C++ now

2025

Harnessing constexpr

A Path to Safer C++

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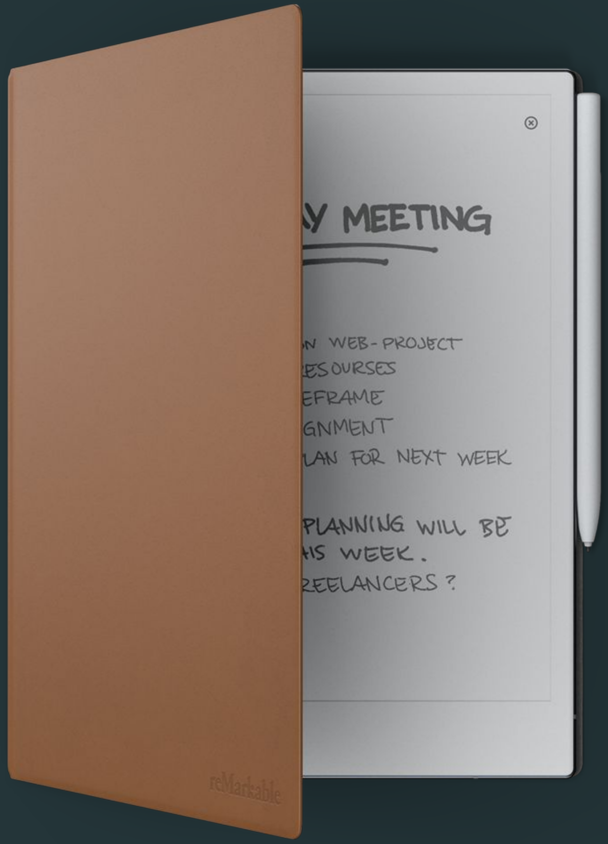
C++ programmer for last 12+ years

Areas: architecture, frameworks, libraries, build systems



Agenda

- Is C++ Safe?
- Common Pitfalls in C++
- Traditional Solutions
- `constexpr`
  - Evolution from C++11 to C++26
  - Case studies
  - Limitations
  - Pushing the limits
- Summary

What are we going to learn today?

- How easy it is to make mistakes in C++
- How to try to protect ourselves from common pitfalls
- How `constexpr` could help

Is C++ a safe language?

Is C++ Safe? - News

- NSA - has recommended adoption of memory-safe programming languages
- CISA - recommends transitioning to memory-safe languages such as Rust
- Google security by design
- Microsoft Azure not allowed to write new code in C++

Is C++ Safe? - News

- The existential threat against C++ and where to go from here - Helge Penne - NDC TechTown 2024

NDC { TechTown }
The existential threat against C++ and where to go from here
Helge Penne
Technical Specialist Software - Thales Norway

Is C++ Safe? - News

- Do not use memory unsafe languages in new products
- Use memory safe language
- **R**ewrite in memory safe language

What is wrong with them?

We all know that C++ is the best!

We all know that C++ is the best!
Right?

Is C++ Safe? - News

- Do not use **memory unsafe languages** in new products
- Use **memory safe language**
- **R**ewrite in **memory safe language**

What is a memory safe language?

Memory safety is the state of being protected from various software bugs and security vulnerabilities when dealing with memory access, such as buffer overflows and dangling pointers. (wiki/Memory_safety*)

* Memory safety without runtime checks or garbage collection - Dhurjati, Dinakar; Kowshik, Sumant; Adve, Vikram; Lattner, Chris (1 January 2003)

What is a memory safe language?

Open Source Security Foundation - A memory safe by default language prevents (by default) common memory safety vulnerabilities, including:

- Access errors (invalid read/write of a pointer)
- Uninitialized variables (variable that has not been assigned a value is used)
- Memory leak (memory usage is not tracked or is tracked incorrectly)
- Race conditions
- Undefined behavior

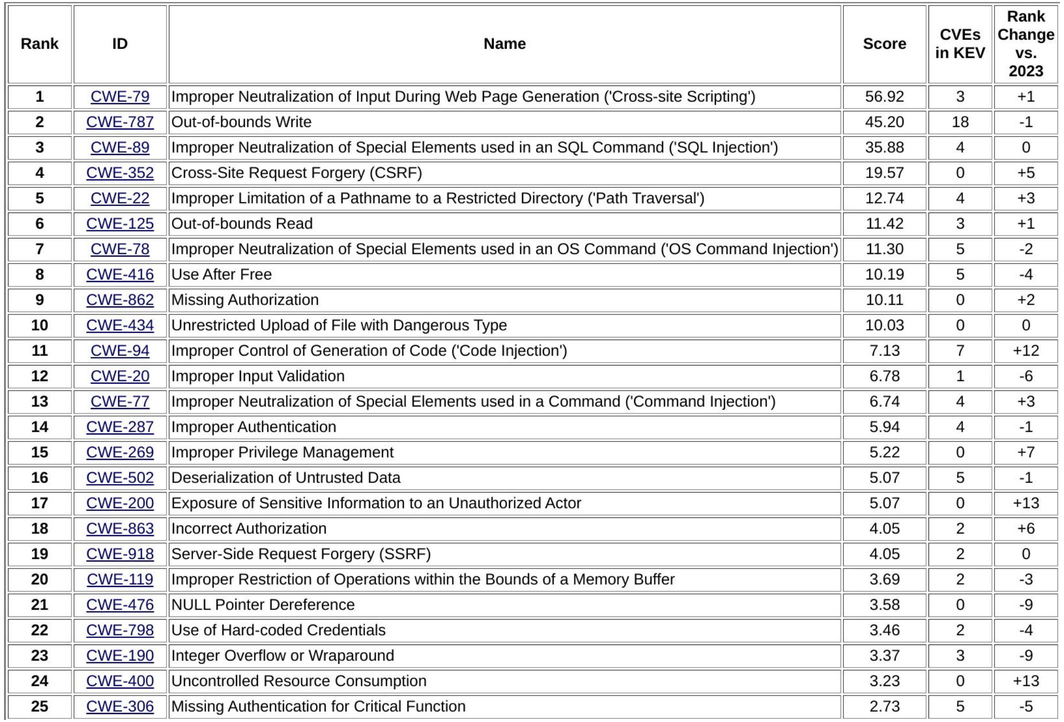
Is C++ is a memory safe language?

Is C++ is a memory safe language?

No

Common pitfalls in C++

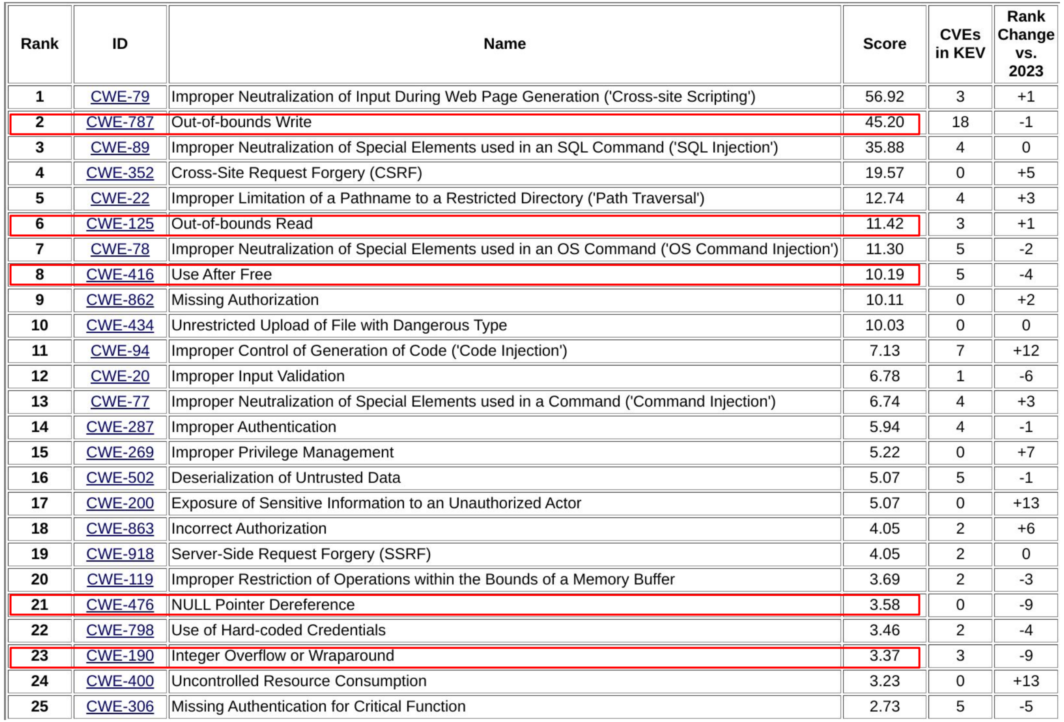
- https://cwe.mitre.org/top25/



Rank	ID	Name	Score	CVEs in KEV	Rank Change vs. 2023
1	CWE-79	Improper Neutralization of Input During Web Page Generation ('Cross-site Scripting')	56.92	3	+1
2	CWE-787	Out-of-bounds Write	45.20	18	-1
3	CWE-89	Improper Neutralization of Special Elements used in an SQL Command ('SQL Injection')	35.88	4	0
4	CWE-352	Cross-Site Request Forgery (CSRF)	19.57	0	+5
5	CWE-22	Improper Limitation of a Pathname to a Restricted Directory ('Path Traversal')	12.74	4	+3
6	CWE-125	Out-of-bounds Read	11.42	3	+1
7	CWE-78	Improper Neutralization of Special Elements used in an OS Command ('OS Command Injection')	11.30	5	-2
8	CWE-416	Use After Free	10.19	5	-4
9	CWE-862	Missing Authorization	10.11	0	+2
10	CWE-434	Unrestricted Upload of File with Dangerous Type	10.03	0	0
11	CWE-94	Improper Control of Generation of Code ('Code Injection')	7.13	7	+12
12	CWE-20	Improper Input Validation	6.78	1	-6
13	CWE-77	Improper Neutralization of Special Elements used in a Command ('Command Injection')	6.74	4	+3
14	CWE-287	Improper Authentication	5.94	4	-1
15	CWE-269	Improper Privilege Management	5.22	0	+7
16	CWE-502	Deserialization of Untrusted Data	5.07	5	-1
17	CWE-200	Exposure of Sensitive Information to an Unauthorized Actor	5.07	0	+13
18	CWE-863	Incorrect Authorization	4.05	2	+6
19	CWE-918	Server-Side Request Forgery (SSRF)	4.05	2	0
20	CWE-119	Improper Restriction of Operations within the Bounds of a Memory Buffer	3.69	2	-3
21	CWE-476	NULL Pointer Dereference	3.58	0	-9
22	CWE-798	Use of Hard-coded Credentials	3.46	2	-4
23	CWE-190	Integer Overflow or Wraparound	3.37	3	-9
24	CWE-400	Uncontrolled Resource Consumption	3.23	0	+13
25	CWE-306	Missing Authentication for Critical Function	2.73	5	-5

Common pitfalls in C++

- https://cwe.mitre.org/top25/



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Common pitfalls in C++

```cpp
template<typename T>
std::expected<T, std::string_view> fromBlob(std::span<const char> input, int base = 10)
{
  T result;
  auto [_, ec] = std::from_chars(input.data(), input.data() + input.size(), result, base);

  if (ec ≠ std::errc()) {
    return std::unexpected{"failed to parse"};
  }

  return result;
}
```

Common pitfalls in C++

```cpp
template<typename T>
std::expected<T, std::string_view> fromBlob(std::span<const char> input, int base = 10)
{
  T result;
  auto [_, ec] = std::from_chars(input.data(), input.data() + input.size(), result, base);

  if (ec != std::errc()) {
    return std::unexpected{
        std::format("failed to parse, error: {}", static_cast<int>(ec))};
  }

  return result;
}
```

Common pitfalls in C++

```cpp
TEST_CASE("valid-input") {
  const auto r = fromBlob<int>(std::string_view{"10"});
  REQUIRE(r.has_value());
  REQUIRE(*r == 10);
}

TEST_CASE("invalid-input") {
  const auto r = fromBlob<int>(std::string_view{"ups"});
  REQUIRE(r.has_value() == false);
  REQUIRE(r.error().ends_with("error: 22"));
}
```

Common pitfalls in C++

```
Test #1: from-blob:valid-input ..............   Passed
Test #2: from-blob:invalid-input ............   Passed
Test #3: production .........................   Failed
```

Common pitfalls in C++

```cpp
template<typename T>
std::expected<T, std::string_view> fromBlob(std::span<const char> input, int base = 10)
{
  T result;
  auto [_, ec] = std::from_chars(input.data(), input.data() + input.size(), result, base);

  if (ec != std::errc()) {
    return std::unexpected{
        std::format("failed to parse, error: {}", static_cast<int>(ec))};
  }

  return result;
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{
  T result;
  auto [_, ec] = std::from_chars(input.data(), input.data() + input.size(), result, base);

  if (ec != std::errc()) {
    return std::unexpected{
        std::format("failed to parse, error: {}", static_cast<int>(ec))};
  }

  return result;
}
```

Common pitfalls in C++ - Use after free

```
template<typename T>
std::expected<T, std::string_view> fromBlob(std::span<const char> input, int base = 10)
{
  T result;
  auto [_, ec] = std::from_chars(input.data(), input.data() + input.size(), result, base);

  if (ec != std::errc()) {
    return std::unexpected{
        std::format("failed to parse, error: {}", static_cast<int>(ec))};
  }

  return result;
}
```

Common pitfalls in C++

```
template<typename T>
std::expected<T, std::string_view> fromBlob(std::span<const char> input, int base = 10)
{
  T result;
  auto [_, ec] = std::from_chars(input.data(), input.data() + input.size(), result, base);

  if (ec != std::errc()) {
    return std::unexpected{
        std::format("failed to parse, error: {}", static_cast<int>(ec))};
  }

  return result;
}
```

Common pitfalls in C++

```
template<typename T>
std::expected<T, std::errc> fromBlob(std::span<const char> input, int base = 10)
{
  T result;
  auto [_, ec] = std::from_chars(input.data(), input.data() + input.size(), result, base);

  if (ec ≠ std::errc()) {
    return std::unexpected{ec};
  }

  return result;
}
```

Common pitfalls in C++

```
Test #1: from-blob:valid-input ..............   Passed
Test #2: from-blob:invalid-input ............   Passed
Test #3: production .........................   Passed
```

Common pitfalls in C++

```
std::expected<Header, std::string> parseHeader(std::span<std::string_view> input)
{
  ...

  const auto version = fromBlob<uint32_t>(input[1]);
  if (*version > 2)
  {
    ...
  }

  ...
  return header;
}
```

Common pitfalls in C++

```
Test #1: parse-header:version-1 .............   Passed
Test #2: parse-header:version-2 .............   Passed
Test #3: production .........................   Failed
```

Common pitfalls in C++

```
std::expected<Header, std::string> parseHeader(std::span<std::string_view> input)
{
  ...

  const auto version = fromBlob<uint32_t>(input[1]);
  if (*version > 2)
  {
    ...
  }

  ...
  return header;
}
```

Common pitfalls in C++

```
std::expected<Header, std::string> parseHeader(std::span<std::string_view> input)
{
  ...

  const auto version = fromBlob<uint32_t>(input[1]);
  if (*version > 2)
  {
    ...
  }


  ...
  return header;
}
```

Common pitfalls in C++

```
std::expected<Header, std::string> parseHeader(std::span<std::string_view> input)
{
  ...

  const auto version = fromBlob<uint32_t>(input[1]); // input[1] = "<!,>"
  if (*version > 2) // version = 22
  {
    ...
  }


  ...
  return header;
}
```

Common pitfalls in C++ - Dereference without check

```
std::expected<Header, std::string> parseHeader(std::span<std::string_view> input)
{
  ...

  const auto version = fromBlob<uint32_t>(input[1]); // input[1] = "<!,>"
  if (*version > 2) // version = 22
  {
    ...
  }


  ...
  return header;
}
```

Common pitfalls in C++

```cpp
std::expected<Header, std::string> parseHeader(std::span<std::string_view> input)
{
  ...

  const auto version = fromBlob<uint32_t>(input[1])
  if (!version.has_value()) {
    return std::unexpected{...};
  }

  if (*version > 2) { ... }

  ...
  return header;
}
```

Common pitfalls in C++

```
Test #1: parse-header:version-1 .............   Passed
Test #2: parse-header:version-2 .............   Passed
Test #3: parse-header:invalid-version........   Passed
Test #4: production .........................   Failed
```

Common pitfalls in C++

```
std::expected<Header, std::string> parseHeader(std::span<std::string_view> input)
{
  ...

  const auto version = fromBlob<uint32_t>(input[1])
  if (!version.has_value()) {
    return std::unexpected{...};
  }

  if (*version > 2) { ... }

  ...
  return header;
}
```

Common pitfalls in C++

```
std::expected<Header, std::string> parseHeader(std::span<std::string_view> input)
{
  ...

  const auto version = fromBlob<uint32_t>(input[1])
  if (!version.has_value()) {
    return std::unexpected{...};
  }

  if (*version > 2) { ... }

  ...
  return header;
}
```

Common pitfalls in C++ - Out of bound read

```
std::expected<Header, std::string> parseHeader(std::span<std::string_view> input)
{
  ...

  const auto version = fromBlob<uint32_t>(input[1])
  if (!version.has_value()) {
    return std::unexpected{...};
  }

  if (*version > 2) { ... }

  ...
  return header;
}
```

Common pitfalls in C++

```
bool Settings::load(const File &file)
{

  ...

}
```

Common pitfalls in C++

```
50:     bool Settings::load(const File &file)
        {

          ...

550:    }
```

Common pitfalls in C++

```
bool Settings::load(const File &file)
{
  ...

  char *someBuffer = (char *)malloc(MaxBufferBytes);


  ...
}
```

Common pitfalls in C++

```
50:    bool Settings::load(const File &file)
       {
         ...

90:      char *someBuffer = (char *)malloc(MaxBufferBytes);

         ...

546:     free(someBuffer);

         ...
550:   }
```

Common pitfalls in C++

```
50:    bool Settings::load(const File &file)
       {
         ...

90:      char *someBuffer = (char *)malloc(MaxBufferBytes);

         ...

250:     if (...) return false;

         ...

546:     free(someBuffer);

         ...
550:   }
```

Common pitfalls in C++

```
50:     bool Settings::load(const File &file)
        {
          ...

90:       char *someBuffer = (char *)malloc(MaxBufferBytes);

          ...

250:      if (...) return false;

          ...

546:      free(someBuffer);

          ...
550:    }
```

Common pitfalls in C++ - Memory leak

```
50:     bool Settings::load(const File &file)
        {
          ...

90:       char *someBuffer = (char *)malloc(MaxBufferBytes);

          ...

250:      if (...) return false;

          ...

546:      free(someBuffer);

          ...
550:    }
```

Common pitfalls in C++ - Reports

- Microsoft ~70% of common vulnerabilities are due to memory safety
- Google's Project Zero team 67% percent of zero-day vulnerabilities in 2021 were memory corruption

How to prevent such issues?

Traditional Solutions

- Static analyzers - detects issues **before execution**
- Sanitizers - detects issues **during execution**

Static analyzers - Overview

- Mostly detects **semantic** issues
- Might generate some **false positives**
- Usually **limited** to a translation unit
- Limited to **predefined** rules
- Does not detect **concurrency** issues
- Increase **build time***

Static analyzers - Tools

3rd-party tools:

- cppcheck
- clang-tidy
- SonarQube
- ...

Builtin:

- gcc -fanalyzer
- clang --analyze
- msvc /analyze

Static analyzers - Integration

```
set(CMAKE_CXX_CPPCHECK cppcheck --enable=all)
set(CMAKE_CXX_CLANG_TIDY clang-tidy
  -checks=-*,clang-analyzer-*,bugprone-*,cppcoreguidelines-*
)

target_compile_options(<target>
  PRIVATE
    $<$<CXX_COMPILER_ID:MSVC>:/analyze>
    $<$<CXX_COMPILER_ID:GNU>:-fanalyzer>
    $<$<CXX_COMPILER_ID:Clang>:--analyze>
)
```

Static analyzers - Case studies

```
Test #1: use-after-free ........................   Passed
Test #2: dereference ...........................   Passed
Test #3: out-of-bound ..........................   Passed
Test #4: memory-leak  ..........................   Failed
```

Sanitizers - Overview

- **0** false positives
- You need to **compile** in a special mode and **run**
  - You need a good test coverage
  - Not available on all platforms (Bare Metal, Embedded*, Windows*)
- Runtime overhead
  - performance from **2x** to **10x**
  - memory usage **2x**
- Increase build time and binary size
- Sometimes hard to read reports*

Sanitizers - Tools

- AddressSanitizer (ASan)
  - detecets addressability issues
- LeakSanitizer (LSan)
  - detects memory leaks
- ThreadSanitizer (TSan)
  - detects data races and deadlocks
- MemorySanitizer (MSan)
  - detects use of uninitialized memory
- UndefinedBehaviorSanitizer (UBSan)
  - detects undefined behavior

Sanitizers - Integration

```
# CMakeLists.txt

target_compile_options(<target>
  PRIVATE
    $<$<CXX_COMPILER_ID:MSVC>:/fsanitize=address>
    $<$<CXX_COMPILER_ID:GNU,Clang>:-fsanitize=address>
)

target_link_options(<target>
  PRIVATE
    $<$<CXX_COMPILER_ID:MSVC>:/fsanitize=address>
    $<$<CXX_COMPILER_ID:GNU,Clang>:-fsanitize=address>
)
```

Sanitizers - Case study

```
Test #1: use-after-free ........................   Failed
Test #2: memory-leak  ..........................   Failed
Test #3: parse-header:version-1 ................   Passed
Test #4: parse-header:version-2 ................   Passed
Test #5: parse-header-dereference:invalid-version  Failed
Test #6: parse-header-out-of-bound:invalid-input   Failed
```

Traditional Solutions - Summary

- Static analyzers - are good for checking semantics
- Sanitizers - actually detects errors
- Increase build time*
- Runtime overhead
- Not enabled by default
- Requires configuration

What else can we do?

constexpr ALL THE THINGS!

BEN DEANE / bdeane@blizzard.com / @ben_deane

JASON TURNER / jason@emptycrate.com / @lefticus

CPPCON / MONDAY 25TH SEPTEMBER 2017

1 / 106

8 years later

`constexpr` ~~all the things~~

most of the things

constexpr - C++11

Language features:

- `constexpr` - specifies that the value of a variable or function can appear in `constant expressions`
- `constant expressions` `[5.19]` is a core constant expression unless:
  - …
  - **an operation that would have undefined behavior**
  - …

Library features:

constexpr - C++11

```cpp
constexpr int fibonacci(int n, int a = 0, b = 1) {
  return n == 0 ? a : fibonacci(n - 1, b, a + b);
}


int main() {
  constexpr int fib10 = fibonacci(10);
  std::cout << fib10 << std::endl;
}
```

constexpr - C++11

```cpp
constexpr int fibonacci(int n, int a = 0, b = 1) {
  return n == 0 ? a : fibonacci(n - 1, b, a + b);
}


int main() {
  constexpr int fib10 = fibonacci(10);
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}
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constexpr - C++11

```
constexpr int fibonacci(int n, int a = 0, b = 1) {
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int main() {
  constexpr int fib10 = fibonacci(10);
  std::cout << fib10 << std::endl;
}
```

constexpr - C++11

```cpp
constexpr int fibonacci(int n, int a = 0, b = 1) {
  return n == 0 ? a : fibonacci(n - 1, b, a + b);
}


int main() {
  std::cout << 55 << std::endl;
}
```

constexpr - C++11

```cpp
constexpr int fibonacci(int n, int a = 0, b = 1) {
  return n == 0 ? a : fibonacci(n - 1, b, a + b);
}


int main() {
  constexpr int fib10 = fibonacci(10);
  std::cout << fib10 << std::endl;
}
```

constexpr - C++11

```cpp
constexpr int fibonacci(int n, int a = 0, b = 1) {
  return n == 0 ? a : fibonacci(n - 1, b, a + b);
}


int main() {
  constexpr int fib47 = fibonacci(47);
  std::cout << fib47 << std::endl;
}
```

constexpr - C++11

```
constexpr int fibonacci(int n, int a = 0, b = 1) {
  return n == 0 ? a : fibonacci(n - 1, b, a + b);
}


int main() {
  constexpr int fib47 = fibonacci(47);
  std::cout << fib47 << std::endl;
}
```

```
main.cpp:11 error: constexpr variable 'fib47' must be initialized by a constant
expression
  constexpr auto fib47 = fibonacci(47);
```

constexpr - C++11

```
constexpr int fibonacci(int n, int a = 0, b = 1) {
  return n == 0 ? a : fibonacci(n - 1, b, a + b);
}


int main() {
  constexpr int fib47 = fibonacci(47);
  std::cout << fib47 << std::endl;
}
```

```
main.cpp:11 error: constexpr variable 'fib47' must be initialized by a constant
expression
  constexpr auto fib47 = fibonacci(47);

main.cpp:6 note: value 2971215073 is outside the range of representable values of
type 'int'
```

constexpr - C++14

Language features:

- More complex expressions allowed: `if/else, for, while, do-while`
- Mutable variables: local variables declared inside constexpr functions

Library features:

- `<complex>`
- `<chrono>`
- `<utility>`
- `std::array*`
- `std::tuple*`

constexpr - C++14

```cpp
constexpr int fibonacci(int n) {
  if (n <= 1) return n;

  int a = 0, b = 1;
  for (int i = 2; i <= n; ++i) {
    int temp = a + b;
    a = b;
    b = temp;
  }
  return b;
}

int main() {
  constexpr int fib10 = fibonacci(10);
  std::cout << fib10 << std::endl;
}
```

constexpr - C++14

```
constexpr int fibonacci(int n) {
  if (n <= 1) return n;

  int a = 0, b = 1;
  for (int i = 2; i <= n; ++i) {
    int temp = a + b;
    a = b;
    b = temp;
  }
  return b;
}

int main() {
  constexpr int fib10 = fibonacci(10);
  std::cout << fib10 << std::endl;
}
```

constexpr - C++14

```cpp
constexpr int fibonacci(int n) {
  if (n <= 1) return n;

  int a = 0, b = 1;
  for (int i = 2; i <= n; ++i) {
    int temp = a + b;
    a = b;
    b = temp;
  }
  return b;
}

int main() {
  std::cout << 55 << std::endl;
}
```

constexpr - C++17

Language features:

- `constexpr` lambda
- `if constexpr`

Library features:

- `std::string_view`
- `std::char_traits`
- `std::chrono::duration*, time_point*`
- `std::atomic<T>::is_always_lock_free`
- `std::addressof`
- `std::reverse_iterator`
- `std::move_iterator`
- `std::array::(c|r)begin, (c|r)end`

constexpr - C++17

```
int main() {
  auto max = [] (int a, int b) {
    if (a > b) {
      return a;
    }

    return b;
  };

  constexpr auto m = max(100, 50);
  std::cout << m << std::endl;
}
```

constexpr - C++17

```cpp
int main() {
  auto max = [] (int a, int b) constexpr {
    if (a > b) {
      return a;
    }

    return b;
  };

  constexpr auto m = max(100, 50);
  std::cout << m << std::endl;
}
```

constexpr - C++17

```cpp
int main() {
  constexpr auto max = [] (int a, int b) {
    if (a > b) {
      return a;
    }

    return b;
  };

  constexpr auto m = max(100, 50);
  std::cout << m << std::endl;
}
```

constexpr - C++17

```cpp
int main() {
  constexpr auto max = [] (int a, int b) {
    if (a > b) {
      return a;
    }

    return b;
  };

  constexpr auto m = max(100, 50);
  std::cout << m << std::endl;
}
```

constexpr - C++17

```
int main() {
  constexpr auto max = [] (int a, int b) {
    if (a > b) {
      return a;
    }

    return b;
  };

  std::cout << 100 << std::endl;
}
```

constexpr - C++17

```cpp
template<typename T, typename ... Ts>
constexpr int sum(T t, Ts ... ts) {
  if constexpr (sizeof...(Ts) == 0) {
    return t;
  } else {
    return t + sum(ts...);
  }
}


int main() {
  constexpr int value = sum(1, 2, 3, 4, 5);
  std::cout << value << std::endl;
}
```

constexpr - C++17

```
template<typename T, typename ... Ts>
constexpr int sum(T t, Ts ... ts) {
  if constexpr (sizeof...(Ts) == 0) {
    return t;
  } else {
    return t + sum(ts...);
  }
}


int main() {
  constexpr int value = sum(1, 2, 3, 4, 5);
  std::cout << value << std::endl;
}
```

constexpr - C++17

```cpp
template<typename T, typename ... Ts>
constexpr int sum(T t, Ts ... ts) {
  if constexpr (sizeof...(Ts) == 0) {
    return t;
  } else {
    return t + sum(ts...);
  }
}


int main() {
  std::cout << 15 << std::endl;
}
```

constexpr - C++20

Language features:

- `consteval`
- `constinit`
- `new/delete`
- `try-catch`
- `virtual` functions
- changing the active member of a `union`

Library features:

- `std::vector`
- `std::string`
- `std::optional`
- `std::variant`
- `std::allocator`
- `std::swap`
- `std::source_location`
- `std::ranges`
- `std::invoke`
- `std::is_constant_evaluated`
- `<algorithm/complex*/numeric>`

constexpr - C++20

```
constexpr auto sort(std::integral auto ... values) {
  std::vector v{values...};
  std::ranges::sort(v);
  return v;
}

int main() {
  constexpr auto result = sort(4, 3, 2, 1);
  return result[0];
}
```

constexpr - C++20

```
constexpr auto sort(std::integral auto ... values) {
  std::vector v{values...};
  std::ranges::sort(v);
  return v;
}

int main() {
  constexpr auto result = sort(4, 3, 2, 1);
  return result[0];
}
```

```
main.cpp:9 error: 'result' is not a constant expression because it refers to a
result of ‘operator new’
```

constexpr - C++20

```
constexpr auto sort(std::integral auto ... values) {
  std::vector v{values...};
  std::ranges::sort(v);
  return v;
}

int main() {
  constexpr auto result = sort(4, 3, 2, 1);
  return result[0];
}
```

```
main.cpp:9 error: 'result' is not a constant expression because it refers to a
result of ‘operator new’
```

constexpr - C++20

```
constexpr auto sort(std::integral auto ... values) {
  std::vector v{values...};
  std::ranges::sort(v);
  return v;
}

int main() {
  return []() consteval {
    auto result = sort(4, 3, 2, 1);
    return result[0];
  }();
}
```

constexpr - C++20

```
constexpr auto sort(std::integral auto ... values) {
  std::vector v{values...};
  std::ranges::sort(v);
  return v;
}

int main() {
  return []() consteval {
    auto result = sort(4, 3, 2, 1);
    return result[0];
  }();
}
```

constexpr - C++20

```
constexpr auto sort(std::integral auto ... values) {
  std::vector v{values...};
  std::ranges::sort(v);
  return v;
}

int main() {
  return 1;
}
```

constexpr - C++23

Language features:

- Permitting `static constexpr` variables in constexpr functions
- `if consteval`
- Non-literal variables (and labels and gotos) in constexpr
- Relaxing some constexpr restrictions

Library features:

- `std::unique_ptr`
- `std::bitset`
- `std::to_char<int>`
- `std::from_chars<int>`
- `std::type_info::operator==()`
- `<cstdlib>*`
- `<cmath>*`

constexpr - C++23

```cpp
constexpr auto sort(std::integral auto ... values) {
  std::vector v{values...};
  std::ranges::sort(v);
  return v;
}

int main() {
  constexpr auto result = sort(4, 3, 2, 1); // error: is not a constant expression…
  return result[0];
}
```

constexpr - C++23

```cpp
template<auto Builder>
consteval auto sort() {
  static constexpr auto s = [] {
    constexpr auto size = [] { return Builder().size(); }();
    const auto v = Builder();

    std::array<typename decltype(v)::value_type, size> result{};
    std::copy(v.begin(), v.end(), result.begin());
    std::ranges::sort(result);
    return result;
  }();

  return std::span{s};
}

int main() {
  constexpr auto result = sort<[] { return std::vector{4,3,2,1}; }>();
  return result[0];
}
```

constexpr - C++23

```cpp
template<auto Builder>
consteval auto sort() {
  static constexpr auto s = [] {
    constexpr auto size = [] { return Builder().size(); }();
    const auto v = Builder();

    std::array<typename decltype(v)::value_type, size> result{};
    std::copy(v.begin(), v.end(), result.begin());
    std::ranges::sort(result);
    return result;
  }();

  return std::span{s};
}

int main() {
  constexpr auto result = sort<[] { return std::vector{4,3,2,1}; }>();
  return result[0];
}
```

constexpr - C++23

```
template<auto Builder>
consteval auto sort() {
  static constexpr auto s = [] {
    constexpr auto size = [] { return Builder().size(); }();
    const auto v = Builder();

    std::array<typename decltype(v)::value_type, size> result{};
    std::copy(v.begin(), v.end(), result.begin());
    std::ranges::sort(result);
    return result;
  }();

  return std::span{s};
}

int main() {
  constexpr auto result = sort<[] { return std::vector{4,3,2,1}; }>();
  return result[0];
}
```

constexpr - C++23

```cpp
template<auto Builder>
consteval auto sort() {
  static constexpr auto s = [] {
    constexpr auto size = [] { return Builder().size(); }();
    const auto v = Builder();

    std::array<typename decltype(v)::value_type, size> result{};
    std::copy(v.begin(), v.end(), result.begin());
    std::ranges::sort(result);
    return result;
  }();

  return std::span{s};
}

int main() {
  constexpr auto result = sort<[] { return std::vector{4,3,2,1}; }>();
  return result[0];
}
```

constexpr - C++23

```
template<auto Builder>
consteval auto sort() {
  static constexpr auto s = [] {
    constexpr auto size = [] { return Builder().size(); }();
    const auto v = Builder();

    std::array<typename decltype(v)::value_type, size> result{};
    std::copy(v.begin(), v.end(), result.begin());
    std::ranges::sort(result);
    return result;
  }();

  return std::span{s};
}

int main() {
  constexpr auto result = sort<[] { return std::vector{4,3,2,1}; }>();
  return result[0];
}
```

constexpr - C++23

```
template<auto Builder>
consteval auto sort() {
  static constexpr auto s = [] {
    constexpr auto size = [] { return Builder().size(); }();
    const auto v = Builder();

    std::array<typename decltype(v)::value_type, size> result{};
    std::copy(v.begin(), v.end(), result.begin());
    std::ranges::sort(result);
    return result;
  }();

  return std::span{s};
}

int main() {
  constexpr auto result = sort<[] { return std::vector{4,3,2,1}; }>();
  return result[0];
}
```

constexpr - C++23

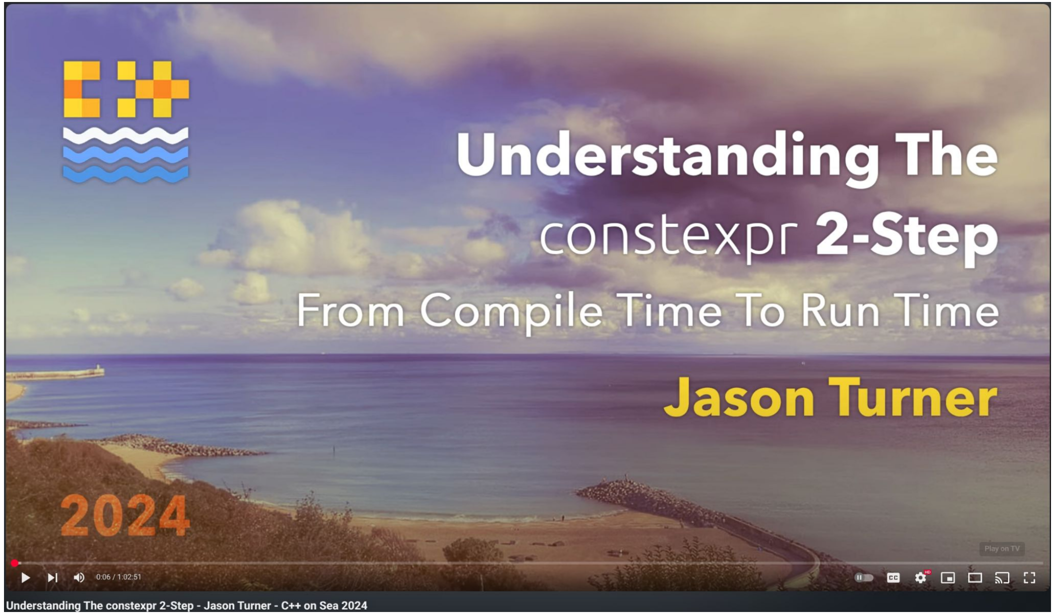
```cpp
template<auto Builder>
consteval auto sort() {
  static constexpr auto s = [] {
    constexpr auto size = [] { return Builder().size(); }();
    const auto v = Builder();

    std::array<typename decltype(v)::value_type, size> result{};
    std::copy(v.begin(), v.end(), result.begin());
    std::ranges::sort(result);
    return result;
  }();

  return std::span{s};
}

int main() {
  return 1;
}
```

constexpr - C++23



Understanding The constexpr 2-Step - Jason Turner - C++ on Sea 2024

[Understanding The constexpr 2-Step - Jason Turner - C++ on Sea 2024]

constexpr - C++26

Language features:

- cast from `void*`
- placement new
- structured bindings and references to constexpr variables
- `constexpr` exceptions
- user-generated `static_assert` messages

Library features:

- `std::stable_sort`
- `std::atomic`
- `std::inplace_vector`
- `std::bad_alloc, bad_cast`
- `<cmath>*`
- `<complex>*`

constexpr - C++26

```cpp
static_assert(false, std::format("The answer is {}.", 42));
```

```
error: call to non-‘constexpr’ function ‘std::string std::format’
```

C++26 - `constexpr std::format` P3391R1 - 🤞

constexpr - C++26

```
static_assert(false, std::format("The answer is {}.", 42)); // with P3391R1
```

constexpr - C++26

```
static_assert(false, std::format("The answer is {}.", 42)); // with P3391R1
```

```
error: static assertion failed: The answer is 42.
```

constexpr - C++26

```cpp
consteval auto parse(std::string_view input) {
  if (input.empty()) {
    throw stdx::format("invalid input = {}", input);
  }

  return 10;
}

int main() {
  constexpr auto r = parse("");
  return r;
}
```

constexpr - C++26

```cpp
consteval auto parse(std::string_view input) {
  if (input.empty()) {
    throw stdx::format("invalid input = {}", input);
  }

  return 10;
}

int main() {
  constexpr auto r = parse(""); // compile time error: invalid input = ''
  return r;
}
```

Let’s sprinkle some `constexpr`

constexpr - Case study - Use after free

```
template<typename T>
std::expected<T, std::string_view> fromBlob(std::span<const char> input, int base = 10)
{
  T result;
  auto [_, ec] = std::from_chars(input.data(), input.data() + input.size(), result, base);

  if (ec ≠ std::errc()) {
    return std::unexpected{std::format("failed to parse, error: {}", static_cast<int>(ec))};
  }

  return result;
}
```

constexpr - Case study - Use after free

```
template<typename T>
constexpr std::expected<T, std::string_view> fromBlob(std::span<const char> input, int base = 10)
{
  T result;
  auto [_, ec] = std::from_chars(input.data(), input.data() + input.size(), result, base);

  if (ec != std::errc()) {
    return std::unexpected{std::format("failed to parse, error: {}", static_cast<int>(ec))};
  }

  return result;
}
```

constexpr - Case study - Use after free

```
TEST_CASE("valid-input") {
  const auto r = fromBlob<int>(std::string_view{"10"});
  REQUIRE(r.has_value());
  REQUIRE(*r == 10);
}

TEST_CASE("invalid-input") {
  const auto r = fromBlob<int>(std::string_view{"ups"});
  REQUIRE(r.has_value() == false);
  REQUIRE(r.error().ends_with("error: 22"));
}
```

constexpr - Case study - Use after free

```
TEST_CASE("valid-input") {
  constexpr auto r = fromBlob<int>(std::string_view{"10"});
  REQUIRE(r.has_value());
  REQUIRE(*r == 10);
}

TEST_CASE("invalid-input") {
  constexpr auto r = fromBlob<int>(std::string_view{"ups"});
  REQUIRE(r.has_value() == false);
  REQUIRE(r.error().ends_with("error: 22"));
}
```

constexpr - Case study - Use after free

```
TEST_CASE("valid-input") {
  constexpr auto r = fromBlob<int>(std::string_view{"10"});
  STATIC_REQUIRE(r.has_value());
  STATIC_REQUIRE(*r == 10);
}

TEST_CASE("invalid-input") {
  constexpr auto r = fromBlob<int>(std::string_view{"ups"});
  STATIC_REQUIRE(r.has_value() == false);
  STATIC_REQUIRE(r.error().ends_with("error: 22"));
}
```

constexpr - Case study - Use after free

```
Test #1: from-blob:valid-input ..............   Failed
Test #2: from-blob:invalid-input ............   Failed
```

```
error: call to non-‘constexpr’ function ‘std::string std::format’
```

constexpr - Case study - Use after free

```
Test #1: from-blob:valid-input ..............   Failed
Test #2: from-blob:invalid-input ............   Failed
```

```
error: call to non-‘constexpr’ function ‘std::string std::format’
```

- C++26 - constexpr std::format P3391R1 - 🤞

constexpr - Case study - Use after free

```cpp
template<typename T>
std::expected<T, std::string_view> fromBlob(std::span<const char> input, int base = 10)
{
  T result;
  auto [_, ec] = std::from_chars(input.data(), input.data() + input.size(), result, base);

  if (ec != std::errc()) {
    return std::unexpected{
        std::format("failed to parse, error: {}", static_cast<int>(ec))};
  }

  return result;
}
```

constexpr - Case study - Use after free

```
template<typename T>
std::expected<T, std::string_view> fromBlob(std::span<const char> input, int base = 10)
{
  T result;
  auto [_, ec] = std::from_chars(input.data(), input.data() + input.size(), result, base);

  if (ec != std::errc()) {
    return std::unexpected{
        stdx::format("failed to parse, error: {}", static_cast<int>(ec))};
  }

  return result;
}
```

constexpr - Case study - Use after free

```
Test #1: from-blob:valid-input ..............   Passed
Test #2: from-blob:invalid-input ............   Failed
```

constexpr - Case study - Use after free

```
Test #1: from-blob:valid-input ..............   Passed
Test #2: from-blob:invalid-input ............   Failed
```

```
test.cpp:41:22: error: constexpr variable 'r' must be initialized by a constant
expression
     constexpr auto r = fromBlob<int>(std::string_view{"ups"});
test.cpp:41:22: note: pointer to subobject of temporary is not a constant expression
test.cpp:28:12: note: temporary created here
     return std::unexpected{std::string{"failed to parse"}};
```

constexpr - Case study - Dereference without check

```
template<typename T>
constexpr std::expected<T, std::errc> fromBlob(std::span<const char> input, int base = 10)
{
  T result;
  auto [_, ec] = std::from_chars(input.data(), input.data() + input.size(), result, base);

  if (ec != std::errc()) {
    return std::unexpected{ec};
  }

  return result;
}
```

constexpr - Case study - Dereference without check

```
constexpr std::expected<Header, std::string> parseHeader(std::span<std::string_view> input)
{
  ...

  const auto version = fromBlob<uint32_t>(input[1]);
  if (*version > 2)
  {
    ...
  }


  ...
  return header;
}
```

constexpr - Case study - Dereference without check

```
TEST_CASE("invalid-version") {
  constexpr std::array input = {
    std::string_view{"0011"},
    std::string_view{"<!.>"},
  };

  constexpr auto h = parseHeader(input);
  ...
}
```

constexpr - Case study - Dereference without check

```
Test #1: parse-header:version-1 .............   Passed
Test #2: parse-header:version-2 .............   Passed
Test #3: parse-header:invalid-version........   Failed
```

constexpr - Case study - Dereference without check

```
Test #1: parse-header:version-1 .............   Passed
Test #2: parse-header:version-2 .............   Passed
Test #3: parse-header:invalid-version........   Failed
```

```
test.cpp:41:22: error: constexpr variable 'h' must be initialized by a constant
expression
     constexpr auto h = parseHeader(input);
test.cpp:41:22: error: accessing std::expected<...>::value instead of initialized
std::expected<...>::error
```

constexpr - Case study - Out of bound read

```
constexpr std::expected<Header, std::string> parseHeader(std::span<std::string_view> input)
{
  ...

  const auto version = fromBlob<uint32_t>(input[1]).value_or(0);
  if (version > 2) {
    ...
  }


  ...
  return header;
}
```

constexpr - Case study - Out of bound read

```
TEST_CASE("invalid-input") {
  constexpr std::array input = {
    std::string_view{"0011"},
  };

  constexpr auto h = parseHeader(input);
  ...
}
```

constexpr - Case study - Out of bound read

```
Test #1: parse-header:invalid-version........   Passed
Test #2: parse-header:invalid-input..........   Failed
```

constexpr - Case study - Out of bound read

```
Test #1: parse-header:invalid-version........   Passed
Test #2: parse-header:invalid-input..........   Failed
```

```
test.cpp:41:22: error: constexpr variable 'h' must be initialized by a constant
expression
     constexpr auto h = parseHeader(input);
test.cpp:41:22:    in ‘constexpr’ expansion of ‘input.std::span<const
std::basic_string_view<char> >::operator[](1)’
test.cpp:41:22: error: array subscript value ‘1’ is outside the bound
```

constexpr - Case study - Memory leak

```
bool Settings::load(const File &file)
{
  ...

  char *someBuffer = (char *)malloc(MaxBufferBytes);

  ...

  if (...) return false;

  ...

  free(someBuffer);

  ...
}
```

constexpr - Case study - Memory leak

```
constexpr bool Settings::load(const File &file)
{
  ...

  char *someBuffer = (char *)malloc(MaxBufferBytes);

  ...

  if (...) return false;

  ...

  free(someBuffer);

  ...
}
```

constexpr - Case study - Memory leak

```
Test #1: settings-load:valid-input ..........   Failed
```

```
error: call to non-‘constexpr’ function ‘File::read’
error: call to non-‘constexpr’ function ‘malloc’
error: call to non-‘constexpr’ function ‘free’
```

constexpr - Case study - Memory leak

```
constexpr bool Settings::load(const File &file)
{
  ...

  char *someBuffer = (char *)malloc(MaxBufferBytes);

  ...

  if (...) return false;

  ...

  free(someBuffer);

  ...
}
```

constexpr - Case study - Memory leak

```
constexpr bool Settings::load(const IFile &file)
{
  ...

  char *someBuffer = (char *)malloc(MaxBufferBytes);

  ...

  if (...) return false;

  ...

  free(someBuffer);

  ...
}
```

constexpr - Case study - Memory leak

```
constexpr bool Settings::load(const IFile &file)
{
    ...

    char *someBuffer = (char *)malloc(MaxBufferBytes);

    ...

    if (...) return false;

    ...

    free(someBuffer);

    ...
}
```

constexpr - Case study - Memory leak

```cpp
constexpr bool Settings::load(const IFile &file)
{
  ...

  auto someBuffer = new char[MaxBufferBytes];

  ...

  if (...) return false;

  ...

  delete someBuffer;

  ...
}
```

constexpr - Case study - Memory leak

```
Test #1: settings-load:valid-input ..........   Passed
Test #2: settings-load:new-condition ........   Failed
```

constexpr - Case study - Memory leak

```
Test #1: settings-load:valid-input ..........   Passed
Test #2: settings-load:new-condition ........   Failed
```

```
test.cpp:90:22: error: is not a constant expression because allocated storage has
not been deallocated
      auto someBuffer = new char[MaxBufferBytes];
```

constexpr - Case study - Memory leak

```
Test #1: settings-load:valid-input ..........   Passed
Test #2: settings-load:new-condition ........   Failed
```

```
test.cpp:90:22: error: is not a constant expression because allocated storage has
not been deallocated
      auto someBuffer = new char[MaxBufferBytes];

test.cpp:546:22: error: non-array deallocation of object allocated with array
allocation
      delete someBuffer;
```

constexpr - Case studies - Summary

- All issues have been caught at compile-time
- Works as sanitizers but at compile-time
- You need to change/split/modify code to be `constexpr` compatible.

constexpr - Limitations

- Language features
- Library features
- Ecosystem

constexpr - Limitations

Language features:

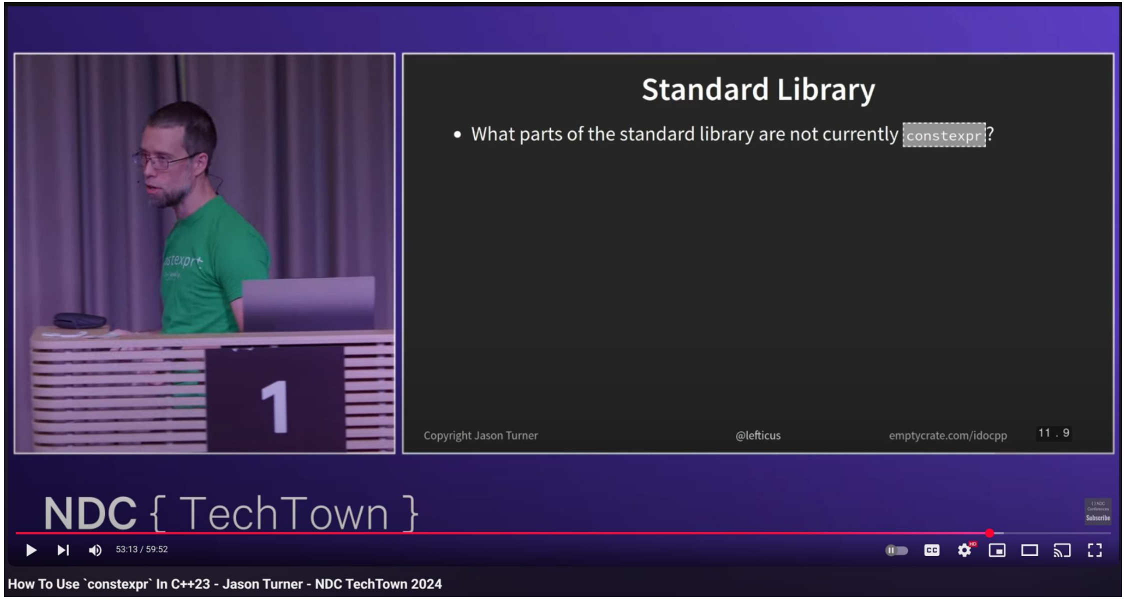
- IO
    - filesystem*
    - network
    - loggers
- threads
- coroutines
- No debugger

constexpr - Limitations

Library features:

constexpr - Limitations

Library features:



Standard Library

- What parts of the standard library are not currently `constexpr`?

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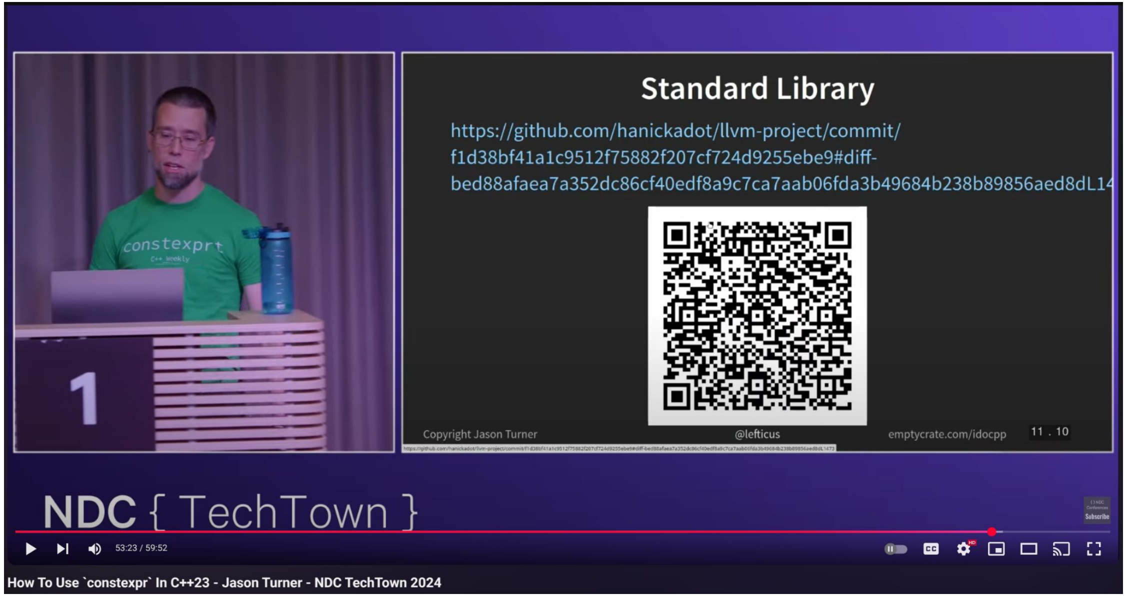
constexpr - Limitations

Library features:



Standard Library

https://github.com/hanickadot/llvm-project/commit/
f1d38bf41a1c9512f75882f207cf724d9255ebe9#diff-
bed88afaea7a352dc86cf40edf8a9c7ca7aab06fda3b49684b238b89856aed8dL14

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[How To Use `constexpr` In C++23 - Jason Turner - NDC TechTown 2024]

constexpr - Limitations

Library features:

- Hana Dusíková - libc++ missing constexpr
- P3372R2 constexpr containers and adaptors

constexpr - Limitations

Ecosystem:

- Missing `constexpr` in 3rd-party libraries
- Test frameworks integrations

Let’s push some limits

constexpr - Pushing the limits

- Language features
- Library features
- Ecosystem

constexpr - Pushing the limits

Language features

- IO
  - filesystem
  - network
  - loggers
- threads
- coroutines
- No debugger

constexpr - Pushing the limits

Language features

- IO
    - filesystem
    - ~~network~~
    - ~~loggers~~
- ~~threads~~
- ~~coroutines~~
- No debugger

constexpr - Pushing the limits

Language features

- Filesystem
- No debugger

constexpr - Pushing the limits

Language features

- Filesystem - read only
  - `#embed`
  - Build systems
- No debugger
  - Good old printfs, but `throw` instead
  - Drop constexpr and re-build in runtime mode

constexpr - Pushing the limits

Library features:

- `std::vector/std::string`
  - `std::span`
  - `gsl::span`
- `std::format`
  - `fmt::format`
- If no replacement
  - fork/copy
    - sprinkle `constexpr`
    - send a pull request (if possible)

constexpr - Pushing the limits

```
static_assert(false, std::format("The answer is {}.", 42));
```

```
error: call to non-‘constexpr’ function ‘std::string std::format’
```

constexpr - Pushing the limits

```
namespace stdx {

consteval std::string format(auto fmt, auto&&... args) {
  std::string text;
  fmt::format_to(std::back_inserter(text), fmt,
                 std::forward<decltype(args)>(args)...);
  return text;
};

} // namespace stdx

static_assert(false, stdx::format(FMT_COMPILE("The answer is {}."), 42));
```

constexpr - Pushing the limits

```
namespace stdx {

consteval std::string format(auto fmt, auto&&... args) {
  std::string text;
  fmt::format_to(std::back_inserter(text), fmt,
                 std::forward<decltype(args)>(args)...);
  return text;
};

} // namespace stdx

static_assert(false, stdx::format(FMT_COMPILE("The answer is {}."), 42));
```

```
error: static assertion failed: The answer is 42.
```

constexpr - Pushing the limits

Ecosystem:

- Missing constexpr in 3rd-party libs
  - `tl::expected` → `std::expected`
  - `range-v3` → `std::ranges`
- Test frameworks integrations

constexpr - Pushing the limits

```
TEST_CASE("...") {
  REQUIRE(10 == 9);
}
```

constexpr - Pushing the limits

```
TEST_CASE("...") {
  REQUIRE(10 == 9);
}
```

```
test.cpp:2: FAILED:  REQUIRE( 10 == 9 )
```

constexpr - Pushing the limits

```
TEST_CASE("...") {
  STATIC_REQUIRE(10 == 9);
}
```

constexpr - Pushing the limits

```
TEST_CASE("...") {
  STATIC_REQUIRE(10 == 9);
}
```

```
test.cpp:2: error:  static assertion failed: 10 == 9
```

constexpr - Pushing the limits

```
TEST_CASE("...") {
  constexpr auto result = 10 == 9;
  REQUIRE(result);
}
```

constexpr - Pushing the limits

```
TEST_CASE("...") {
  constexpr auto result = 10 == 9;
  REQUIRE(result);
}
```

```
test.cpp:2: FAILED:  REQUIRE( result )
```

constexpr - Pushing the limits

```
TEST_CASE("...") {
  std::array data = {6, 5, 4, 3};
  std::ranges::sort(data);

  REQUIRE(data[0] == 4);
}
```

constexpr - Pushing the limits

```
TEST_CASE("...") {
  std::array data = {6, 5, 4, 3};
  std::ranges::sort(data);

  REQUIRE(data[0] == 4);
}
```

```
test.cpp:5: FAILED: REQUIRE( data[0] == 4 )
with expansion:
  3 == 4
```

constexpr - Pushing the limits

```
TEST_CASE("...") {
  std::array data = {6, 5, 4, 3};
  std::ranges::sort(data);

  STATIC_REQUIRE(data[0] == 4);
}
```

constexpr - Pushing the limits

```
TEST_CASE("...") {
  std::array data = {6, 5, 4, 3};
  std::ranges::sort(data);

  STATIC_REQUIRE(data[0] == 4);
}
```

```
test.cpp:2:26: error: the value of ‘data’ is not usable in a constant expression
             : note: ‘data’ was not declared ‘constexpr’
```

constexpr - Pushing the limits

```
TEST_CASE("...") {
  constexpr std::array data = {6, 5, 4, 3};
  std::ranges::sort(data);

  STATIC_REQUIRE(data[0] == 4);
}
```

constexpr - Pushing the limits

```
TEST_CASE("...") {
  constexpr std::array data = {6, 5, 4, 3};
  std::ranges::sort(data);

  STATIC_REQUIRE(data[0] == 4);
}
```

```
test.cpp:3: error: no match for call to ‘(const std::ranges::__sort_fn) (const
std::array<int, 4>&)’
```

constexpr - Pushing the limits

```
TEST_CASE("...") {
  [] () consteval {
    std::array data = {6, 5, 4, 3};
    std::ranges::sort(data);

    STATIC_REQUIRE(data[0] == 4);
  }();

}
```

constexpr - Pushing the limits

```
TEST_CASE("...") {
  [] () consteval {
    std::array data = {6, 5, 4, 3};
    std::ranges::sort(data);

    STATIC_REQUIRE(data[0] == 4);
  }();

}
```

constexpr - Pushing the limits

```
TEST_CASE("...") {
  [] () consteval {
    std::array data = {6, 5, 4, 3};
    std::ranges::sort(data);

    STATIC_REQUIRE(data[0] == 4);
  }();

}
```

```
test.cpp:3:26: error: the value of ‘data’ is not usable in a constant expression
             : note: ‘data’ was not declared ‘constexpr’
```

constexpr - Pushing the limits

```cpp
TEST_CASE("...") {
  constexpr auto result = []() {
    std::array data = {6, 5, 4, 3};
    std::ranges::sort(data);
    return data;
  }();

  STATIC_REQUIRE(result[0] == 4);
}
```

constexpr - Pushing the limits

```
TEST_CASE("...") {
  constexpr auto result = []() {
    std::array data = {6, 5, 4, 3};
    std::ranges::sort(data);
    return data;
  }();

  STATIC_REQUIRE(result[0] == 4);
}
```

```
test.cpp:7: error:  static assertion failed: result[0] == 4
```

constexpr - Pushing the limits

```
TEST_CASE("...") {
  constexpr auto result = []() {
    std::array data = {6, 5, 4, 3};
    std::ranges::sort(data);
    return data;
  }();

  STATIC_REQUIRE(result[0] == 4);
}
```

```
test.cpp:7: error:  static assertion failed: result[0] == 4
```

constexpr - Pushing the limits

```
TEST_CASE("...") {
  constexpr auto result = []() {
    std::array data = {6, 5, 4, 3};
    std::ranges::sort(data);
    return data;
  }();

  STATIC_REQUIRE(result[0] == 4);
}
```

```
test.cpp:7: error:  static assertion failed: result[0] == 4
           : note: the comparison reduces to ‘(3 == 4)’ - only for simple types
```

constexpr - Pushing the limits

```
TEST_CASE("...") {
  constexpr auto result = []() {
    std::array data = {6, 5, 4, 3};
    std::ranges::sort(data);
    return data;
  }();

  STATIC_REQUIRE(result[0] == 4);
}
```

```
test.cpp:7: error:  static assertion failed: result[0] == 4
```

constexpr - Pushing the limits

```
TEST_CASE("...") {
  constexpr auto result = []() {
    std::array data = {6, 5, 4, 3};
    std::ranges::sort(data);
    return data;
  }();

  STATIC_REQUIRE(result[0] == 4);
}
```

```
test.cpp:7: error:  static assertion failed: (3 == 4)
```

constexpr - Pushing the limits

```
TEST_CASE("...") {
  constexpr auto result = []() {
    std::array data = {6, 5, 4, 3};
    std::ranges::sort(data);
    return data;
  }();

  static_assert(result[0] == 4, stdx::format(“{} != 4”, result[0]));
}
```

constexpr - Pushing the limits

```
TEST_CASE("...") {
  constexpr auto result = []() {
    std::array data = {6, 5, 4, 3};
    std::ranges::sort(data);
    return data;
  }();

  static_assert(result[0] == 4, stdx::format(“{} != 4”, result[0]));
}
```

```
test.cpp:7: error:  static assertion failed: (3 != 4)
```

constexpr - Pushing the limits

```
TEST_CASE("...") {
  std::array data = {6, 5, 4, 3};
  std::ranges::sort(data);

  REQUIRE(data[0] == 4);

  // other operations
  REQUIRE(...);
}
```

constexpr - Pushing the limits

```
TEST_CASE("...") {
  constexpr auto result = []() → std::expected<void, std::string> {
    std::array data = {6, 5, 4, 3};
    std::ranges::sort(data);

    if (data[0] ≠ 4) { return std::unexpected{stdx::format("{} ≠ 4", data[0])}; }
    ...
    return {};
  }();

  static_assert(result.has_value(), result.error());
}
```

constexpr - Pushing the limits

```
TEST_CASE("...") {
  constexpr auto result = []() -> std::expected<void, std::string> {
    std::array data = {6, 5, 4, 3};
    std::ranges::sort(data);

    if (data[0] != 4) { return std::unexpected{stdx::format("{} != 4", data[0])}; }
    ...
    return {};
  }();

  static_assert(result.has_value(), result.error());
}
```

```
test.cpp:11: error: ‘result’ is non-constant condition for static assertion
```

constexpr - Pushing the limits

```
TEST_CASE("...") {
  auto test_case = []() -> std::expected<void, std::string> {
    std::array data = {6, 5, 4, 3};
    std::ranges::sort(data);

    if (data[0] != 4) { return std::unexpected{stdx::format("{} != 4", data[0])}; }
    ...
    return {};
  };

  constexpr auto error = run_test_case<test_case>(); // 2-step constexpr model
  static_assert(error.empty(), error);
}
```

constexpr - Pushing the limits

```
TEST_CASE("...") {
  auto test_case = []() → std::expected<void, std::string> {
    std::array data = {6, 5, 4, 3};
    std::ranges::sort(data);

    if (data[0] ≠ 4) { return std::unexpected{stdx::format("{} ≠ 4", data[0])}; }
    ...
    return {};
  };

  constexpr auto error = run_test_case<test_case>(); // 2-step constexpr model
  static_assert(error.empty(), error);
}
```

```
test.cpp:11: error: static assertion failed: 3 ≠ 4
```

constexpr - Pushing the limits

```
TEST_CASE("...") {
  auto test_case = []() -> std::expected<void, std::string> {
    std::array data = {6, 5, 4, 3};
    std::ranges::sort(data);

    if (data[0] != 4) { return std::unexpected{stdx::format("{} != 4", data[0])}; }
    ...
    return {};
  };

  constexpr auto error = run_test_case<test_case>(); // 2-step constexpr model
  static_assert(error.empty(), error); // What if don’t have C++26
}
```

constexpr - Pushing the limits

```cpp
TEST_CASE("...") {
  auto test_case = []() -> std::expected<void, std::string> {
    std::array data = {6, 5, 4, 3};
    std::ranges::sort(data);

    if (data[0] != 4) { return std::unexpected{stdx::format("{} != 4", data[0])}; }
    ...
    return {};
  };

  constexpr auto error = run_test_case<test_case>(); // 2-step constexpr model
  static_assert(stdx::static_verify<error.empty(), error>);
}
```

constexpr - Pushing the limits

```
namespace stdx {

template <bool C, static_string msg>
concept _static_assert = C;

template <bool C, static_string msg>
concept static_verify = _static_assert<C, msg>;

} // namespace stdx
```

constexpr - Pushing the limits

```
constexpr stdx::static_string msg = "3 != 4";
static_assert(stdx::static_verify<3 == 4, msg>);

<source>:1: static assertion failed
test.cpp:1: note: because 'stdx::static_verify<3 == 4, msg>' evaluated to false
            note: because '_static_assert<false, static_string<7UL>{{"3 != 4"}}>
            msvc: because 'static_string<7UL>{char{51, 32, 33, 61, 32, 52, 0}}
```

constexpr - Pushing the limits

```
constexpr stdx::static_string msg = "3 != 4";
static_assert(stdx::static_verify<3 == 4, msg>);  // works with c++23/20

<source>:1: static assertion failed
test.cpp:1: note: because 'stdx::static_verify<3 == 4, msg>' evaluated to false
            note: because '_static_assert<false, static_string<7UL>{{"3 != 4"}}>
            msvc: because 'static_string<7UL>{char{51, 32, 33, 61, 32, 52, 0}}
```

constexpr - Pushing the limits

- boost.pfr / magic_enum / fmt
- Jason Turner constexpr
- Ben Dean
  - Formatted Diagnostics with C++20
  - Intel standard library extensions

Summary

- `constexpr` is **memory safest subset** of C++
- `constexpr` partially replaces Sanitizers (lack of concurrency support)
- `constexpr` partially replaces Static analyzers
    - does not work without tests
- `constexpr` requires adaptation (sprinkle `constexpr`)
- `constexpr` is a builtin feature which almost works out the box

Thank you!
Questions?

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