(raw, 4);
32
33     // Modern call with std::span
34     int arr[2] = {10, 20};
35     proc.process(std::span<int>(arr));
36     for (int x : arr) {
37         std::cout << x << " "; // 20 40

```

```
38     }  
39     std::cout << std::endl;  
40     return 0;  
41 }
```

This pattern preserves the old API while providing a safer alternative for new callers. Over time, the old API can be deprecated and eventually removed.

Chapter conclusion: Buffer overflows and out-of-bounds access are among the most common and exploitable memory safety vulnerabilities in C++. They arise from inadequate bounds checking and incorrect size calculations. Modern C++ provides bounds-safe alternatives through standard containers, `std::span` and the `at()` method. Refactoring C-style array and pointer interfaces to use these alternatives is one of the most impactful changes you can make to improve memory safety in an existing codebase.

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