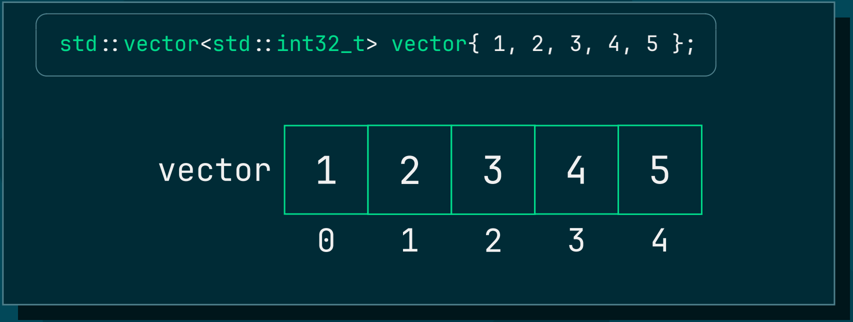

```
std::vector<std::int32_t> vector{ 1, 2, 3, 4, 5 };
```

Vectors

Data Structures – C++ Fundamentals

Agenda

- What Are Vectors?
  - Properties
  - Benefits
  - Drawbacks
- Dynamic-array Details
  - Abstract Data Types
  - How Do They Work?
  - Operations
  - Vector-specific Details
- Dynamic Allocation
  - The Stack
  - Return-value Optimization
  - The Heap
  - Vectors and the Heap
- Working with Vectors
  - Syntax
  - Undefined Behavior
  - Iterator Invalidation

What Are Vectors?

Vector Properties

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Vectors are C++'s implementation of a data abstraction known as a *dynamic array*

What is a dynamic array?

A *dynamic array* is a dynamically sizable array

- Dynamic arrays share the same properties as arrays
- Dynamic arrays resize themselves as elements are added

Dynamic-array Properties

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- Values are stored contiguously
- Values can be accessed at random
- Values are ordered (indexed for dynamic arrays)

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  - Can be subsequenced

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Dynamic-array Details

Abstract Data Types

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An *abstract data type* (ADT) is a theoretical representation of a data type which outlines its properties and abilities

- They don’t mention concrete implementation details
- They allow for classifying a data type based on its properties and operations rather than on its implementation
- Programmers can abstract away any implementation details that don’t matter by using ADTs

Data Abstractions

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- Data abstractions are ADTs that are meant for representing data structures
- *Data structures* are concrete implementations of data abstractions using a particular representation of the data
- A dynamic array is a data abstraction since there are multiple data structures that could implement it

How Might We Implement a Dynamic Array?

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- Let’s say we want to write a program which asks a user to enter an unlimited number of integers until they enter “stop”

How Might We Implement a Dynamic Array?

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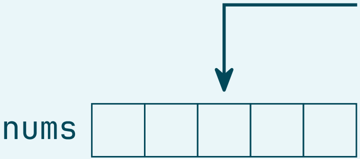
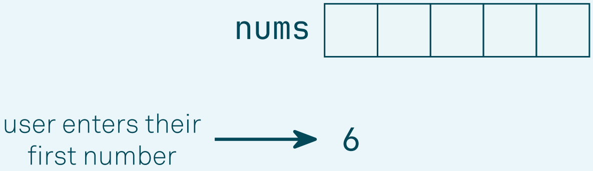
- How could we store the user’s numbers using only `std::array`?

How Might We Implement a Dynamic Array?



create initial array
with most probable size

How Might We Implement a Dynamic Array?

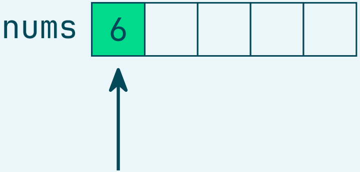


`nums`

user enters their first number

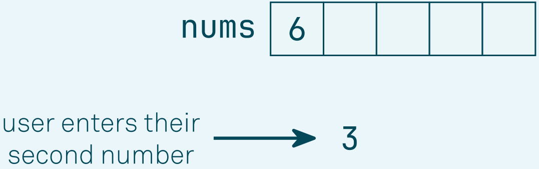
6

How Might We Implement a Dynamic Array?



number is stored
in first slot

How Might We Implement a Dynamic Array?



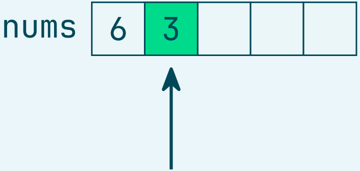
nums

6

user enters their second number

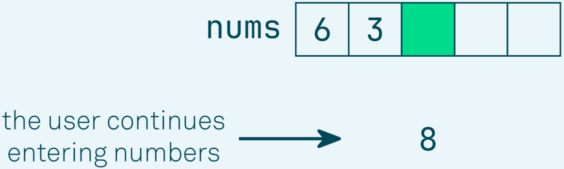
3

How Might We Implement a Dynamic Array?



number is stored
in second slot

How Might We Implement a Dynamic Array?



nums

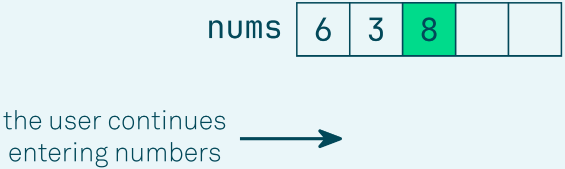
6

3

the user continues entering numbers

8

How Might We Implement a Dynamic Array?

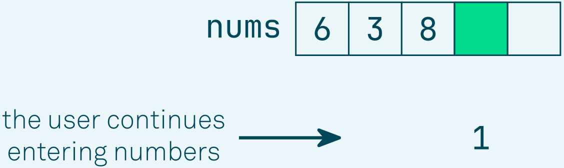


nums

6	3	8		

the user continues entering numbers →

How Might We Implement a Dynamic Array?



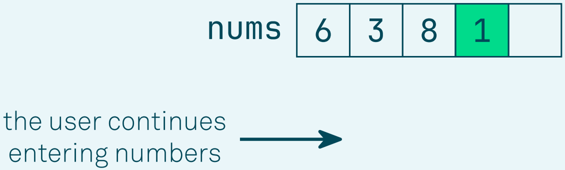
nums

6	3	8	🟩	

the user continues entering numbers →

1

How Might We Implement a Dynamic Array?

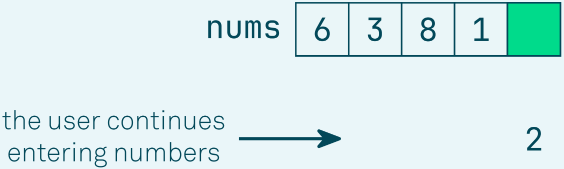


nums

6	3	8	1	

the user continues entering numbers

How Might We Implement a Dynamic Array?



the user continues entering numbers

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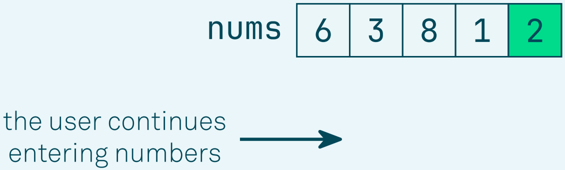

the user continues entering numbers

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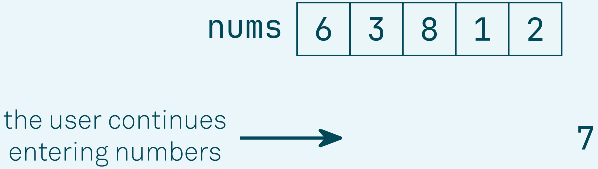
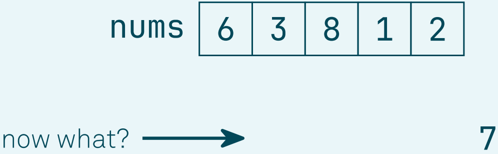


nums					
	6	3	8	1	2

the user continues entering numbers

7

How Might We Implement a Dynamic Array?

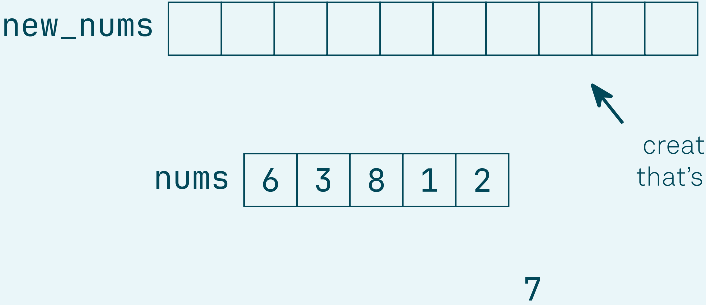


nums				
6	3	8	1	2

now what? →

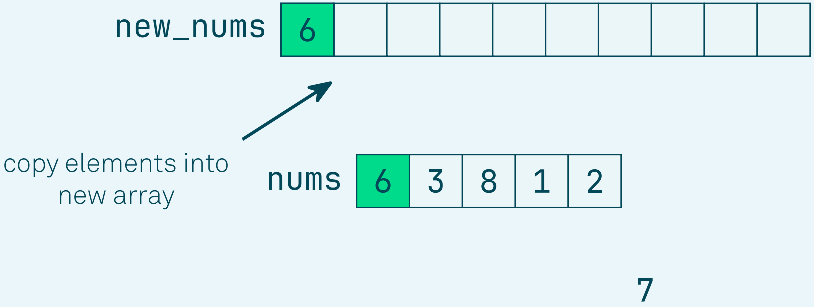
7

How Might We Implement a Dynamic Array?



create a new array that's 1.5 to 2 times bigger

How Might We Implement a Dynamic Array?



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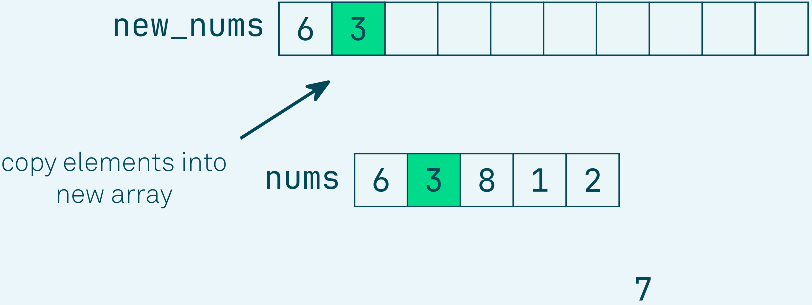

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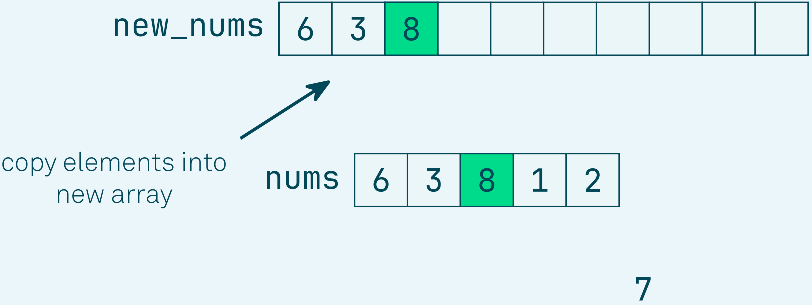


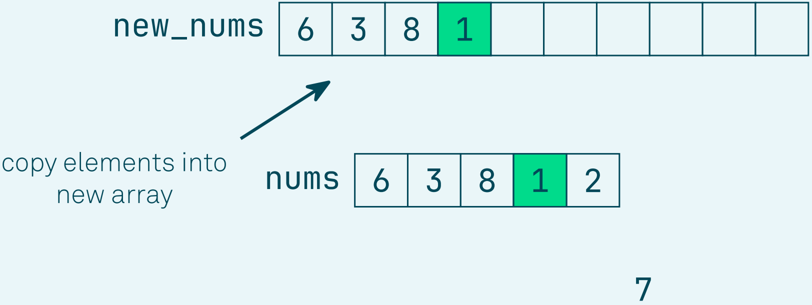
new_nums 6 3 8

copy elements into new array

nums 6 3 8 1 2

7

How Might We Implement a Dynamic Array?



new_nums

6	3	8	1						

copy elements into new array

nums

6	3	8	1	2

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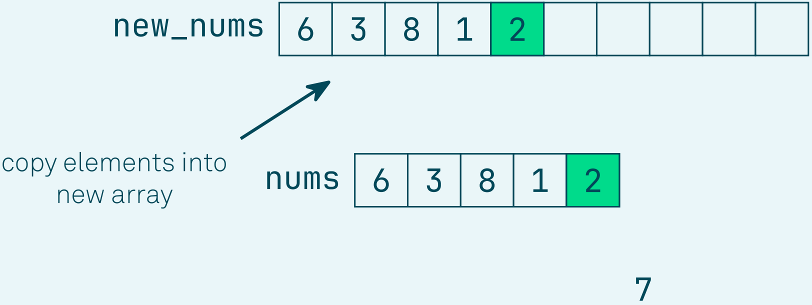

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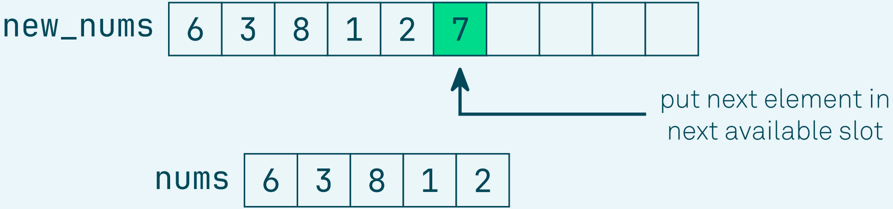

new_nums	6	3	8	1	2	7				

put next element in
next available slot

nums	6	3	8	1	2

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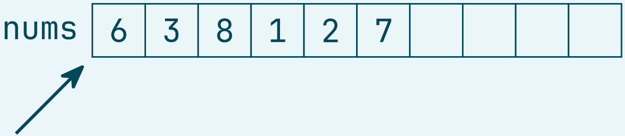

nums	6	3	8	1	2	7				

replace old array
with new array

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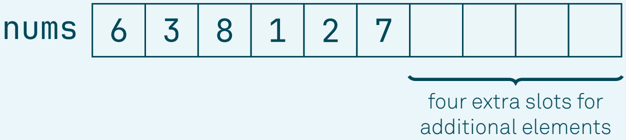

nums

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four extra slots for additional elements

Dynamic-array Operations

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- First element added triggers allocation of an array with one slot. From there, array size increases by a factor of two

Dynamic Allocation

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- The memory allocated for a function called is known as a *stack frame*

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- Are there ways to avoid these copies?

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  - Named return-value optimization (NRVO)

URVO Example

```cpp
#include <array>
#include <cstdint>
#include <cstdlib>

std::array<std::int32_t, 5> get_nums() noexcept {
   return std::array{ 1, 2, 3, 4, 5 };
}

int main() {
   const auto nums{get_nums()};
   return EXIT_SUCCESS;
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```

returned value is a *temporary*

array will be created and stored directly in `nums`

Things to Know about URVO

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NRVO Example

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#include <array>
#include <cstdint>
#include <cstdlib>

#include <UTL/random.hpp>

std::array<std::int32_t, 5> get_random_nums() {
   namespace rand = utl::random;
   std::array<std::int32_t, 5> nums{};
   for (std::int32_t &num : nums) {
      num = rand::uniform<std::int32_t>(-10, 10);
   }
   return nums;
}

int main() {
   const auto nums{get_random_nums()};
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NRVO Example

return value is created before return statement

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NRVO Example

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return value can be created directly in result variable

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Copy elision

The creation of an object from an object of the same type can be omitted, even if the creation or destruction would have side effects

- Copy elision is one of two allowed optimizations that can change observable side effects
- Copy elision is *optional* for compilers to perform

Things RVO Can't Fix

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- The stack isn’t that big, so storing large amounts of data is difficult

What Is the Heap?

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- The heap is large region of memory available for on-demand (dynamic) allocations

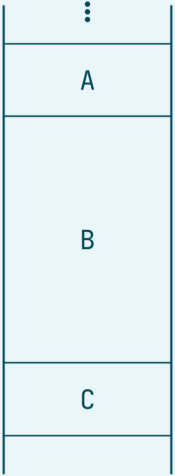
What Is the Heap?

- The heap is large region of memory available for on-demand (dynamic) allocations
- The structure of the stack makes it inconvenient for storing data which needs to persist for a while

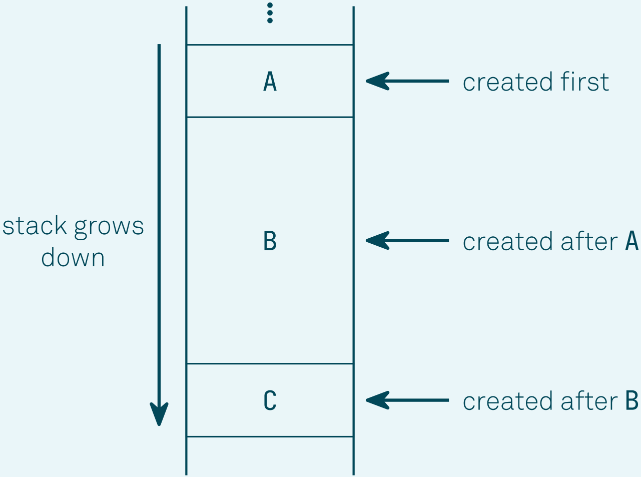
What Is the Heap?

- The heap is large region of memory available for on-demand (dynamic) allocations
- The structure of the stack makes it inconvenient for storing data which needs to persist for a while
- Newer memory must be freed before older memory can be freed

What Is the Heap?



What Is the Heap?



stack grows down

A

B

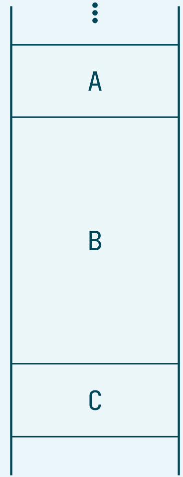
C

created first

created after A

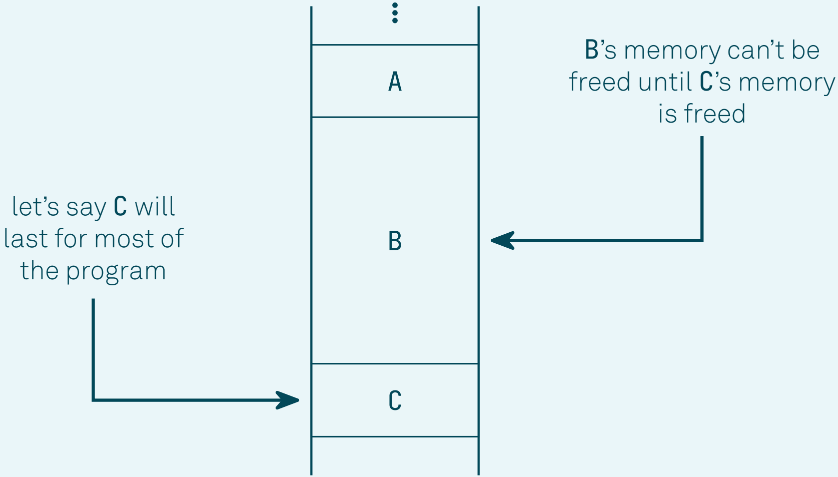
created after B

What Is the Heap?



let’s say C will last for most of the program

What Is the Heap?



B's memory can't be freed until C's memory is freed

let's say C will last for most of the program

What Is the Heap?

- The heap can be used to allocate large chunks of memory which need to last for a while

What Is the Heap?

- The heap can be used to allocate large chunks of memory which need to last for a while
- Each of these chunks can be freed at any time, regardless of when it was allocated

How Do Vectors Use Dynamic Allocation?

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How Do Vectors Use Dynamic Allocation?

- Information like the size and the capacity is stored on the stack
- Elements are stored on the heap
- New elements can be added or removed without worrying about the stack
- Old backing arrays can have their memories freed as soon as they’re no longer needed
- Only the existing elements will need to get copied when a new backing array is created

Working with Vectors

Vector Syntax: Creation

Vector Syntax: Creation

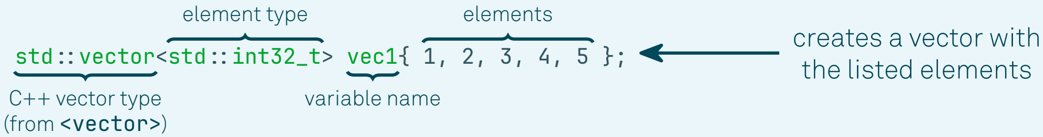
```
std::vector<std::int32_t> vec1{ 1, 2, 3, 4, 5 };
```

Vector Syntax: Creation

```
std::vector<std::int32_t> vec1{ 1, 2, 3, 4, 5 };
```

creates a vector with the listed elements

Vector Syntax: Creation



```
std::vector<std::int32_t> vec1{ 1, 2, 3, 4, 5 };
```

element type

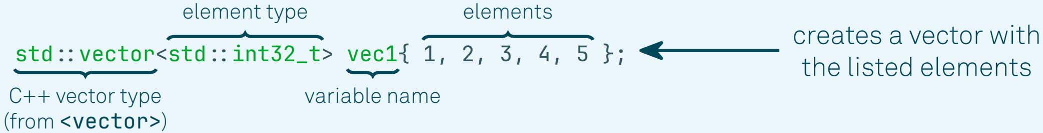
elements

creates a vector with the listed elements

C++ vector type (from `<vector>`)

variable name

Vector Syntax: Creation



element type

elements

```
std::vector<std::int32_t> vec1{ 1, 2, 3, 4, 5 };
```

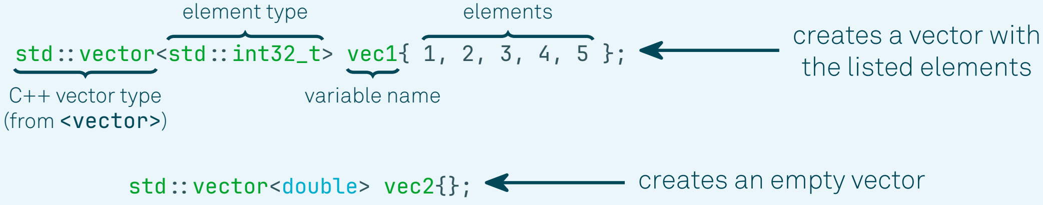
C++ vector type (from **`<vector>`**)

variable name

creates a vector with the listed elements

```
std::vector<double> vec2{};
```

Vector Syntax: Creation



element type

elements

```
std::vector<std::int32_t> vec1{ 1, 2, 3, 4, 5 };
```

creates a vector with the listed elements

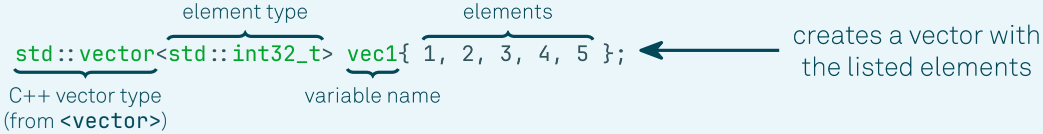
C++ vector type (from `<vector>`)

variable name

```
std::vector<double> vec2{};
```

creates an empty vector

Vector Syntax: Creation



```
std::vector<std::int32_t> vec1{ 1, 2, 3, 4, 5 };
```

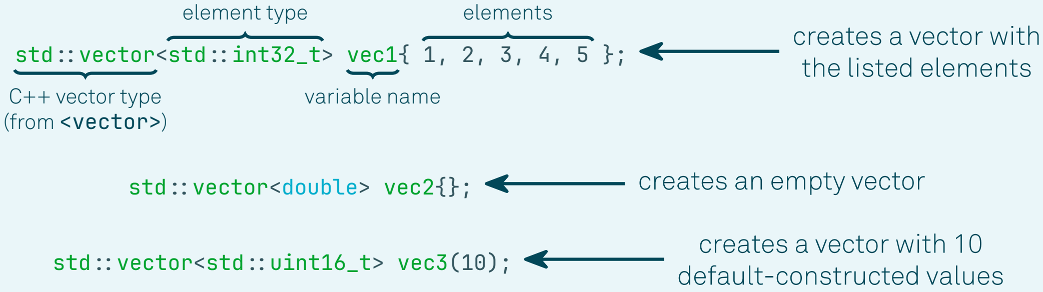
creates a vector with the listed elements

```
std::vector<double> vec2{};
```

creates an empty vector

```
std::vector<std::uint16_t> vec3(10);
```

Vector Syntax: Creation



```
std::vector<std::int32_t> vec1{ 1, 2, 3, 4, 5 };
```

creates a vector with the listed elements

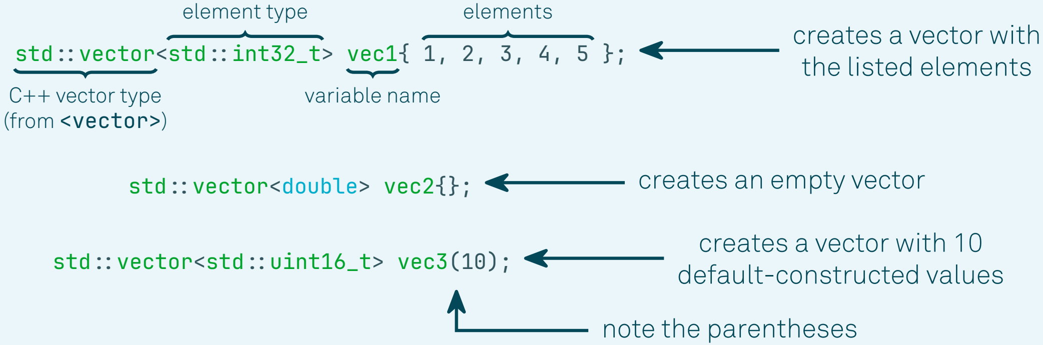
```
std::vector<double> vec2{};
```

creates an empty vector

```
std::vector<std::uint16_t> vec3(10);
```

creates a vector with 10 default-constructed values

Vector Syntax: Creation



element type

elements

```cpp
std::vector<std::int32_t> vec1{ 1, 2, 3, 4, 5 };
```

creates a vector with the listed elements

C++ vector type (from `<vector>`)

variable name

```cpp
std::vector<double> vec2{};
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creates an empty vector

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note the parentheses

Vector Syntax: Creation

element type

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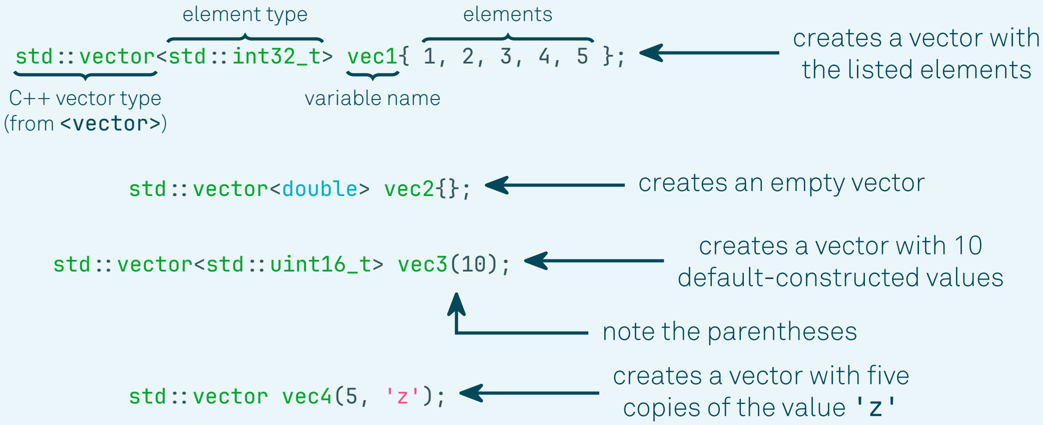
note the parentheses

```
std::vector vec4(5, 'z');
```

Vector Syntax: Creation



element type

elements

```
std::vector<std::int32_t> vec1{ 1, 2, 3, 4, 5 };
```

creates a vector with the listed elements

C++ vector type (from **<vector>**)

variable name

```
std::vector<double> vec2{};
```

creates an empty vector

```
std::vector<std::uint16_t> vec3(10);
```

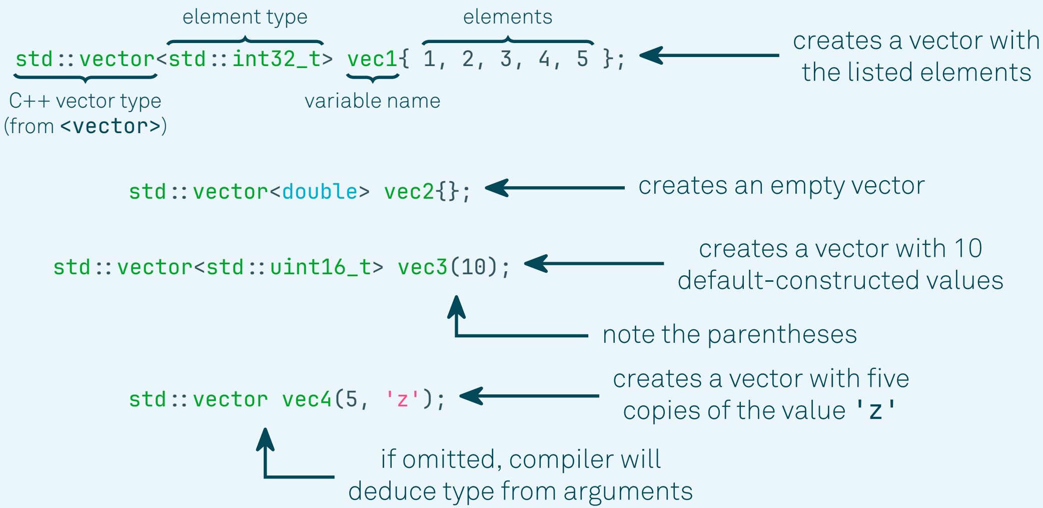
creates a vector with 10 default-constructed values

note the parentheses

```
std::vector vec4(5, 'z');
```

creates a vector with five copies of the value **'z'**

Vector Syntax: Creation



```cpp
std::vector<std::int32_t> vec1{ 1, 2, 3, 4, 5 };
```

element type

elements

C++ vector type (from `<vector>`)

variable name

creates a vector with the listed elements

```cpp
std::vector<double> vec2{};
```

creates an empty vector

```cpp
std::vector<std::uint16_t> vec3(10);
```

creates a vector with 10 default-constructed values

note the parentheses

```cpp
std::vector vec4(5, 'z');
```

creates a vector with five copies of the value `'z'`

if omitted, compiler will deduce type from arguments

Vector Syntax: Accessing

```cpp
std::vector<std::int32_t> vec{ 1, 2, 3, 4, 5 };
cout << vec.front() << '\n';
```

Vector Syntax: Accessing

```cpp
std::vector<std::int32_t> vec{ 1, 2, 3, 4, 5 };
cout << vec.front() << '\n';
```

```
1
```

Vector Syntax: Accessing

```
std::vector<std::int32_t> vec{ 1, 2, 3, 4, 5 };
cout << vec.front() << '\n';
```

```
1
```

```
cout << vec.back() << '\n';
```

Vector Syntax: Accessing

```cpp
std::vector<std::int32_t> vec{ 1, 2, 3, 4, 5 };
cout << vec.front() << '\n';
```

```
1
```

```cpp
cout << vec.back() << '\n';
```

```
5
```

Vector Syntax: Accessing

```
std::vector<std::int32_t> vec{ 1, 2, 3, 4, 5 };
cout << vec.front() << '\n';
```

```
1
```

```
cout << vec.back() << '\n';
```

```
5
```

```
cout << vec.at(2) << '\n';
```

Vector Syntax: Accessing

```
std::vector<std::int32_t> vec{ 1, 2, 3, 4, 5 };
cout << vec.front() << '\n';
```

```
1
```

```
cout << vec.back() << '\n';
```

```
5
```

```
cout << vec.at(2) << '\n';
```

```
3
```

Vector Syntax: Accessing

```cpp
cout << "size: " << vec.size() << '\n';
```

Vector Syntax: Accessing

```
cout << "size: " << vec.size() << '\n';
```

```
size: 5
```

Vector Syntax: Accessing

```
cout << "size: " << vec.size() << '\n';
```

```
size: 5
```

```
cout << "capacity: " << vec.capacity() << '\n';
```

Vector Syntax: Accessing

```
cout << "size: " << vec.size() << '\n';
```

```
size: 5
```

```
cout << "capacity: " << vec.capacity() << '\n';
```

```
capacity: 5
```

Vector Syntax: Accessing

```cpp
cout << "size: " << vec.size() << '\n';
```

```
size: 5
```

```cpp
cout << "capacity: " << vec.capacity() << '\n';
```

```
capacity: 5
```

```cpp
cout << vec.at(17) << '\n';
```

Vector Syntax: Accessing

```
cout << "size: " << vec.size() << '\n';
```

```
size: 5
```

```
cout << "capacity: " << vec.capacity() << '\n';
```

```
capacity: 5
```

```
cout << vec.at(17) << '\n';
```

```
libc++abi: terminating due to uncaught exception of type std::out_of_range: vector

Process finished with exit code 134 (interrupted by signal 6:SIGABRT)
```

Vector Syntax: Modifying

```cpp
std::vector words{ "hello", "world", "C++" };
words.front() = "goodbye";
cout << words.front() << '\n';
```

Vector Syntax: Modifying

```cpp
std::vector words{ "hello", "world", "C++" };
words.front() = "goodbye";
cout << words.front() << '\n';
```

```
goodbye
```

Vector Syntax: Modifying

```
std::vector words{ "hello", "world", "C++" };
words.front() = "goodbye";
cout << words.front() << '\n';
```

```
goodbye
```

```
words.at(2) = "Java";
cout << words.at(2) << '\n';
```

Vector Syntax: Modifying

```
std::vector words{ "hello", "world", "C++" };
words.front() = "goodbye";
cout << words.front() << '\n';
```

```
goodbye
```

```
words.at(2) = "Java";
cout << words.at(2) << '\n';
```

```
Java
```

Vector Syntax: Modifying

```
std::vector words{ "hello", "world", "C++" };
words.front() = "goodbye";
cout << words.front() << '\n';
```

```
goodbye
```

```
words.at(2) = "Java";
cout << words.at(2) << '\n';
```

```
Java
```

```
words.at(-1) = "word";
```

Vector Syntax: Modifying

```
std::vector words{ "hello", "world", "C++" };
words.front() = "goodbye";
cout << words.front() << '\n';
```

```
goodbye
```

```
words.at(2) = "Java";
cout << words.at(2) << '\n';
```

```
Java
```

```
words.at(-1) = "word";
```

```
libc++abi: terminating due to uncaught exception of type std::out_of_range: vector

Process finished with exit code 134 (interrupted by signal 6:SIGABRT)
```

Vector Syntax: Adding

```cpp
std::vector<std::uint16_t> nums{};
for (std::uint16_t i{1U}; i <= 5U; ++i) {
   nums.push_back(i);
}
// Assumes insertion operator has been overloaded for vectors.
cout << nums << '\n';
```

Vector Syntax: Adding

```cpp
std::vector<std::uint16_t> nums{};
for (std::uint16_t i{1U}; i <= 5U; ++i) {
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// Assumes insertion operator has been overloaded for vectors.
cout << nums << '\n';
```

```
[1, 2, 3, 4, 5]
```

Vector Syntax: Adding

```
std::vector<std::uint16_t> nums{};
for (std::uint16_t i{1U}; i <= 5U; ++i) {
   nums.push_back(i);
}
// Assumes insertion operator has been overloaded for vectors.
cout << nums << '\n';
```

```
[1, 2, 3, 4, 5]
```

```
auto middle_iter{std::next(nums.begin(), nums.size() >> 1)};
cout << "middle element: " << *middle_iter << '\n';
middle_iter = nums.insert(middle_iter, 0U);
cout << "new middle element: " << *middle_iter << '\n';
cout << nums << '\n';
```

Vector Syntax: Adding

```cpp
std::vector<std::uint16_t> nums{};
for (std::uint16_t i{1U}; i <= 5U; ++i) {
   nums.push_back(i);
}
// Assumes insertion operator has been overloaded for vectors.
cout << nums << '\n';
```

```
[1, 2, 3, 4, 5]
```

```cpp
auto middle_iter{std::next(nums.begin(), nums.size() >> 1)};
cout << "middle element: " << *middle_iter << '\n';
middle_iter = nums.insert(middle_iter, 0U);
cout << "new middle element: " << *middle_iter << '\n';
cout << nums << '\n';
```

```
middle element: 3
new middle element: 0
[1, 2, 0, 3, 4, 5]
```

Vector Syntax: Adding

```
nums.insert(nums.begin(), { 7U, 8U, 9U });
cout << nums << '\n';
```

Vector Syntax: Adding

```cpp
nums.insert(nums.begin(), { 7U, 8U, 9U });
cout << nums << '\n';
```

```
[7, 8, 9, 1, 2, 0, 3, 4, 5]
```

Vector Syntax: Adding

```cpp
nums.insert(nums.begin(), { 7U, 8U, 9U });
cout << nums << '\n';
```

```
[7, 8, 9, 1, 2, 0, 3, 4, 5]
```

```cpp
nums.insert(nums.end(), 2U, 6U);
cout << nums << endl;
```

Vector Syntax: Adding

```cpp
nums.insert(nums.begin(), { 7U, 8U, 9U });
cout << nums << '\n';
```

```
[7, 8, 9, 1, 2, 0, 3, 4, 5]
```

```cpp
nums.insert(nums.end(), 2U, 6U);
cout << nums << endl;
```

```
[7, 8, 9, 1, 2, 0, 3, 4, 5, 6, 6]

Process finished with exit code 0
```

Vector Syntax: Emplacing

Vector Syntax: Emplacing

- What if we wanted to add an object to a vector?

Vector Syntax: Emplacing

- What if we wanted to add an object to a vector?

```
std::vector<std::bitset<8>> bitsets{};
bitsets.push_back(std::bitset<8>{0b11001100});
cout << bitsets << '\n';
```

Vector Syntax: Emplacing

- What if we wanted to add an object to a vector?

```cpp
std::vector<std::bitset<8>> bitsets{};
bitsets.push_back(std::bitset<8>{0b11001100});
cout << bitsets << '\n';
```

```
[11001100]
```

Vector Syntax: Emplacing

- What if we wanted to add an object to a vector?

```
std::vector<std::bitset<8>> bitsets{};
bitsets.push_back(std::bitset<8>{0b11001100});
cout << bitsets << '\n';
```

```
[11001100]
```

- This works, but it’s annoying to write the type every time

Vector Syntax: Emplacing

- What if we wanted to add an object to a vector?

```
std::vector<std::bitset<8>> bitsets{};
bitsets.push_back(std::bitset<8>{0b11001100});
cout << bitsets << '\n';
```

```
[11001100]
```

- This works, but it’s annoying to write the type every time
- This solution is also not as efficient as it could be

Vector Syntax: Emplacing

- This is where *emplacing* comes in!

Vector Syntax: Emplacing

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Vector Syntax: Emplacing

- This is where *emplacing* comes in!
- Emplacing lets us construct objects in place

```
const auto &r_last_element{bitsets.emplace_back(0b10101010)};
cout << "last element: " << r_last_element << '\n';
cout << bitsets << '\n';
```

Vector Syntax: Emplacing

- This is where *emplacing* comes in!
- Emplacing lets us construct objects in place

```cpp
const auto &r_last_element{bitsets.emplace_back(0b10101010)};
cout << "last element: " << r_last_element << '\n';
cout << bitsets << '\n';
```

```
last element: 10101010
[11001100, 10101010]
```

Vector Syntax: Emplacing

- This is where *emplacing* comes in!
- Emplacing lets us construct objects in place

```cpp
const auto &r_last_element{bitsets.emplace_back(0b10101010)};
cout << "last element: " << r_last_element << '\n';
cout << bitsets << '\n';
```

```
last element: 10101010
[11001100, 10101010]
```

```cpp
const auto start_iter{bitsets.emplace(bitsets.begin(), 0b11110000)};
cout << "first element: " << *start_iter << '\n';
cout << bitsets << '\n';
```

Vector Syntax: Emplacing

- This is where *emplacing* comes in!
- Emplacing lets us construct objects in place

```
const auto &r_last_element{bitsets.emplace_back(0b10101010)};
cout << "last element: " << r_last_element << '\n';
cout << bitsets << '\n';
```

```
last element: 10101010
[11001100, 10101010]
```

```
const auto start_iter{bitsets.emplace(bitsets.begin(), 0b11110000)};
cout << "first element: " << *start_iter << '\n';
cout << bitsets << '\n';
```

```
first element: 11110000
[11110000, 11001100, 10101010]
```

Vector Syntax: Removing

```cpp
std::vector letters{ 'a', 'b', 'a', 'b', 'c', 'd', 'e', 'f', 'g' };
cout << letters << '\n';
letters.pop_back();
cout << letters << '\n';
```

Vector Syntax: Removing

```
std::vector letters{ 'a', 'b', 'a', 'b', 'c', 'd', 'e', 'f', 'g' };
cout << letters << '\n';
letters.pop_back();
cout << letters << '\n';
```

```
[a, b, a, b, c, d, e, f, g]
[a, b, a, b, c, d, e, f]
```

Vector Syntax: Removing

```cpp
std::vector letters{ 'a', 'b', 'a', 'b', 'c', 'd', 'e', 'f', 'g' };
cout << letters << '\n';
letters.pop_back();
cout << letters << '\n';
```

```
[a, b, a, b, c, d, e, f, g]
[a, b, a, b, c, d, e, f]
```

```cpp
auto middle_iter{std::next(letters.begin(), letters.size() >> 1)};
cout << *middle_iter << '\n';
middle_iter = letters.erase(middle_iter);
cout << *middle_iter << '\n';
cout << letters << '\n';
```

Vector Syntax: Removing

```
std::vector letters{ 'a', 'b', 'a', 'b', 'c', 'd', 'e', 'f', 'g' };
cout << letters << '\n';
letters.pop_back();
cout << letters << '\n';
```

```
[a, b, a, b, c, d, e, f, g]
[a, b, a, b, c, d, e, f]
```

```
auto middle_iter{std::next(letters.begin(), letters.size() >> 1)};
cout << *middle_iter << '\n';
middle_iter = letters.erase(middle_iter);
cout << *middle_iter << '\n';
cout << letters << '\n';
```

```
c
d
[a, b, a, b, d, e, f]
```

Vector Syntax: Removing

```cpp
const auto start_iter{std::prev(letters.end(), 3)};
auto end_iter{std::prev(letters.end())};
cout << *start_iter << ' ' << *end_iter << '\n';
end_iter = letters.erase(start_iter, end_iter);
cout << *end_iter << '\n'; // `start_iter` is no longer valid
cout << letters << '\n';
```

Vector Syntax: Removing

```cpp
const auto start_iter{std::prev(letters.end(), 3)};
auto end_iter{std::prev(letters.end())};
cout << *start_iter << ' ' << *end_iter << '\n';
end_iter = letters.erase(start_iter, end_iter);
cout << *end_iter << '\n'; // `start_iter` is no longer valid
cout << letters << '\n';
```

```
d f
f
[a, b, a, b, f]
```

Vector Syntax: Removing

```cpp
const auto start_iter{std::prev(letters.end(), 3)};
auto end_iter{std::prev(letters.end())};
cout << *start_iter << ' ' << *end_iter << '\n';
end_iter = letters.erase(start_iter, end_iter);
cout << *end_iter << '\n'; // `start_iter` is no longer valid
cout << letters << '\n';
```

```
d f
f
[a, b, a, b, f]
```

```cpp
std::size_t removed_count{std::erase(letters, 'a')};
cout << "removed " << removed_count << '\n';
cout << letters << '\n';
```

Vector Syntax: Removing

```cpp
const auto start_iter{std::prev(letters.end(), 3)};
auto end_iter{std::prev(letters.end())};
cout << *start_iter << ' ' << *end_iter << '\n';
end_iter = letters.erase(start_iter, end_iter);
cout << *end_iter << '\n'; // `start_iter` is no longer valid
cout << letters << '\n';
```

```
d f
f
[a, b, a, b, f]
```

```cpp
std::size_t removed_count{std::erase(letters, 'a')};
cout << "removed " << removed_count << '\n';
cout << letters << '\n';
```

```
removed 2
[b, b, f]
```

Vector Syntax: Removing

```cpp
std::vector<std::int16_t> nums{ 1, 2, 3, 4, 5, 6, 7, 8 };
cout << nums << '\n';
removed_count = std::erase_if(nums, [](const std::int16_t num) noexcept {
   return 3 <= num && num <= 6;
});
cout << "removed " << removed_count << '\n';
cout << nums << endl;
```

Vector Syntax: Removing

```cpp
std::vector<std::int16_t> nums{ 1, 2, 3, 4, 5, 6, 7, 8 };
cout << nums << '\n';
removed_count = std::erase_if(nums, [](const std::int16_t num) noexcept {
    return 3 <= num && num <= 6;
});
cout << "removed " << removed_count << '\n';
cout << nums << endl;
```

```
[1, 2, 3, 4, 5, 6, 7, 8]
removed 4
[1, 2, 7, 8]

Process finished with exit code 0
```

Vector Syntax: Misc.

```cpp
std::vector nums{ 1.2, 3.4, 4.7 };
cout << nums << " : size: " << nums.size() << ", cap: ";
cout << nums.capacity() << ", empty: " << nums.empty() << '\n';
nums.clear();
cout << nums << " : size: " << nums.size() << ", cap: ";
cout << nums.capacity() << ", empty: " << nums.empty() << endl;
```

Vector Syntax: Misc.

```cpp
std::vector nums{ 1.2, 3.4, 4.7 };
cout << nums << " : size: " << nums.size() << ", cap: ";
cout << nums.capacity() << ", empty: " << nums.empty() << '\n';
nums.clear();
cout << nums << " : size: " << nums.size() << ", cap: ";
cout << nums.capacity() << ", empty: " << nums.empty() << endl;
```

```
[1.2, 3.4, 4.7] : size: 3, cap: 3, empty: false
[] : size: 0, cap: 3, empty: true

Process finished with exit code 0
```

Vector Syntax: Resizing

```cpp
std::vector<std::int32_t> nums{};
cout << nums << " : cap: " << nums.capacity() << ", size: " << nums.size() << '\n';
nums.reserve(10U); // can only increase capacity
cout << nums << " : cap: " << nums.capacity() << ", size: " << nums.size() << '\n';
for (std::int32_t i{0}; i < 10; ++i) { nums.push_back(i); }
cout << nums << " : cap: " << nums.capacity() << ", size: " << nums.size() << '\n';
```

Vector Syntax: Resizing

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for (std::int32_t i{0}; i < 10; ++i) { nums.push_back(i); }
cout << nums << " : cap: " << nums.capacity() << ", size: " << nums.size() << '\n';
```

```
[] : cap: 0, size: 0
[] : cap: 10, size: 0
[0, 1, 2, 3, 4, 5, 6, 7, 8, 9] : cap: 10, size: 10
```

Vector Syntax: Resizing

```cpp
nums.push_back(10);
cout << nums << " : cap: " << nums.capacity() << ", size: " << nums.size() << '\n';
nums.shrink_to_fit(); // may or may not shrink capacity to size
cout << nums << " : cap: " << nums.capacity() << ", size: " << nums.size() << endl;
```

Vector Syntax: Resizing

```
nums.push_back(10);
cout << nums << " : cap: " << nums.capacity() << ", size: " << nums.size() << '\n';
nums.shrink_to_fit(); // may or may not shrink capacity to size
cout << nums << " : cap: " << nums.capacity() << ", size: " << nums.size() << endl;
```

```
[0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10] : cap: 20, size: 11
[0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10] : cap: 11, size: 11

Process finished with exit code 0
```

Vector Syntax: Resizing

```cpp
nums.push_back(10);
cout << nums << " : cap: " << nums.capacity() << ", size: " << nums.size() << '\n';
nums.shrink_to_fit(); // may or may not shrink capacity to size
cout << nums << " : cap: " << nums.capacity() << ", size: " << nums.size() << endl;
```

```
[0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10] : cap: 20, size: 11
[0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10] : cap: 11, size: 11

Process finished with exit code 0
```

- Don’t overuse these methods!

Vector Syntax: Resizing

```cpp
std::vector nums{ 1.1, 2.2, 3.3, 4.4, 5.5 };
cout << nums << '\n';
nums.resize(10U);
cout << nums << '\n';
nums.resize(3U);
cout << nums << '\n';
```

Vector Syntax: Resizing

```cpp
std::vector nums{ 1.1, 2.2, 3.3, 4.4, 5.5 };
cout << nums << '\n';
nums.resize(10U);
cout << nums << '\n';
nums.resize(3U);
cout << nums << '\n';
```

```
[1.1, 2.2, 3.3, 4.4, 5.5]
[1.1, 2.2, 3.3, 4.4, 5.5, 0, 0, 0, 0, 0]
[1.1, 2.2, 3.3]
```

Vector Syntax: Resizing

```
nums.resize(6U, 3.14);
cout << nums << '\n';
nums.resize(4U, -2.71);
cout << nums << endl;
```

Vector Syntax: Resizing

```cpp
nums.resize(6U, 3.14);
cout << nums << '\n';
nums.resize(4U, -2.71);
cout << nums << endl;
```

```
[1.1, 2.2, 3.3, 3.14, 3.14, 3.14]
[1.1, 2.2, 3.3, 3.14]

Process finished with exit code 0
```

Vector Syntax: Iteration

```
const std::vector<std::int16_t> nums{ 1, -2, 23, 4, 13 };
```

```
cout << "nums: ";
for (std::size_t i{0U}; i < nums.size(); ++i) {
   cout << nums.at(i) << ' ';
}
cout << '\n';
```

Output:

```
nums: 1 -2 23 4 13
```

Vector Syntax: Iteration

```
const std::vector<std::int16_t> nums{ 1, -2, 23, 4, 13 };
```

```
cout << "nums: ";
for (std::size_t i{0U}; i < nums.size(); ++i) {
   cout << nums.at(i) << ' ';
}
cout << '\n';
```

Output:

```
nums: 1 -2 23 4 13
```

```
cout << "nums: ";
for (std::size_t i{nums.size()}; i > 0U; --i) {
   cout << nums.at(i - 1U) << ' ';
}
cout << '\n';
```

Output:

```
nums: 13 4 23 -2 1
```

Vector Syntax: Iteration

```cpp
cout << "nums: ";
for (auto iter{nums.cbegin()}; iter != nums.cend(); ++iter) {
    cout << *iter << ' ';
}
cout << '\n';
```

Output:

```
nums: 1 -2 23 4 13
```

Vector Syntax: Iteration

```cpp
cout << "nums: ";
for (auto iter{nums.cbegin()}; iter != nums.cend(); ++iter) {
   cout << *iter << ' ';
}
cout << '\n';
```

Output:

```
nums: 1 -2 23 4 13
```

```cpp
cout << "nums: ";
for (auto iter{nums.crbegin()}; iter != nums.crend(); ++iter) {
   cout << *iter << ' ';
}
cout << '\n';
```

Output:

```
nums: 13 4 23 -2 1
```

Vector Syntax: Iteration

```cpp
cout << "nums: ";
for (const std::int16_t num : nums) { cout << num << ' '; }
cout << '\n';
```

Output:

```
nums: 1 -2 23 4 13
```

Undefined Behavior

```
std::vector<std::int16_t> nums{ 1, -2, 23, 4, 13 };
cout << nums[2] << '\n'; // UB if index out of range
cout << nums.front() << '\n'; // UB if `nums` is empty
cout << nums.back() << '\n'; // UB if `nums` is empty
nums.pop_back(); // UB if `nums` is empty
```

Undefined Behavior

```cpp
std::vector<std::int16_t> nums{ 1, -2, 23, 4, 13 };
cout << nums[2] << '\n'; // UB if index out of range
cout << nums.front() << '\n'; // UB if `nums` is empty
cout << nums.back() << '\n'; // UB if `nums` is empty
nums.pop_back(); // UB if `nums` is empty
```

- Additionally, we’re met with UB if certain requirements aren’t met for type T

Iterator Invalidation

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Iterator invalidation is when an existing iterator is rendered unusable by an operation performed on the underlying object

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- The data they point to is no longer in the underlying object
- The memory an iterator points to has been deallocated or repurposed

Iterator Invalidation

- Any time a vector resizes, all iterators are invalidated

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- Any time an element is removed, iterators pointing to that element or any element after it in the sequence are invalidated

Iterator Invalidation

- Any time a vector resizes, all iterators are invalidated
- Any time an element is removed, iterators pointing to that element or any element after it in the sequence are invalidated
- These both include the end iterator

Iterator Invalidation

```cpp
std::vector<std::int32_t> nums{ 1, 2, 3 };
const auto end_iter{nums.end()};
const auto middle_iter{std::next(nums.begin(), nums.size() >> 1)};
nums.erase(middle_iter); // middle_iter and all after invalidated
cout << *middle_iter << '\n'; // 🤖
for (auto iter{nums.begin()}; iter != end_iter; ++iter) { // 🤖
   cout << *iter << ' ';
}
cout << '\n';
```

Iterator Invalidation

```cpp
std::vector<std::int32_t> nums{ 1, 2, 3 };
const auto end_iter{nums.end()};
const auto middle_iter{std::next(nums.begin(), nums.size() >> 1)};
nums.erase(middle_iter); // middle_iter and all after invalidated
cout << *middle_iter << '\n'; // 🤖
for (auto iter{nums.begin()}; iter != end_iter; ++iter) { // 🤖
   cout << *iter << ' ';
}
cout << '\n';
```

```
3
1 3 3
```

Iterator Invalidation

```cpp
std::vector words{ "hello"s, "world"s };
const auto begin_iter{words.begin()};
words.push_back("word"s); // all iterators invalidated due to resize
cout << *begin_iter << endl; // 🤖
```

Iterator Invalidation

```cpp
std::vector words{ "hello"s, "world"s };
const auto begin_iter{words.begin()};
words.push_back("word"s); // all iterators invalidated due to resize
cout << *begin_iter << endl; // 🤖
```

```
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Process finished with exit code 0
```