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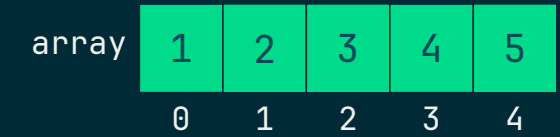

Arrays

Data Structures – C++ Fundamentals

Agenda

- What Are Arrays?
  - Properties
  - Benefits
  - Drawbacks
- Arrays and Memory
  - Cache Locality
  - Memory Levels
  - Memory Lookup
- Working with Arrays
  - Operations
  - Indexing
  - Syntax
- Special Considerations
  - Printing
  - Functions Accepting Arrays
  - Undefined Behavior
- Multi-dimensional Arrays

What Are Arrays?

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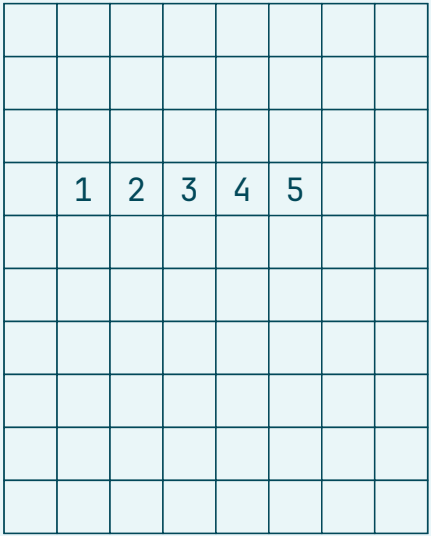

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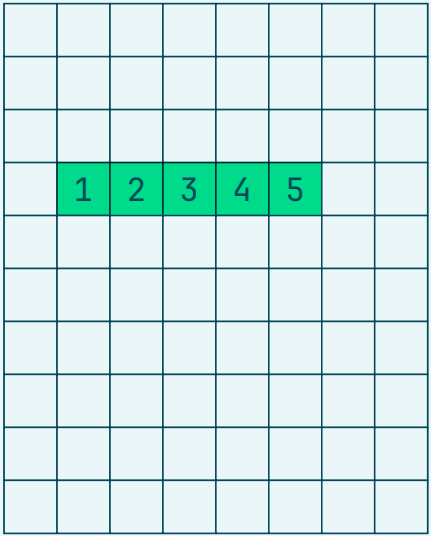

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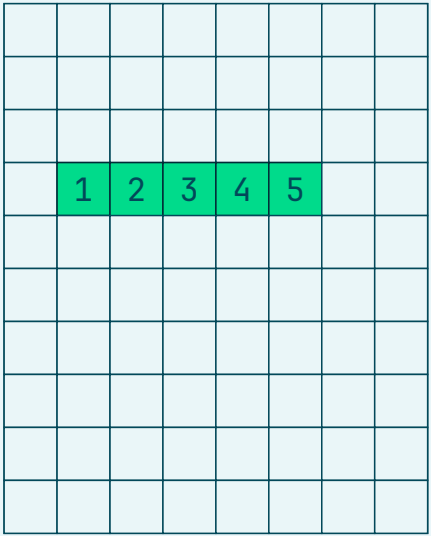

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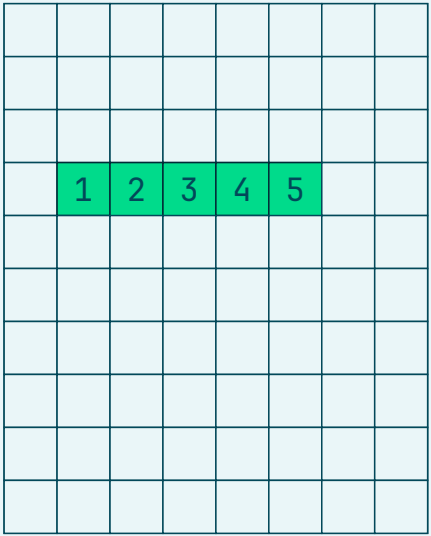

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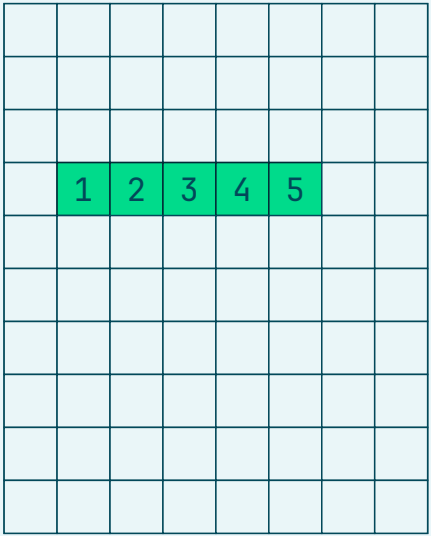

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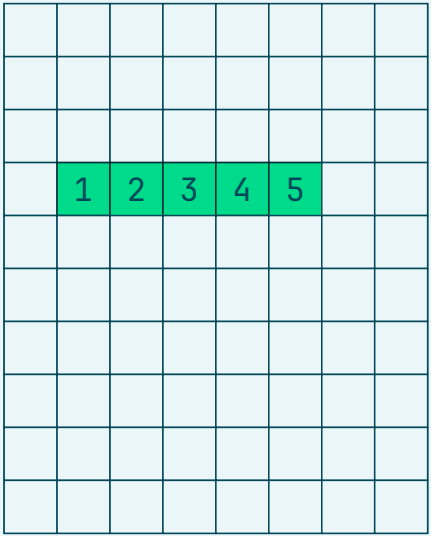

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- Size must be known at compile-time
  - Can’t create arrays from sizes computed at runtime
- Size is fixed
  - Must know exactly how many slots are needed, or must guess safely over the estimated number of slots (e.g., choosing a size of 50 if an actual size of around 20 is expected)

Arrays and Memory

Cache Locality

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What does cache locality refer to?

The tendency of an application to access the same set of memory locations repeatedly over a short period of time

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Cache Locality

What does cache locality refer to?

The tendency of an application to access the same set of memory locations repeatedly over a short period of time

- Temporal locality: recently accessed data is likely to be accessed again
- Spatial locality: data near recently accessed data is likely to be accessed next

How Does Computer Memory Work?

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- Where is computer data permanently stored?

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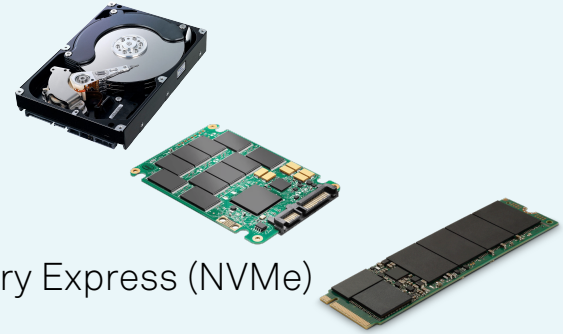

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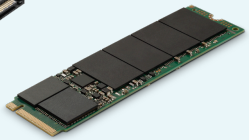

- Retained after shutdown, but slow to access

How Does Computer Memory Work?

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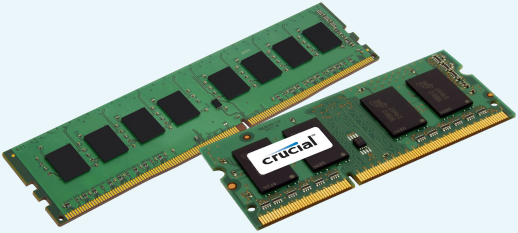
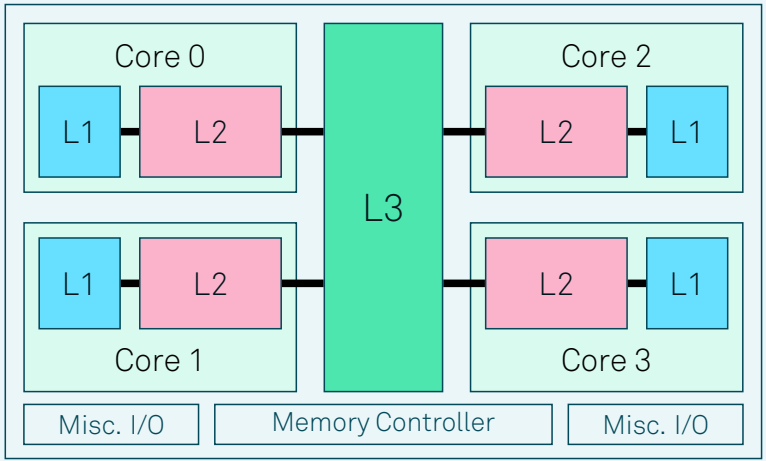


Dynamic Random-access Memory (DRAM)

How Does Computer Memory Work?



CPU

Static
Random-
Access
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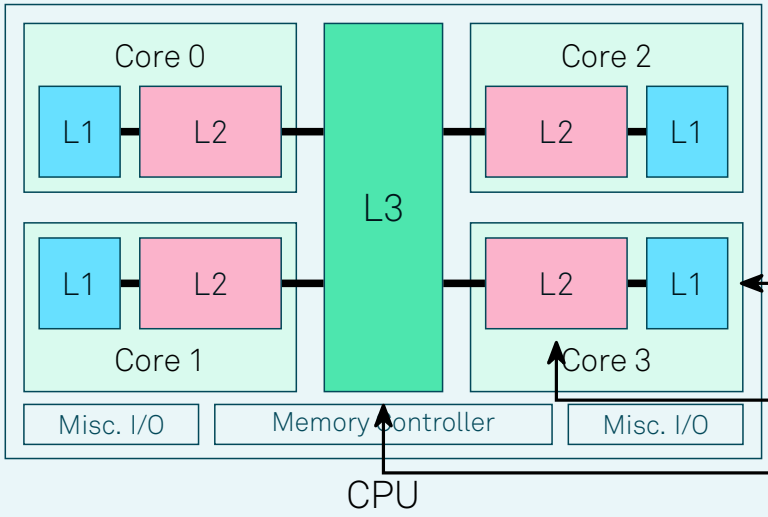

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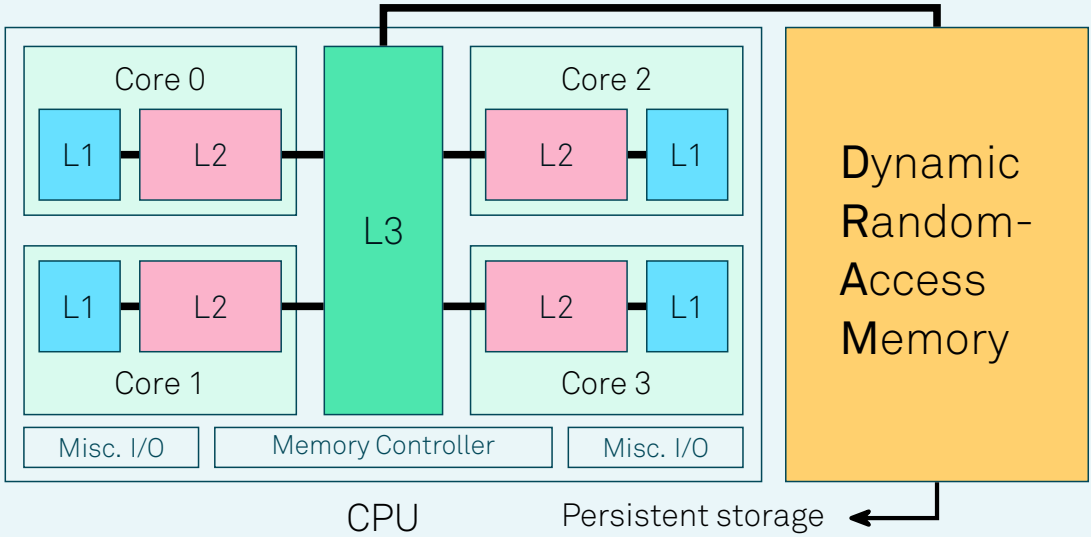
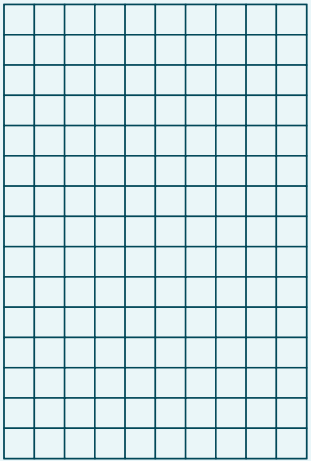


How Do Computers Look Up Data?



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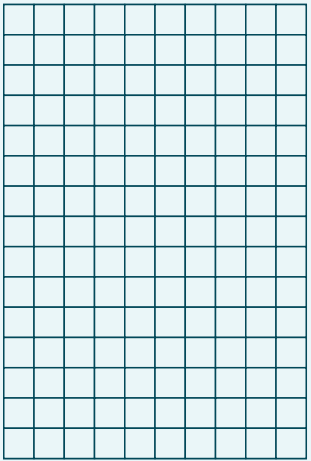

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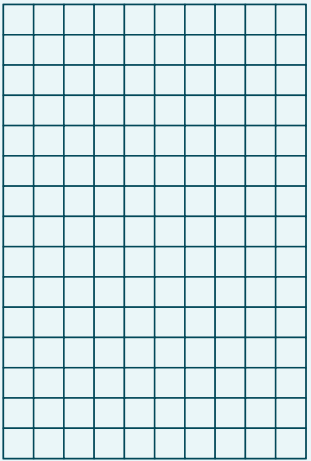

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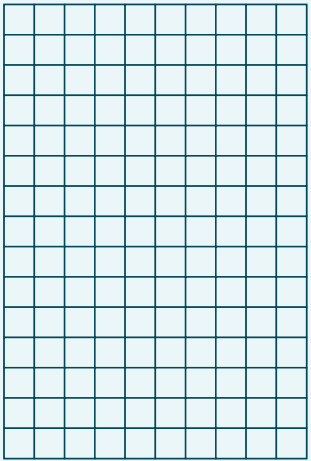

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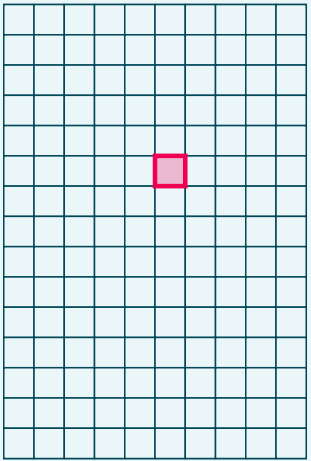

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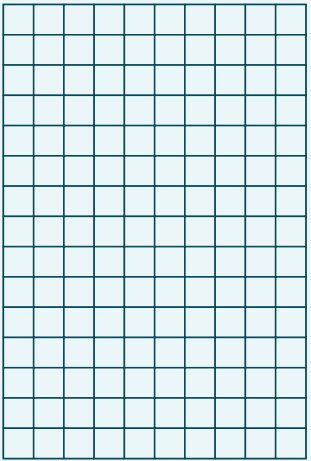

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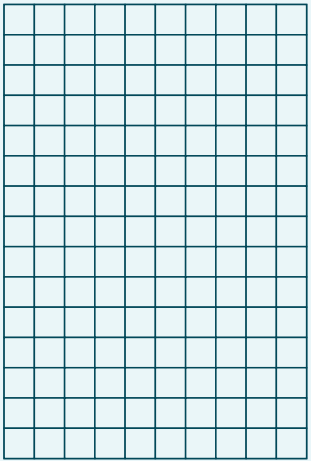

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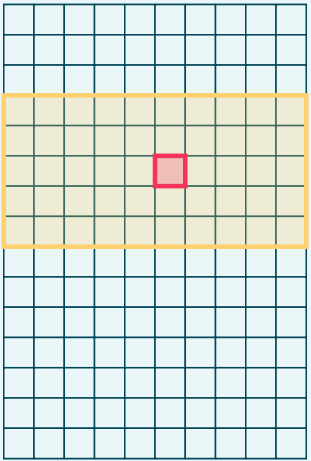

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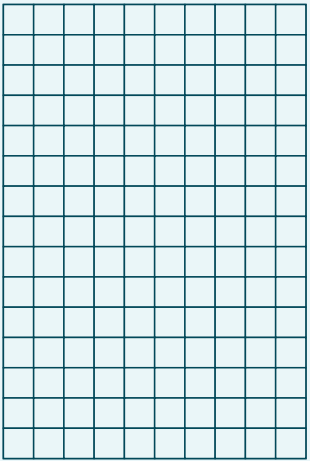

Page 2

Why do arrays have good cache locality?

Working with Arrays

Array Operations

- What operations do arrays have?

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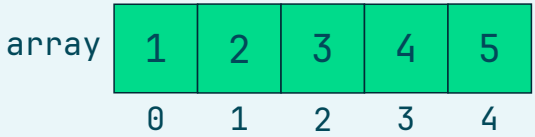
- Some languages allow negative index values (e.g., Python), but C++ is not one of them

Accessing Elements



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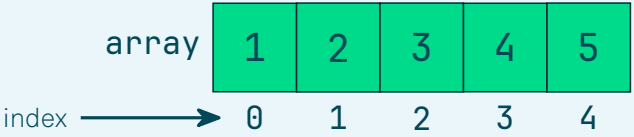

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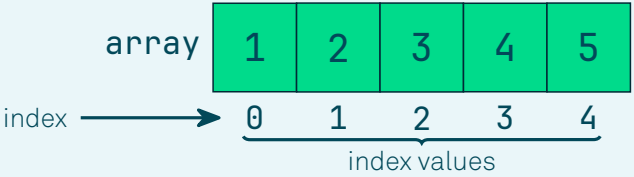

Array Syntax: Creation

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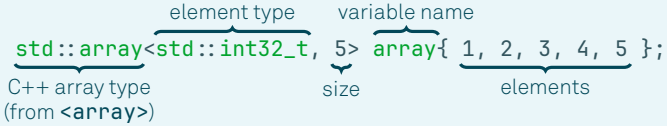

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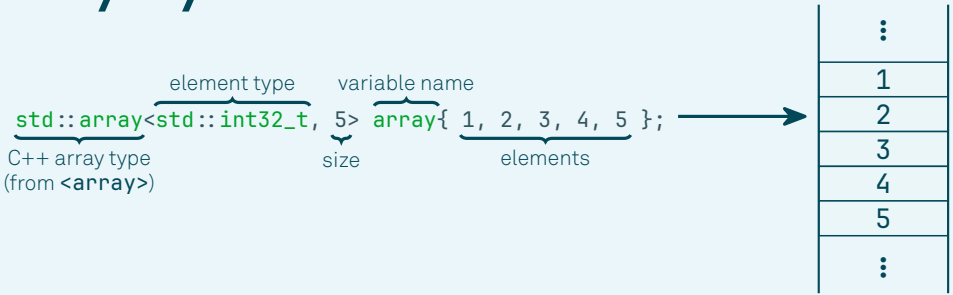

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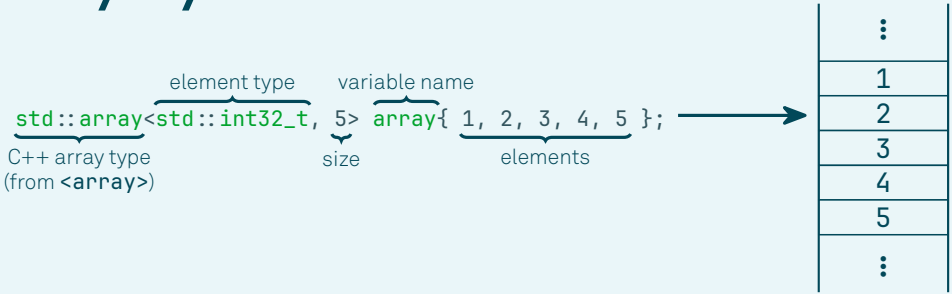


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```

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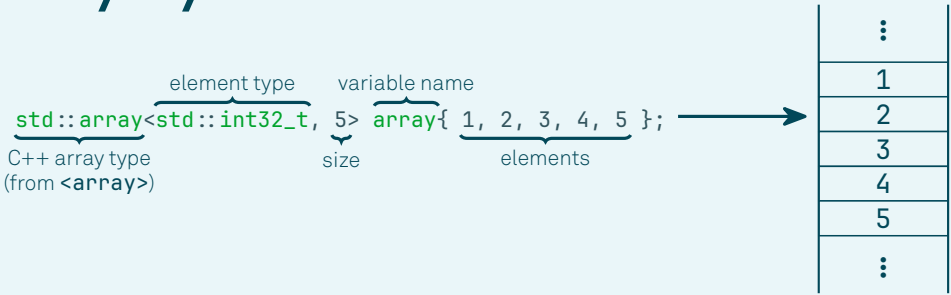


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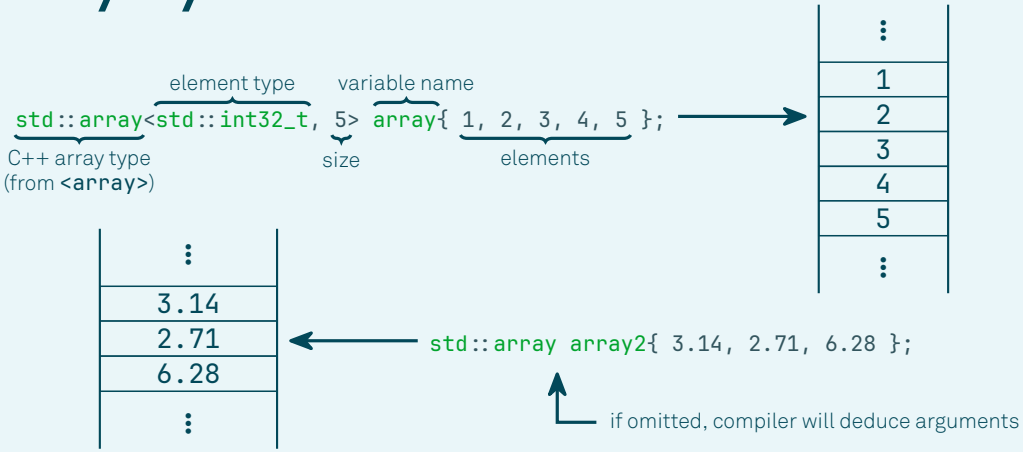
if omitted, compiler will deduce arguments

Array Syntax: Creation



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```
std::array<std::uint64_t, 5> array3{};
```

Array Syntax: Creation

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```
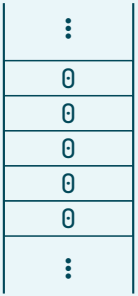

perform zero-initialization
array will be uninitialized without these



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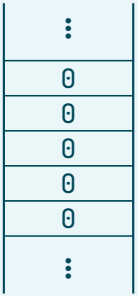
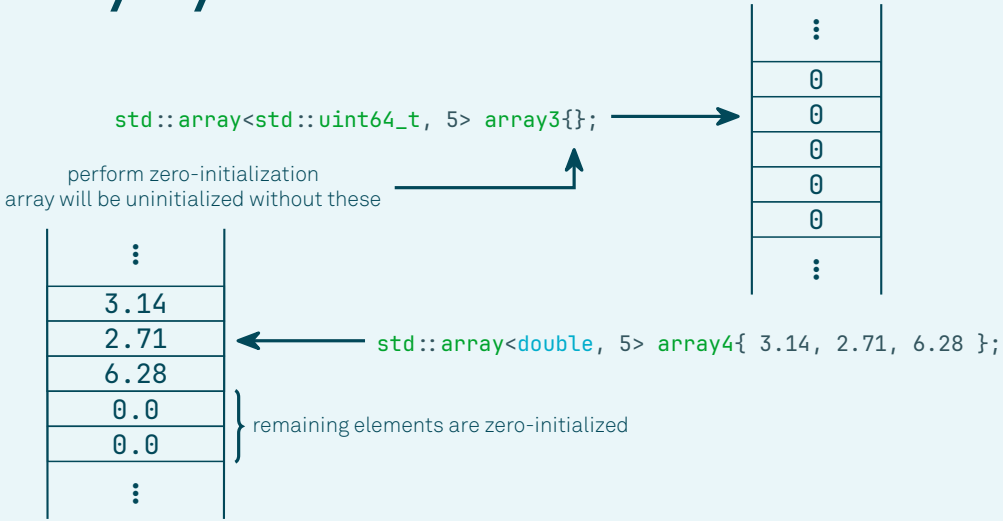



```
std::array<double, 5> array4{ 3.14, 2.71, 6.28 };
```

Array Syntax: Creation



Array Syntax: Creation

```
1  std::array<char, 3> chars{ 'a', 'b', 'c', 'd' };
```

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```
/project/src/main.cpp:1:47: error: excess elements in struct initializer
    1 |     std::array<char, 3> chars{ 'a', 'b', 'c', 'd' };
      |                                               ^~~
1 error generated.
```

Array Syntax: Accessing

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

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```
1
```

Array Syntax: Accessing

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

```
1
```

```
3  cout << array.back() << '\n';
```

Array Syntax: Accessing

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

```
1
```

```
3  cout << array.back() << '\n';
```

```
5
```

Array Syntax: Accessing

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

```
1
```

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

```
5
```

```cpp
cout << array.at(1) << '\n';
```

Array Syntax: Accessing

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

```
1
```

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

```
5
```

```cpp
cout << array.at(1) << '\n';
```

```
2
```

Array Syntax: Accessing

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

Array Syntax: Accessing

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

```
size: 5
```

Array Syntax: Accessing

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

```
size: 5
```

```
6  cout << array.at(array.size() >> 1) << endl;
```

Array Syntax: Accessing

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

```
size: 5
```

```
6  cout << array.at(array.size() >> 1) << endl;
```

```
3

Process finished with exit code 0
```

Array Syntax: Accessing

```
1  std::array<double, 10> numbers{};
2  cout << numbers.at(17) << endl;
```

Array Syntax: Accessing

```
1  std::array<double, 10> numbers{};
2  cout << numbers.at(17) << endl;
```

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

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

Array Syntax: Modifying

```
1  std::array<std::string, 3> words{};
2  words.front() = "hello";
3  cout << words.front() << '\n';
```

Array Syntax: Modifying

```
1  std::array<std::string, 3> words{};
2  words.front() = "hello";
3  cout << words.front() << '\n';
```

```
"hello"
```

Array Syntax: Modifying

```
1  std::array<std::string, 3> words{};
2  words.front() = "hello";
3  cout << words.front() << '\n';
```

```
"hello"
```

```
4  words.at(1) = "world";
5  cout << words.at(1) << endl;
```

Array Syntax: Modifying

```
1  std::array<std::string, 3> words{};
2  words.front() = "hello";
3  cout << words.front() << '\n';
```

```
"hello"
```

```
4  words.at(1) = "world";
5  cout << words.at(1) << endl;
```

```
"world"

Process finished with exit code 0
```

Array Syntax: Modifying

```
1  std::array<bool, 10> flags{};
2  flags.at(-5) = true;
```

Array Syntax: Modifying

```
1  std::array<bool, 10> flags{};
2  flags.at(-5) = true;
```

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

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

Array Syntax: Misc.

```
1  std::array<std::int32_t, 10> values{};
2  values.fill(1);
3  cout << "values: " << values << '\n';
```

Array Syntax: Misc.

```
1  std::array<std::int32_t, 10> values{};
2  values.fill(1);
3  cout << "values: " << values << '\n';
```

```
values: [1, 1, 1, 1, 1, 1, 1, 1, 1, 1]
```

Array Syntax: Misc.

```
1  std::array<std::int32_t, 10> values{};
2  values.fill(1);
3  cout << "values: " << values << '\n';
```

```
values: [1, 1, 1, 1, 1, 1, 1, 1, 1, 1]
```

```
4  cout << boolalpha << "is values empty: " << values.empty() << '\n';
```

Array Syntax: Misc.

```
1  std::array<std::int32_t, 10> values{};
2  values.fill(1);
3  cout << "values: " << values << '\n';
```

```
values: [1, 1, 1, 1, 1, 1, 1, 1, 1, 1]
```

```
4  cout << boolalpha << "is values empty: " << values.empty() << '\n';
```

```
is values empty: false

Process finished with exit code 0
```

Array Syntax: Iteration

```
1  constexpr std::array<std::int16_t, 5> nums{ 1, -2, 23, 4, 13 };
```

```
2  cout << "nums: ";
3  for (std::size_t i{0U}; i < nums.size(); ++i) {
4     cout << nums.at(i) << ' ';
5  }
6  cout << '\n';
```

Output:

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

Array Syntax: Iteration

```cpp
constexpr std::array<std::int16_t, 5> nums{ 1, -2, 23, 4, 13 };
```

```cpp
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
```

```cpp
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
```

Array Syntax: Iteration

```
12  cout << "nums: ";
13  for (auto iter{nums.cbegin()}; iter =/= nums.cend(); ++iter) {
14     cout << *iter << ' ';
15  }
16  cout << '\n';
```

Output:

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

Array Syntax: Iteration

```
12  cout << "nums: ";
13  for (auto iter{nums.cbegin()}; iter != nums.cend(); ++iter) {
14     cout << *iter << ' ';
15  }
16  cout << '\n';
```

Output:

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

```
17  cout << "nums: ";
18  for (auto iter{nums.crbegin()}; iter != nums.crend(); ++iter) {
19     cout << *iter << ' ';
20  }
21  cout << '\n';
```

Output:

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

Array Syntax: Iteration

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

Output:

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

Special Considerations

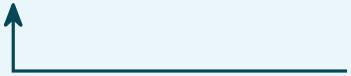
Array Syntax: Printing

- By default, arrays are not printable with `std::cout`

Array Syntax: Printing

- By default, arrays are not printable with `std::cout`

```
std::array<std::uint16_t, 3> scores{};
cout << scores << endl;
```

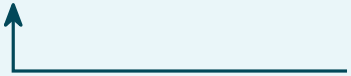


C++ has no idea how to use the insertion operator with `std::array`

Array Syntax: Printing

- By default, arrays are not printable with **`std::cout`**

```
std::array<std::uint16_t, 3> scores{};
cout << scores << endl;
```



C++ has no idea how to use the insertion operator with **`std::array`**

- What if we could tell C++ what to do?

Array Syntax: Printing

Operator overloading

Operator overloading is when we tell a programming language how to use a particular operator with certain types

Array Syntax: Printing

Operator overloading

Operator overloading is when we tell a programming language how to use a particular operator with certain types

- New types feel like existing types

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- New types feel like existing types
- Can specify operator behavior externally

Array Syntax: Printing

Operator overloading

Operator overloading is when we tell a programming language how to use a particular operator with certain types

- New types feel like existing types
- Can specify operator behavior externally
- Can make code both more readable and less readable

Array Syntax: Printing

- How do we overload operators?

```
constexpr std::string name{"Stroustrup"};
cout << "Nice to meet you, " << name << "!\n";
```

Array Syntax: Printing

- How do we overload operators? Operators are actually functions!

```
constexpr std::string name{"Stroustrup"};
cout << "Nice to meet you, " << name << "!\n";
```

```
constexpr std::string name{"Stroustrup"};
operator<<(operator<<(operator<<(cout, "Nice to meet you, "), name), "!\n");
```

Array Syntax: Printing

- How do we overload operators? Operators are actually functions!

```
constexpr std::string name{"Stroustrup"};
cout << "Nice to meet you, " << name << "!\n";
```

```
constexpr std::string name{"Stroustrup"};
operator<<(operator<<(operator<<(cout, "Nice to meet you, "), name), "!\n");
```

```
Nice to meet you, Stroustrup!
```

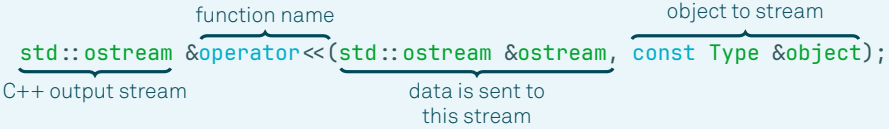
Array Syntax: Printing

- To overload the insertion operator, we need to define a function with the following signature:

```
std::ostream &operator<<(std::ostream &ostream, const Type &object);
```

Array Syntax: Printing

- To overload the insertion operator, we need to define a function with the following signature:



Array Syntax: Printing

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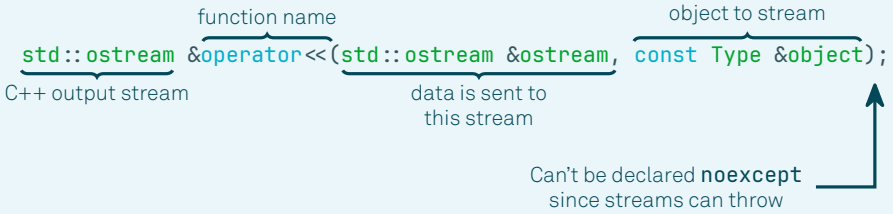
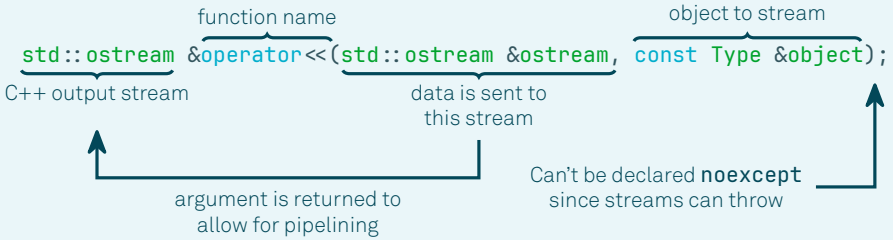


Array Syntax: Printing

- To overload the insertion operator, we need to define a function with the following signature:



Array Syntax: Printing

- This means our insertion operator should look like the following:

```
std::ostream &operator<<(std::ostream &ostream,
                         const std::array<std::int32_t, 5> &array);
```

Array Syntax: Printing

- This means our insertion operator should look like the following:

```
std::ostream &operator<<(std::ostream &ostream,
                         const std::array<std::int32_t, 5> &array);
```

- Does this look good?

Array Syntax: Printing

- How do we write generic functions that accept different types of arrays?

Array Syntax: Printing

- How do we write generic functions that accept different types of arrays? Templating!

Array Syntax: Printing

- How do we write generic functions that accept different types of arrays? Templating!

What is templating?

Templating is a way of writing code that allows us to define a *family* of code entities

Array Syntax: Printing

```
std::int32_t add(const std::int32_t a, const std::int32_t b) noexcept {
   return a + b;
}
```

Array Syntax: Printing

```
std::int32_t add(const std::int32_t a, const std::int32_t b) noexcept {
   return a + b;
}
```

- What about this function is specific to `std::int32_t` values?

Array Syntax: Printing

```
std::int32_t add(const std::int32_t a, const std::int32_t b) noexcept {
   return a + b;
}
```

- What about this function is specific to `std::int32_t` values?
- How can we write this function so it works with any type that supports `operator+`?

Array Syntax: Printing

```
template <typename T>
T add(const T &a, const T &b) { return a + b; }
```

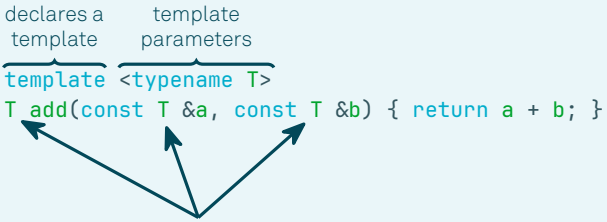
Array Syntax: Printing

declares a template

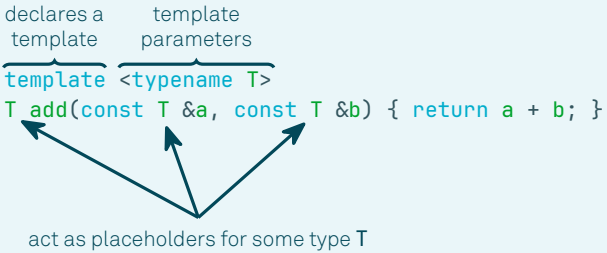
template parameters

```
template <typename T>
T add(const T &a, const T &b) { return a + b; }
```

Array Syntax: Printing

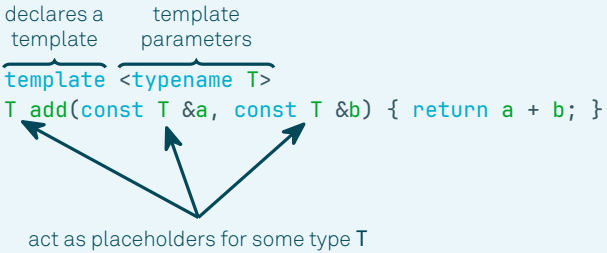


Array Syntax: Printing



- Represents a family of functions where T could be any type.

Array Syntax: Printing



- Represents a family of functions where T could be any type.
- Does this function seem like it would cause any issues?

Array Syntax: Printing

```
constexpr std::string string1{"Hello, "};
constexpr std::string string2{"world!"};
cout << "add(3, 5) = " << add(3, 5) << '\n';
cout << "add(3.14, 2.71) = " << add(3.14, 2.71) << '\n';
cout << "add(string1, string2) = " << add(string1, string2) << '\n';
```

```
add(3, 5) = 8
add(3.14, 2.71) = 5.85
add(string1, string2) = Hello, world!
```

Array Syntax: Printing

```
constexpr std::string string1{"Hello, "};
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cout << "add(3, 5) = " << add(3, 5) << '\n';
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cout << "add(string1, string2) = " << add(string1, string2) << '\n';
```

```
add(3, 5) = 8
add(3.14, 2.71) = 5.85
add(string1, string2) = Hello, world!
```

- How do templates work?

Array Syntax: Printing

```
constexpr std::string string1{"Hello, "};
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cout << "add(3, 5) = " << add(3, 5) << '\n';
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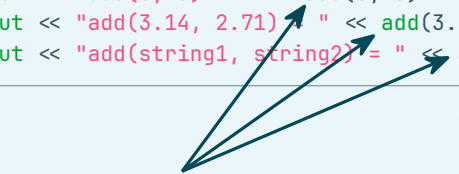
cout << "add(string1, string2) = " << add(string1, string2) << '\n';
```



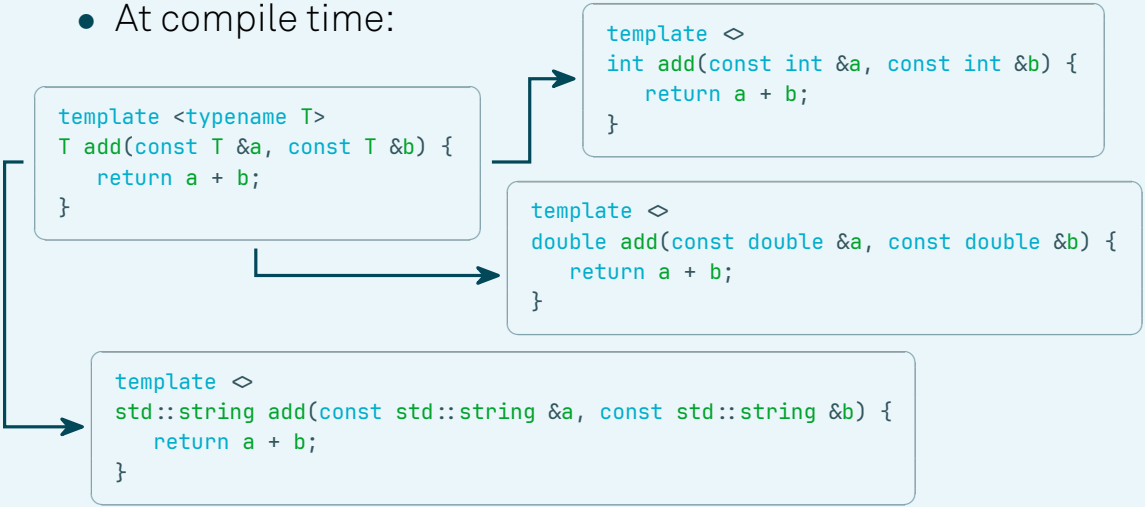
at compile-time, compiler generates a version for each function call

```
add(3, 5) = 8
add(3.14, 2.71) = 5.85
add(string1, string2) = Hello, world!
```

- How do templates work?

Array Syntax: Printing

- At compile time:



Array Syntax: Printing

- Key aspects of templates

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  - Templates represent families of different code entities (for now, we only care about function templates)

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  - Templates are resolved at compile-time

Array Syntax: Printing

- Key aspects of templates
  - Templates represent families of different code entities (for now, we only care about function templates)
  - Templates are resolved at compile-time
  - After templates are resolved, it's as if we wrote separate versions for each code entity

Array Syntax: Printing

- Implications of templates

Array Syntax: Printing

- Implications of templates
  - What code will be generated if we don't use templated code?

Array Syntax: Printing

- Implications of templates
  - If a template is not used, no code is generated

Array Syntax: Printing

- Implications of templates
  - If a template is not used, no code is generated
  - How might templates negatively affect compilation, if at all?

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  - Templated code takes longer to compile

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  - If a template is not used, no code is generated
  - Templated code takes longer to compile
  - How might templates negatively affect application size, if at all?

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  - If a template is not used, no code is generated
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  - The more templated code is used, the more code is generated

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Array Syntax: Printing

- Implications of templates
  - If a template is not used, no code is generated
  - Templated code takes longer to compile
  - The more templated code is used, the more code is generated
  - Templates don't negatively affect runtime since the magic happens at compile-time

Array Syntax: Printing

- How does this help with our insertion-operator overload?

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```
std::ostream &operator<<(std::ostream &ostream,
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- How does this help with our insertion-operator overload?

```
std::ostream &operator<<(std::ostream &ostream,
                         const std::array<std::int32_t, 5> &array);
```

```
template <typename T>
std::ostream &operator<<(std::ostream &ostream,
                         const std::array<T, 5> &array);
```

Array Syntax: Printing

- How does this help with our insertion-operator overload?

```
std::ostream &operator<<(std::ostream &ostream,
                         const std::array<std::int32_t, 5> &array);
```

```
template <typename T>
std::ostream &operator<<(std::ostream &ostream,
                         const std::array<T, 5> &array);
```

```
template <typename T, std::size_t size>
std::ostream &operator<<(std::ostream &ostream,
                         const std::array<T, size> &array);
```

Array Syntax: Printing

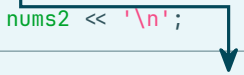
- At compile time:

```
constexpr std::array nums{ 3.14, 2.71, 6.28 };
constexpr std::array<std::int32_t, 2> nums2{ 1, 2 };
cout << "nums: " << nums << '\n';
cout << "nums2: " << nums2 << '\n';
```

Array Syntax: Printing

- At compile time:

```
constexpr std::array nums{ 3.14, 2.71, 6.28 };
constexpr std::array<std::int32_t, 2> nums2{ 1, 2 };
cout << "nums: " << nums << '\n';
cout << "nums2: " << nums2 << '\n';
```



```
template <>
std::ostream &operator<<(std::ostream &ostream, const std::array<double, 3> &array);
```

Array Syntax: Printing

- At compile time:

```
constexpr std::array nums{ 3.14, 2.71, 6.28 };
constexpr std::array<std::int32_t, 2> nums2{ 1, 2 };
cout << "nums: " << nums << '\n';
cout << "nums2: " << nums2 << '\n';
```

```
template <>
std::ostream &operator<<(std::ostream &ostream, const std::array<double, 3> &array);
```

```
template <>
std::ostream &operator<<(std::ostream &ostream, const std::array<std::int32_t, 2> &array);
```

Undefined Behavior

- We can also use the subscript operator (`[]`) to access elements:

```
std::array nums{ 1.1, 2.2, 3.3 };
cout << "nums: " << nums << '\n';
nums[0] = 4.4;
cout << "first element: " << nums[0] << '\n';
cout << "nums: " << nums << '\n';
```

```
nums: [1.1, 2.2, 3.3]
first element: 4.4
nums: [4.4, 2.2, 3.3]

Process finished with exit code 0
```

Undefined Behavior

- What will happen if this code is run?

```
1  constexpr std::array nums{ 1.1, 2.2, 3.3, 4.4, 5.5 };
2  std::array nums2{ 1.23, 4.56, 2.2 };
3  cout << "nums[100]: " << nums[100] << '\n';
4  cout << "nums2[-20]: " << nums2[-20] << '\n';
```

Undefined Behavior

- What will happen if this code is run?

```
1  constexpr std::array nums{ 1.1, 2.2, 3.3, 4.4, 5.5 };
2  std::array nums2{ 1.23, 4.56, 2.2 };
3  cout << "nums[100]: " << nums[100] << '\n';
4  cout << "nums2[-20]: " << nums2[-20] << '\n';
```

```
nums[100]: 4.44388e+252
nums2[-20]: 2.15003e-314
```

Undefined Behavior

- What will happen if this code is run?

```
1  constexpr std::array nums{ 1.1, 2.2, 3.3, 4.4, 5.5 };
2  std::array nums2{ 1.23, 4.56, 2.2 };
3  cout << "nums[100]: " << nums[100] << '\n';
4  cout << "nums2[-20]: " << nums2[-20] << '\n';
```

```
nums[100]: 4.44388e+252
nums2[-20]: 2.15003e-314
```

```
5  nums2[5] = -33.3;
6  cout << "nums: " << nums << '\n';
```

Undefined Behavior

- What will happen if this code is run?

```
1  constexpr std::array nums{ 1.1, 2.2, 3.3, 4.4, 5.5 };
2  std::array nums2{ 1.23, 4.56, 2.2 };
3  cout << "nums[100]: " << nums[100] << '\n';
4  cout << "nums2[-20]: " << nums2[-20] << '\n';
```

```
nums[100]: 4.44388e+252
nums2[-20]: 2.15003e-314
```

```
5  nums2[5] = -33.3;
6  cout << "nums: " << nums << '\n';
```

```
nums: [1.1, 2.2, -33.3, 4.4, 5.5]

Process finished with exit code 0
```

Undefined Behavior

- How far can this be pushed?

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```
7  cout << "nums[1'000]: " << nums[1'000] << endl;
```

Undefined Behavior

- How far can this be pushed?

```
7  cout << "nums[1'000]: " << nums[1'000] << endl;
```

```
Process finished with exit code 139 (interrupted by signal 11:SIGSEGV)
```

Undefined Behavior

- How far can this be pushed?

```
7  cout << "nums[1'000]: " << nums[1'000] << endl;
```

```
Process finished with exit code 139 (interrupted by signal 11:SIGSEGV)
```

- Why allow this?

Multi-dimensional Arrays

Two-dimensional Arrays

- Arrays of arrays

Two-dimensional Arrays

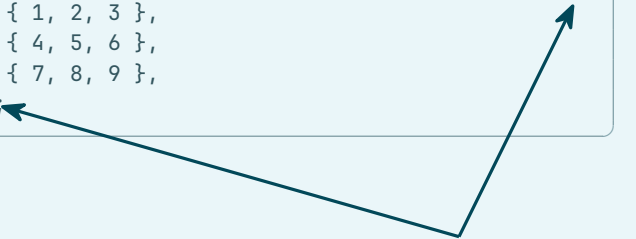
- Arrays of arrays

```
std::array<std::array<std::int32_t, 3>, 3> grid{{
   { 1, 2, 3 },
   { 4, 5, 6 },
   { 7, 8, 9 },
}};
```

Two-dimensional Arrays

- Arrays of arrays

```
1  std::array<std::array<std::int32_t, 3>, 3> grid{{
2     { 1, 2, 3 },
3     { 4, 5, 6 },
4     { 7, 8, 9 },
5  }};
```



Two-dimensional Arrays

- Arrays of arrays

```
1  std::array<std::array<std::int32_t, 3>, 3> grid{{
2     { 1, 2, 3 },
3     { 4, 5, 6 },
4     { 7, 8, 9 },
5  }};
```

note the double curly brackets
needed for multi-dimensional arrays

grid	0	1	2
0	1	2	3
1	4	5	6
2	7	8	9

Two-dimensional Arrays

```
6  cout << "grid: " << grid << '\n';
7  cout << "center value: " << grid.at(1).at(1) << '\n';
8  grid.at(1) = { 40, 50, 60 };
9  cout << "grid: " << grid << endl;
```

```
grid: [[1, 2, 3], [4, 5, 6], [7, 8, 9]]
center value: 5
grid: [[1, 2, 3], [40, 50, 60], [7, 8, 9]]
```

Two-dimensional Arrays

- What do two-dimensional arrays look like in memory?

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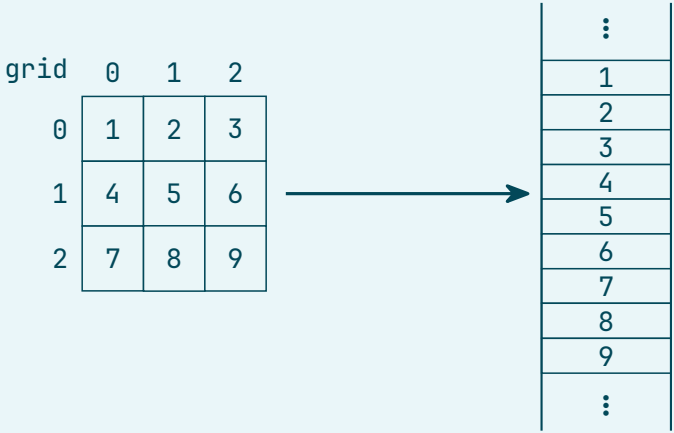

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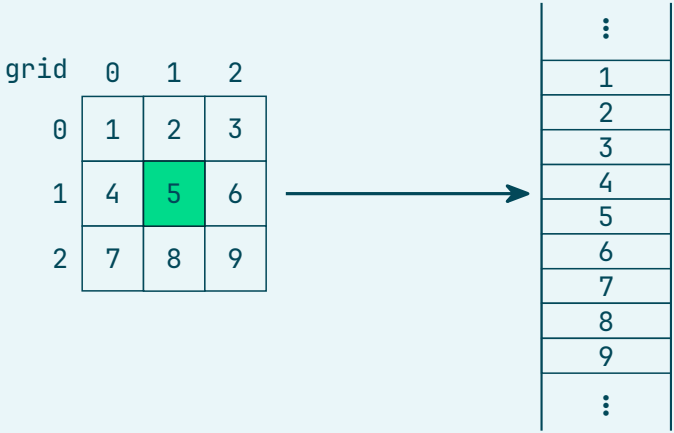

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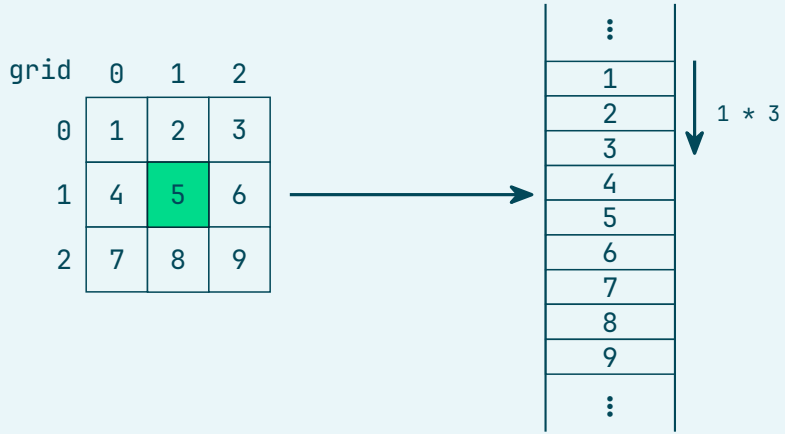

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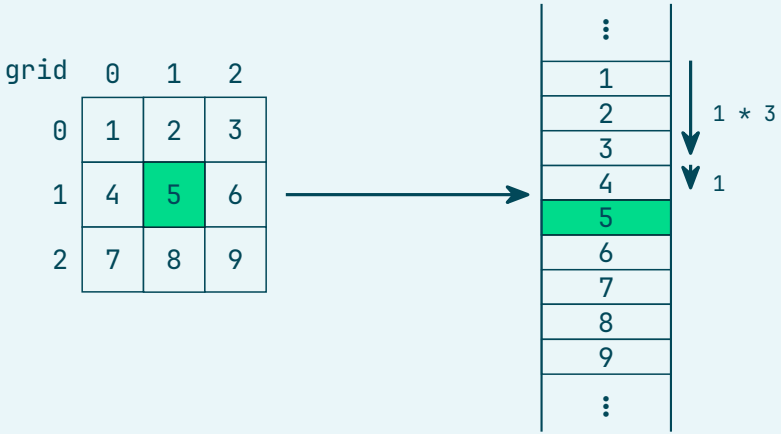

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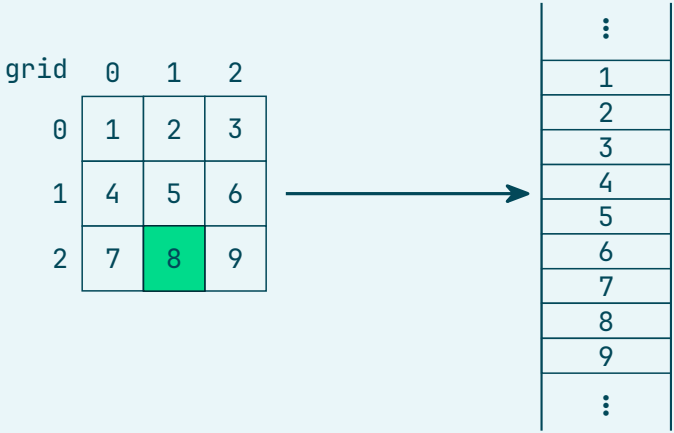

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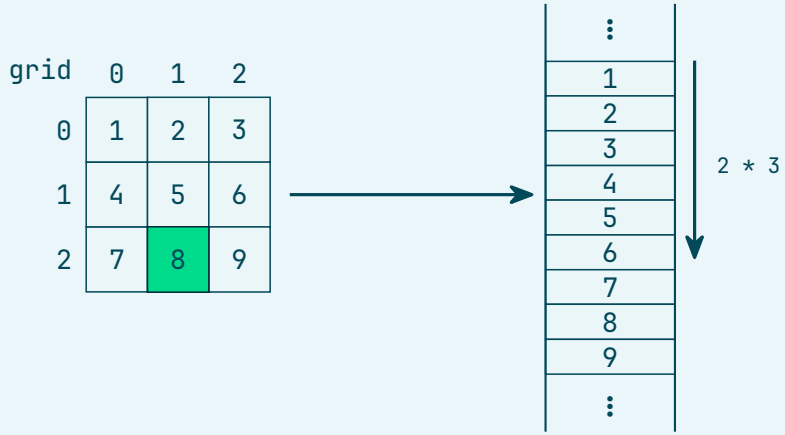

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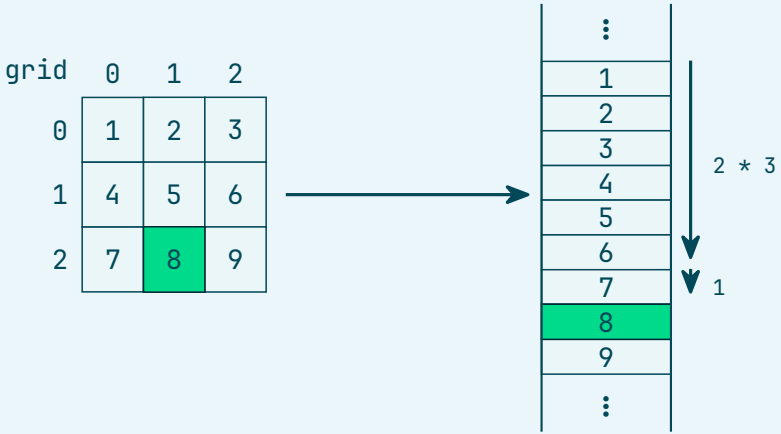

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Multi-dimensional Arrays

- These concepts extend to more than two dimensions
  - Three-dimensional array: rectangular prism
  - Four-dimensional array: hyper rectangular prism
  - *n*-dimensional array: *n*-dimensional shape
- Most uses of multi-dimensional arrays in systems programming stop at three-dimensional arrays

Any Questions?