C++ 23 Language Features

Contents

[a) Core Language Features 2](#_Toc191297454)

[1. Compile-time conditional execution - if consteval 2](#_Toc191297455)

[2. Deducing this 3](#_Toc191297456)

[b) Library Features 7](#_Toc191297457)

[3. Standardized way to handle errors without exceptions - std::expected 7](#_Toc191297458)

[4. Monadic operations for std::optional, std::expected 8](#_Toc191297459)

[5. Convert ranges into containers 12](#_Toc191297460)

[6. Better support for constexpr in standard library algorithms 14](#_Toc191297461)

[7. Extended Algorithms 15](#_Toc191297462)

[8. Faster Sorted Containers - std::flat\_map and std::flat\_set 17](#_Toc191297463)

[9. Implicit move constructors 20](#_Toc191297464)

[10. The std::vector<bool> 21](#_Toc191297465)

[11. Multidimensional std::mdspan 22](#_Toc191297466)

[12. Standard Library Module 25](#_Toc191297467)

[13. The std::print 27](#_Toc191297468)

[14. The std::generator 30](#_Toc191297469)

[15. The std::stacktrace 31](#_Toc191297470)

# Core Language Features

### Compile-time conditional execution - if consteval

* C++ already has constexpr and consteval to enforce compile-time evaluation:
  + constexpr allows a function to be evaluated at compile-time or runtime.
  + consteval forces a function to be evaluated only at compile-time.
* Sometimes, you want to do optimizations or use different algorithms depending on whether a value is known at compile time. For example, if you know a value is constant, you might be able to precalculate something during compilation, making your program run faster.

#### Enter if consteval

* if consteval is a conditional statement that is evaluated at compile time. It's like a regular if statement, but the compiler checks the condition while compiling the code, not while the program is running.

|  |
| --- |
| #include <iostream>  using namespace std;  constexpr int square(int x) {  if consteval { // Compile-time calculation  return x \* x;  }  else { // Runtime calculation  return x \* x;  }  }  int main() {  // Computed at compile-time  constexpr int result1 = square(5);  cout << "Compiletime Result1: " << result1 << "\n";  int y = 6;  // Computed at runtime  int result2 = square(y);  cout << "Runtime Result2: " << result2 << "\n";  } |

### Deducing this

#### The ‘this’ pointer

* In C++, when you write a **member function** (a function that belongs to a class), the ‘this’ pointer is implicitly passed to the function. This ‘this’ pointer points to the current object instance, allowing you to access its members.

|  |
| --- |
| class MyClass {  public:  void print() {  std::cout << "Hello from MyClass!\n";  }  };  MyClass obj;  obj.print(); |

* When you call obj.print(), the this pointer inside print() points to obj.

#### The "Deducing this" feature

* The "Deducing this" feature allows you to explicitly capture the ‘this’ pointer as a parameter in a member function template.
* Before C++23, if you wanted to write a member function template that could work with different types of objects (e.g., base class or derived class), you had to rely on workarounds like Curiously Recurring Template Pattern (CRTP) or manually deducing the type. This could get messy and hard to read.

#### CRTP

* What is the CRTP?
  + The CRTP is a design pattern in C++ where a class derives from a class template, and the template argument is the class itself. It sounds a bit circular, and that's why it's called "curiously recurring."
* Why is it used?
  + The CRTP allows you to achieve static polymorphism (compile-time polymorphism). This means that the specific behaviour is determined at compile time, rather than at runtime.
* A Simple Example

|  |
| --- |
| #include <iostream>  using namespace std;  template <typename Derived>  class Base {  public:  void interface() {  static\_cast<Derived\*>(this)->implementation();  }  void implementation() {  cout << "Base implementation\n";  }  };  class Derived : public Base<Derived> {  public:  void implementation() {  cout << "Derived implementation\n";  }  };  int main() {  Derived d;  d.interface(); // Calls Derived::implementation  return 0;  }  // Derived implementation |

* Explanation:
  + template <typename Derived>: Base is a class template. The template parameter Derived is what makes this the **CRTP**.
  + class Derived:public Base<Derived>: This is the "**curiously recurring**" part. Derived inherits from Base, but the template argument to Base is Derived itself. So, Base is instantiated with Derived as its template parameter.
  + void interface(): This function is in the base class. It's the key to how the CRTP works.
  + static\_cast<Derived\*>(this): Inside interface(), we're casting this (which is a pointer to Base) to a pointer to Derived. This is safe because, in this specific CRTP usage, we know that this is actually pointing to a Derived object. This is because Derived inherits from Base<Derived>.
  + ->implementation(): After the cast, we call the implementation() function. Because of the cast, the compiler knows we are calling the implementation() function of the Derived class.
* How it works:
  + When you create a Derived object and call d.interface(), the following happens:
    - d.interface() is called. This is the interface() function in the Base<Derived> class.
    - Inside interface(), this points to the Derived object d.
    - static\_cast<Derived\*>(this) converts the Base\* to a Derived\*.
    - ->implementation() calls the implementation() function of the Derived class.

#### Coming back to ‘Deducing this’

|  |
| --- |
| #include <iostream>  using namespace std;  class Base {  public:  template <typename Self>  void print(this Self&& self) {  std::cout << "Hello from Base!\n";  }  };  class Derived : public Base {  public:  void print() {  std::cout << "Hello from Derived!\n";  }  };  int main() {  Base obj;  obj.print(); // Calls Base::print  Derived derivedObj;  derivedObj.print(); // Calls Derived::print  }  // Hello from Base!  // Hello from Derived! |

* Key Points
  + this Self&& self:
    - This is the new syntax introduced in C++23.
    - Self is a template parameter that deduces the type of the object (Base, Derived, etc.).
    - self is the explicit this pointer, which can be used to access the object's members.
  + Flexibility:
    - The print function template can now work with any type of object, including derived classes.
    - If you call print on a Derived object, Self will be deduced as Derived.
  + No More CRTP:
    - Before C++23, you might have used CRTP (Curiously Recurring Template Pattern) to achieve similar behaviour. Now, you can avoid that complexity.

#### How This Feature Helps

* Deducing this allows us to write more generic member functions.
* It enables CRTP-like behaviours without explicitly using CRTP.

# Library Features

### Standardized way to handle errors without exceptions - std::expected

#### What is std::expected?

* std::expected<T, E> is a new C++23 feature that provides a standardized way to handle errors without using exceptions.
* It’s part of the <expected> header and is designed to make error handling more explicit, predictable, and efficient.
* It is useful when a function can either:
  + Return a **valid result** (T) OR
  + Return an **error value** (E)
* Think of it as a "box" that can hold either:
  + A successful result (the value you wanted), or
  + An error (something went wrong).
* It's like std::optional<T>, but instead of just "**value** or **nothing**," it stores an error when something goes wrong.

|  |
| --- |
| #include <iostream>  #include <expected> // C++23 feature  using namespace std;  // Function that returns either a valid result (double) or  // an error message (string)  expected<double, string> divide(double a, double b) {  if (b == 0) {  // Return an error  return unexpected("Error: Division by zero!");  }  return a / b; // Return the valid result  }  int main() {  auto result = divide(10, 2); // Should return 5.0  if (result) { // Check if the operation was successful  // \*result gives the valid value  cout << "Result: " << \*result << "\n";  }  else { // Retrieve the error message  cout << result.error() << "\n";  }  // Should return an error  auto result2 = divide(10, 0);  if (result2) {  cout << "Result: " << \*result2 << "\n";  }  else {  // Prints: Error: Division by zero!  cout << result2.error() << "\n";  }  } |

### Monadic operations for std::optional, std::expected

* The meaning of Monad - a single unit; the number one.

#### What is std::optional?

* std::optional <T> is a feature from C++17 that represents a value that might be missing.
  + If it contains a value → You can access it.
  + If it doesn't → You must handle the missing case.
* Before C++23, handling std::optional required manual if checks.
* Now, C++23 introduces monadic operations (and\_then, or\_else, and transform) that make code more concise and functional.

#### Why Monadic Operations?

* These functions avoid manual if checks and allow you to chain operations smoothly, making code cleaner and more readable.

| **Monadic Function** | **Use Case** |
| --- | --- |
| and\_then(f) | Apply f **only if** optional **has a value** |
| or\_else(f) | Call f **only if** optional **is empty** |
| transform(f) | Modify the value **if present** |

#### Example 1: and\_then – Chain Dependent Operations

* If the std::optional has a value, and\_then(f) calls f and returns its result.
* If empty, it returns std::nullopt.

|  |
| --- |
| #include <iostream>  #include <optional>  #include <string>  using namespace std;  // Function that returns an optional integer  optional<int> parse\_int(const string& str) {  try {  return stoi(str);  }  catch (...) {  return nullopt;  }  }  // Function that returns an optional integer  optional<int> doubleIfPositive(int x) {  if (x > 0)  return x \* 2;  return nullopt; // No value if x is negative  }  int main() {  string number;  cout << "Enter a number: ";  cin >> number;  // Call `doubleIfPositive` only if `number` has a value  optional<int> result = parse\_int(number)  .and\_then(doubleIfPositive);  if (result) cout << "Doubled: " << \*result << "\n";  else cout << "No value\n";  }  /\*  Enter a number: 12  Doubled: 24  Enter a number: ABC  No value  \*/ |

* If number contains a value (12), doubleIfPositive(12) is called, and it returns 24.
* If number was std::nullopt, it would remain empty.

#### Example 2: or\_else – Provide a Default Value

|  |
| --- |
| #include <iostream>  #include <optional>  #include <string>  using namespace std;  // Function that returns an optional integer  optional<int> parse\_int(const string& str) {  try {  return stoi(str);  }  catch (...) {  return nullopt;  }  }  // Function returning a default value  std::optional<int> getDefaultValue() {  return 10; // Some default value  }  int main() {  string number;  cout << "Enter a number: ";  cin >> number;  // If parse\_int has a value, then assign it  // to result or else call getDefaultValue  optional<int> result = parse\_int(number)  .or\_else(getDefaultValue);  if (result)  cout << "Result: " << \*result << "\n";  else  cout << "No value\n";  }  /\*  Enter a number: 12  Result: 12  Enter a number: ABC  Doubled: 10  \*/ |

* If parse\_int returns a value after parsing, then it will assign it to result variable.
* If parse\_int returns std::nullopt then, getDefaultValue is called.

#### Example 3: transform – Modify the Value if Present

|  |
| --- |
| #include <iostream>  #include <optional>  #include <string>  using namespace std;  // Function that returns an optional integer  optional<int> parse\_int(const string& str) {  try {  return stoi(str);  }  catch (...) {  return nullopt;  }  }  // Function to square a number  int square(int x) {  return x \* x;  }  int main() {  string number;  cout << "Enter a number: ";  cin >> number;  // If parse\_int has a value, then call  // transform.  optional<int> result = parse\_int(number)  .transform(square);  if (result)  cout << "Result: " << \*result << "\n";  else  cout << "No value\n";  }  /\*  Enter a number: 33  Result: 1089  Enter a number: ABC  No value  \*/ |

* If parse\_int returns a value, then apply ‘square’ transform.
* If parse\_int returns std::nullopt, then result would be empty.

#### Summary:

* In C++23, std::optional and std::expected, received new utility functions—and\_then, or\_else, and transform—which make handling these types more convenient and expressive.
* Here's a table comparing these functions:

| **Feature** | and\_then | or\_else | transform |
| --- | --- | --- | --- |
| **Purpose** | Chains another operation if the **value is present** (std::optional is engaged, or std::expected has a valid value). | Specifies an alternative action when there is **no valid value** (std::optional is disengaged, or std::expected has an error). | Transforms the contained **value if it's present**. |
| **Works on** | std::optional, std::expected | std::optional, std::expected | std::optional, std::expected |
| **When it's executed** | If the **value is present**, applies the provided function and returns the result. Otherwise, returns an empty state (std::nullopt or **error**). | If the **value is missing**, applies the provided function to handle the alternative case. If the value is present, it remains unchanged. | If the **value is present**, applies the transformation function. Otherwise, it remains unchanged. |
| **Return Type** | Can return another std::optional or std::expected (typically used for function chaining). | Returns the same type as the original but with a potentially modified state. | Returns the same type but with a transformed contained value. |
| **Example Use Case** | Used for **chaining operations** when an optional or expected contains a value. | Used to **recover from an error** case or **provide an alternative value**. | Used for **modifying a valid value** without affecting error states. |

### Convert ranges into containers

* A range is anything that you can iterate over using a loop (e.g., a std::vector, a std::array, a std::string, iterators, views, spans or even a custom sequence).
* In C++23, a new feature called std::ranges::to was introduced, which makes it **easier and more convenient** to convert ranges (like iterators, views, or spans) into standard containers (like std::vector, std::set, etc.).
* Before C++23, if we had a range (like a std::vector or std::set) and wanted to convert it into another container, we had to do it manually using constructors or iterators.
* For example, let's say we have a std::vector<int> and want to convert it into a std::set<int> (which removes duplicates and sorts elements).

|  |
| --- |
| #include <vector>  #include <set>  #include <iostream>  int main() {  std::vector<int> vec = { 3, 1, 4, 1, 5, 9, 2 };  // Manually converting to std::set  std::set<int> s(vec.begin(), vec.end());  for (int num : s) {  std::cout << num << " ";  }  } // 1 2 3 4 5 9 |

* C++23 introduces std::ranges::to, which makes it much simpler to convert ranges into containers.

|  |
| --- |
| #include <vector>  #include <set>  #include <deque>  #include <iostream>  #include <ranges> // Required for ranges::to  using namespace std;  int main() {  vector<int> vec = { 3, 1, 4, 1, 5, 9, 2 };  // Easy conversion to set using ranges::to  set<int> s = ranges::to<set>(vec);  for (int num : s) {  cout << num << " ";  } // 1 2 3 4 5 9  cout << "\n";  // Convert to set, but keep only even numbers  set<int> even\_numbers = ranges::to<set>(  vec | views::filter([](int n) { return n % 2 == 0; })  );  for (int num : even\_numbers) {  cout << num << " ";  } // 2 4  cout << "\n";  // Convert to deque  deque<int> deq = ranges::to<deque>(vec);  for (int num : deq) {  cout << num << " ";  } // 3 1 4 1 5 9 2  cout << "\n";  } |

### Better support for constexpr in standard library algorithms

* Before C++23, many standard library algorithms (like std::sort, std::find, std::transform, etc.) were not fully constexpr-friendly. This limited the amount of computation you could do at compile time.

|  |
| --- |
| constexpr void sortArray() {  std::array<int, 3> arr = { 3, 1, 2 };  // ERROR: std::sort is NOT constexpr before C++23  std::sort(arr.begin(), arr.end());  } |

* In C++23, many **standard library algorithms** (like std::sort, std::unique, std::remove\_if, etc.) now have constexpr **support**. This means you can now **run these algorithms at compile time**, making your code more **efficient** and **faster** at runtime.

|  |
| --- |
| #include <algorithm>  #include <array>  #include <iostream>  constexpr std::array<int, 3> sortArray() {  std::array<int, 3> arr = { 3, 1, 2 };  std::sort(arr.begin(), arr.end());  return arr;  }  int main() {  // Computed at compile time!  constexpr auto sortedArr = sortArray();  for (int num : sortedArr) {  std::cout << num << " "; // Output: 1 2 3  }  } |

### Extended Algorithms

* C++23 introduces several new algorithms that enhance the capabilities of the C++ standard library.

#### Combine Multiple Ranges - std::views::zip

* std::views::zip takes **multiple ranges (like vectors, arrays, etc.)** and **pairs corresponding elements** together.

|  |
| --- |
| #include <iostream>  #include <vector>  #include <ranges>  #include <tuple>  int main() {  std::vector names = { "Alice", "Bob", "Charlie" };  std::vector ages = { 25, 30, 35 };  // Zip the two vectors together  for (auto [name, age] : std::views::zip(names, ages)) {  std::cout << name << " is " << age << " years old.\n";  }  }  /\*  Alice is 25 years old.  Bob is 30 years old.  Charlie is 35 years old.  \*/ |

#### Flatten a Range - std::views::join

* std::views::join **flattens** a range of **nested containers** (e.g., a vector<vector<int>>) into **one continuous sequence**.

|  |
| --- |
| #include <iostream>  #include <vector>  #include <ranges>  #include <string>  using namespace std;  int main() {  vector<vector<int>> numbers = {  {1, 2},  {3, 4},  {5, 6}  };  // Flatten (join) the nested vectors  for (int num : numbers | views::join) {  cout << num << " "; // 1 2 3 4 5 6  }  cout << "\n";  vector<string> words = {  "Hello",  "Hi",  "Dear"  };  for (auto i : words | views::join) {  cout << i << " "; // H e l l o H i D e a r  }  cout << "\n";  } |

#### Splitting a Range - std::views::split

* std::views::split **splits a range** into subranges based on a delimiter (like std::string\_view::split but for general ranges).

|  |
| --- |
| #include <iostream>  #include <ranges>  #include <string\_view>  int main() {  std::string\_view text = "Hello world from C++23";  // Split by space  for (auto word : text | std::views::split(' ')) {  std::cout << std::string\_view(word) << "\n";  }  }  /\*  Hello  world  from  C++23  \*/ |

### Faster Sorted Containers - std::flat\_map and std::flat\_set

* **Associative containers** store elements in a **sorted order**, allowing for efficient lookup, insertion, and deletion of elements based on their keys. std::map and std::set are the most commonly used associative containers.
* The **Cache Locality** Problem:
  + Traditional associative containers like std::map (implemented as a tree) can suffer from poor cache locality. When you access elements in a std::map, the elements might be scattered throughout memory, making it more likely that the CPU will have to wait for data to be loaded from slower memory (cache misses). This can slow down your program.
* C++23 introduces std::flat\_map and std::flat\_set, which are **sorted associative containers** **optimized for cache locality**. They work similarly to std::map and std::set but are more **cache-friendly** and can be faster in certain cases.

#### Cache Locality

* Cache locality refers to the proximity of data in memory and how it affects the efficiency of cache usage. There are two main types of cache locality:
  + **Temporal Locality**:
    - If a piece of data is accessed once, it’s likely to be accessed again soon.
    - Example: A variable used repeatedly in a loop.
    - The CPU keeps this data in the cache to avoid fetching it from RAM multiple times.
  + **Spatial Locality**:
    - If a piece of data is accessed, nearby data is also likely to be accessed soon.
    - Example: Iterating over an array or a contiguous block of memory.
    - The CPU loads a block of memory (called a cache line) into the cache, anticipating that nearby data will be needed.
* Cache Locality in Action:

|  |
| --- |
| #include <iostream>  #include <vector>  int main() {  std::vector<int> arr = { 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 };  int sum = 0;  for (int i = 0; i < arr.size(); ++i) {  sum += arr[i]; // Accessing elements sequentially  }  std::cout << "Sum: " << sum << std::endl;  return 0;  } |

* Why it’s good: The elements of arr are stored contiguously in memory. When the CPU accesses arr[0], it loads a cache line containing nearby elements (arr[1], arr[2], etc.). Subsequent accesses to arr[1], arr[2], etc., are fast because the data is already in the cache.

#### The std::flat\_map

* **Like** std::map: std::flat\_map stores key-value pairs, sorted by key.
* **Cache-friendly**: Elements are stored contiguously to improve cache locality.

|  |
| --- |
| #include <iostream>  #include <flat\_map> // Include the <flat\_map> header  using namespace std;  int main() {  flat\_map<string, int> ages;  ages["Alice"] = 30;  ages["Bob"] = 25;  ages["Charlie"] = 35;  for (const auto& [name, age] : ages) {  cout << name << ": " << age << endl;  }  // Accessing elements:  cout << "Bob's age: " << ages["Bob"] << endl;  return 0;  }  /\*  Alice: 30  Bob: 25  Charlie: 35  Bob's age: 25  \*/ |

#### The std::flat\_set

* **Like** std::set: std::flat\_set stores unique elements, sorted by their value.
* **Cache-friendly**: Elements are stored contiguously to improve cache locality.

|  |
| --- |
| #include <iostream>  #include <flat\_set>  using namespace std;  int main() {  flat\_set<int> fs = { 3, 1, 2 };  // Elements are always sorted  for (int num : fs) {  cout << num << " ";  }  // Fast lookup  if (fs.contains(2)) {  cout << "\n2 is in the set!";  }  }  /\*  1 2 3  2 is in the set!  \*/ |

#### When to Use?

* Use std::flat\_map/std::flat\_set when you do more lookups & iterations than insertions.
* Use std::map/std::set when you frequently insert/delete elements dynamically.

### Implicit move constructors

* In C++, objects can be copied or moved:
  + Copying (Copy Constructor) → Creates a new object by duplicating the original.
  + Moving (Move Constructor) → Transfers ownership of resources from one object to another, avoiding unnecessary copies.

|  |
| --- |
| class Data {  public:  std::vector<int> values;  // Move Constructor (C++11 and later)  Data(Data&& other) noexcept :  values(std::move(other.values)) {}  }; |

* + std::move(other.values) moves the resource instead of copying it.
* The Problem Before C++23, the compiler did not generate an implicit move constructor if:
  + A **copy constructor** was **explicitly defined** (even if you didn't need it).
  + A **destructor** was defined, even if it didn't do anything.
* Example:

|  |
| --- |
| class Data {  public:  std::vector<int> values;  Data() = default;  // Explicitly defined copy constructor  Data(const Data& other) : values(other.values) {}  // Explicit destructor (even if empty)  ~Data() {}  };  Data createData() {  Data d;  // Will copy instead of move.  return d;  }  int main() {  // Copy constructor is used instead of move constructor.  Data d1 = createData();  } |

* Even though we are returning Data from a function, **a copy happens instead of a move** because defining a copy constructor prevents the compiler from generating a move constructor.

#### C++23 Implicit move constructors

* C++23 now allows the compiler to generate an implicit move constructor even if:
  + You define a **copy constructor**.
  + You define a **destructor**.

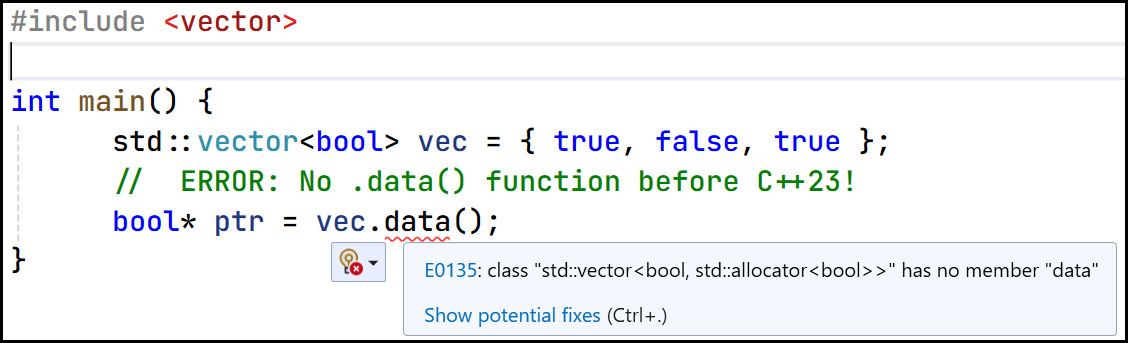
|  |
| --- |
| Data createData() {  Data d;  // Move happens instead of copy  return d;  }  int main() {  // Move happens instead of copy  Data d1 = createData();  } |

* This will help…
  + If you are working with large objects, reducing unnecessary copies will improve performance.
  + If your class defines a copy constructor or destructor, C++23 ensures move semantics still work properly.

### The std::vector<bool>

#### Before C++23

* The std::vector<bool> is a specialized version of std::vector<T>, but it does not behave like a normal container.
* Instead of storing bool values as separate bytes (like std::vector<int> stores integers), std::vector<bool> was optimized to store multiple bool values in a compact **bit-packed representation**.
* This optimization caused several problems:
  + No direct access to elements (operator[] does not return bool&).
  + Iterators behave differently.
  + No data() function (so you couldn't get a pointer to the underlying storage).
* Example: Before C++23



#### What Did C++23 Fix?

* C++23 made std::vector<bool> behave more like a normal container:
  + Added .data() – You can now access the underlying storage.
  + Improved iterator support – Now behaves more like std::vector<int>.
  + Better compatibility with standard algorithms.

As of now, GCC, Clang, and MSVC have not yet implemented the std::vector<bool>::data() member function introduced in C++23. This is a notable improvement in the C++23 standard, but compiler support for this specific feature is still pending.

### Multidimensional std::mdspan

#### What is std::span?

* std::span (introduced in C++20) is a **view** over a sequence of elements.
* **It does not own the data** - it simply provides access to an existing array or contiguous memory.
* It helps in avoiding raw pointers and makes function parameters safer.

|  |
| --- |
| #include <iostream>  #include <span>  #include <array>  #include <vector>  using namespace std;  // Takes any contiguous int collection  void print(span<int> arr) {  for (int num : arr) {  cout << num << " ";  }  cout << "\n";  }  int main() {  int num1[] = { 1, 2, 3, 4, 5 }; // C-style array  print(num1); // Passes entire array  std::array num2 = { 1, 2, 3, 4, 5 }; // std::array  print(num2); // Passes entire std::array  vector num3 = { 1, 2, 3, 4, 5 }; // std::vector  print(num3); // Passes entire std::vector  std::span num4 = num3; // std::span  print(num4); // Passes entire std::span  int\* ptr = num3.data();  size\_t size = num3.size();  print({ ptr, size }); // Construct std::span<int>  print(std::span(num4.begin() + 1,  num4.begin() + 4)); // Pass a subrange  } |

#### What is std::mdspan?

* std::mdspan is like a **view into your grid data**. It **doesn't own** the data; it just refers to it. Think of it as a **window** through which you can see and access the elements of your grid. The key is that this **window can be configured** to view grids stored in different ways.

#### Why Do We Need std::mdspan?

* Before C++23, handling multi-dimensional arrays was inefficient and cumbersome:
  + **C-style arrays** (T arr[3][3])
    - Hard to use and pass as function arguments.
    - Cannot change size dynamically.
  + std::vector<std::vector<T>> (Nested std::vector)
    - Memory is not contiguous → slower performance.
    - Extra memory overhead for each std::vector.
  + Raw pointers (T\* data) with manual indexing
    - Hard to manage correctly.
    - No built-in bounds checking → risk of segmentation faults.
* std::mdspan fixes these problems by providing a safe, efficient, and flexible way to access multi-dimensional data.

|  |
| --- |
| #include <vector>  #include <mdspan>  #include <iostream>  int main()  {  std::vector v{ 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12 };  // View data as 3 X 4  auto threeCrossFour = std::mdspan(v.data(), 3, 4);    for (std::size\_t i = 0; i != threeCrossFour.extent(0); i++)  {  for (std::size\_t j = 0; j != threeCrossFour.extent(1); j++)  {  std::cout << threeCrossFour[i, j] << ' ';  }  std::cout << '\n';  }  std::cout << "Row Size:" << threeCrossFour.extent(0) << '\n';  std::cout << "Column Size:" << threeCrossFour.extent(1) << '\n';  return 0;  }  /\*  1 2 3 4  5 6 7 8  9 10 11 12  Row Size:3  Column Size:4  \*/ |

* Here std::mdspan creates a 3×4 view over a 1D std::vector<int> ‘v’.
* extent(N) returns the size of dimension N in std::mdspan.
  + extent(0): Number of rows.
  + extent(1): Number of columns.

### Standard Library Module

* In older versions of C++, we included standard library headers using #include. For example, to use std::vector, we would write #include <vector>.
* This #include mechanism is a text-based inclusion. The compiler literally copies and pastes the contents of the <vector> header file into your code.
* This has several drawbacks:
  + **Slow Compilation**: Including many headers can make compilation slow because the compiler has to process a lot of code, even if you only use a small part of it.
  + **Name Collisions**: Headers might define the same names, leading to conflicts.
  + **Order Dependence**: The order of #include directives can sometimes matter, which can be confusing.
* Example: Before import std;

|  |
| --- |
| #include <vector>  #include <set>  #include <deque>  #include <iostream>  #include <ranges>  using namespace std;  int main() {  vector<int> vec = { 3, 1, 4, 1, 5, 9, 2 };  // Easy conversion to set using ranges::to  set<int> s = ranges::to<set>(vec);  for (int num : s) {  cout << num << " ";  } // 1 2 3 4 5 9  cout << "\n";  // Convert to set, but keep only even numbers  set<int> even\_numbers = ranges::to<set>(  vec | views::filter([](int n) { return n % 2 == 0; })  );  for (int num : even\_numbers) {  cout << num << " ";  } // 2 4  cout << "\n";  // Convert to deque  deque<int> deq = ranges::to<deque>(vec);  for (int num : deq) {  cout << num << " ";  } // 3 1 4 1 5 9 2  cout << "\n";  } |

#### Using import std;

* Now, you can **replace multiple includes** with a single line: import std;

|  |
| --- |
| import std;  using namespace std;  int main() {  vector<int> vec = { 3, 1, 4, 1, 5, 9, 2 };  // Easy conversion to set using ranges::to  set<int> s = ranges::to<set>(vec);  for (int num : s) {  cout << num << " ";  } // 1 2 3 4 5 9  cout << "\n";  // Convert to set, but keep only even numbers  set<int> even\_numbers = ranges::to<set>(  vec | views::filter([](int n) { return n % 2 == 0; })  );  for (int num : even\_numbers) {  cout << num << " ";  } // 2 4  cout << "\n";  // Convert to deque  deque<int> deq = ranges::to<deque>(vec);  for (int num : deq) {  cout << num << " ";  } // 3 1 4 1 5 9 2  cout << "\n";  } |

#### **Why Is** import std; **Better?**

| **Feature** | #include **(C++98 - C++20)** | import std; **(C++23)** |
| --- | --- | --- |
| **Compilation Speed** | Slower (text inclusion) | Faster (precompiled module) |
| **Code Simplicity** | Many #include lines | Just import std; |
| **Redundancy** | Same headers parsed repeatedly | Uses precompiled interface |
| **Scalability** | More includes slow builds | Efficient for large projects |

### The std::print

#### Why std::print?

* While std::cout is a C++ essential, it can be a bit complex for beginners (and sometimes even for experienced programmers). Formatting output with std::cout often involves using manipulators (like std::setw, std::fixed, std::setprecision), which can be a bit cumbersome.
* In C++23, a new feature called std::print was introduced, which provides a **simpler and more efficient** alternative to std::cout for printing output to the console.
* **It is similar** to std::format which creates a formatted string.
* The formatting rules and syntax used within the format string (the first argument) of std::print are exactly the same as those used with std::format.

|  |
| --- |
| #include <print>  int main() {  int age = 30;  std::string name = "Alice";  double height = 5.8;  // Basic usage:  std::print("{}! You are {} years old and {} feet tall.\n",  name, age, height);  // Formatting:  std::print("{:10} {:5d} {:6.2f}\n",  name, age, height);  return 0;  } |

* {:10}: Specifies that the name should be printed in a field of width 10.
* {:5d}: Specifies that the age should be printed as a decimal integer in a field of width 5.
* {:6.2f}: Specifies that the height should be printed as a floating-point number with 2 decimal places, in a field of width 6.

#### Custom Formatter for a class

* By default, std::print **only supports built-in types** like int, double, and std::string.
* In C++20, std::format was introduced as a modern, type-safe way to format strings, and C++23 allows you to **customize how your own types are formatted** by writing a **custom formatter**.

|  |
| --- |
| import std;  using namespace std;  class Student {  private:  string name;  int age;  vector<int> grades;  public:  Student(string name, int age, vector<int> grades)  : name{ move(name) }, age{ age }, grades{ move(grades) } {  }  const string& getName() const { return name; }  int getAge() const { return age; }  const vector<int>& getGrades() const { return grades; }  };  template <> // Full specialization of formatter for Student  struct formatter<Student> : std::formatter<std::string> {  auto format(Student h, format\_context& ctx) const {  return formatter<string>::format(  std::format("Student{{name = {}, age = {}, grades ={}}}",  h.getName(), h.getAge(), h.getGrades()), ctx);  }  };  int main() {  Student alice{ "Alice", 20, {85, 92, 78} };  Student bob{ "Bob", 22, {90, 88, 95, 92} };  println("{}", alice);  println("{}", bob);  return 0;  }  // Output: Student{name = Alice, age = 20, grades =[85, 92, 78]}  // Output: Student{name = Bob, age = 22, grades =[90, 88, 95, 92]} |

#### Explanation:

* template <> struct formatter<Student>
  + This tells the compiler that you're specializing the formatter template for the Student type.
  + formatter<Student> will now handle formatting for any Student objects.
* std::formatter<std::string>
  + You're inheriting from std::formatter<std::string>, which is the standard formatter for strings.
  + This means you're leveraging the string formatting capabilities to format your Student object.
* auto format(Student h, format\_context& ctx) const
  + This function is the core of the custom formatter. It tells the compiler how to format a Student object.
  + Student h is the Student object that needs to be formatted.
  + format\_context& ctx is the context where the formatting happens, but you don't need to worry about its details here.
* std::format("Student{{name = {}, age = {}, grades ={}}}", ...)
  + This line constructs a formatted string for the Student.
  + std::format is used to format the output by substituting placeholders {} with values (like name, age, grades).
* formatter<string>::format(..., ctx)
  + This line calls the base string formatter to actually format and output the final string.
  + The formatted string from the previous step is passed into formatter<string>::format, which outputs it in the desired format.

### The std::generator

* C++23 introduces std::generator, which allows writing **lazy sequences** using coroutines.
* This makes it easier to create **iterators that generate values on demand**, reducing memory usage and improving performance.
* Before C++23, generating sequences required:
  + Precomputing all elements and storing them in a container (e.g., std::vector).
  + Manually managing iterators to avoid unnecessary computations.
* With std::generator, values are computed only when needed (lazy evaluation).

|  |
| --- |
| import std;  std::generator<int> fibonacci() {  int a = 0, b = 1;  while (true) { // Infinite lazy sequence  co\_yield a; // Yield the current number  int next = a + b;  a = b;  b = next;  }  }  int main() {  int count = 10;  for (int num : fibonacci()) {  if (count-- == 0) break;  std::cout << num << " ";  }  }// 0 1 1 2 3 5 8 13 21 34 |

* How std::generator Works
  + Uses co\_yield to return a value without ending the function.
  + Execution pauses at co\_yield and resumes from there the next time the generator is accessed.
  + Unlike return, co\_yield allows continuing execution later.

### The std::stacktrace

* In **C++23**, the std::stacktrace feature was introduced to help developers **capture and print stack traces** easily. This is particularly useful for debugging runtime issues such as crashes or exceptions.

#### **What is a Stack Trace?**

* A **stack trace** is a list of function calls that **shows how a program reached a certain point** during execution. It is commonly used to **debug errors** by tracking the sequence of function calls.
* For example, if your program crashes due to an **unhandled exception**, a **stack trace** can help you find which functions were called before the crash.

|  |
| --- |
| import std;  void functionC() {  std::cout << "Currently Inside functionC\n";  // Capture the stack trace here  std::stacktrace st = std::stacktrace::current();  // Print the stack trace  std::cout << st << std::endl;  }  void functionB() {  std::cout << "Inside functionB\n";  functionC();  }  void functionA() {  std::cout << "Inside functionA\n";  functionB();  }  int main() {  std::cout << "Inside main\n";  functionA();  return 0;  }  /\*  Inside main  Inside functionA  Inside functionB  Currently Inside functionC  0> C:\Users\write\source\repos\CPP23\CPP23\FileName.cpp(6): CPP23!functionC+0x78  1> C:\Users\write\source\repos\CPP23\CPP23\FileName.cpp(13): CPP23!functionB+0x35  2> C:\Users\write\source\repos\CPP23\CPP23\FileName.cpp(18): CPP23!functionA+0x35  3> C:\Users\write\source\repos\CPP23\CPP23\FileName.cpp(23): CPP23!main+0x35  4> D:\a\\_work\1\s\src\vctools\crt\vcstartup\src\startup\exe\_common.inl(79): CPP23!invoke\_main+0x39  5> D:\a\\_work\1\s\src\vctools\crt\vcstartup\src\startup\exe\_common.inl(288): CPP23!\_\_scrt\_common\_main\_seh+0x132  6> D:\a\\_work\1\s\src\vctools\crt\vcstartup\src\startup\exe\_common.inl(331): CPP23!\_\_scrt\_common\_main+0xE  7> D:\a\\_work\1\s\src\vctools\crt\vcstartup\src\startup\exe\_main.cpp(17): CPP23!mainCRTStartup+0xE  8> KERNEL32!BaseThreadInitThunk+0x17  9> ntdll!RtlUserThreadStart+0x2C  \*/ |

#### Benefits of std::stacktrace

* Simplifies debugging with a standard way to get stack traces.
* Helps log function call sequences in error logs.
* Portable across different operating systems.