



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

array

1	2	3	4	5
0	1	2	3	4

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?

Array Properties

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An *array* is a fixed-length, contiguous, random-access sequence of homogeneous values

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- The size of an array must be known at *compile-time*
- Values are stored in adjacent memory slots
- Any value can be accessed at random
- Values are ordered (indexed for arrays)

Benefits of Arrays

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- Fixed-size benefits

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 - Optimized

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1	2	3	4	5	

Benefits of Arrays

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 - Stored on the stack
 - Contiguous benefits
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 - Elements can be traversed in particular orders
 - Can be subsequenced

Drawbacks of Arrays

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Drawbacks of Arrays

- 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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How Does Computer Memory Work?

- Where is computer data permanently stored? Persistent storage!
 - Hard Disk Drive (HDD)
 - Solid-state Drive (SSD)
 - Non-volatile Memory Express (NVMe)
- Retained after shutdown, but slow to access



How Does Computer Memory Work?

- What do CPUs use?

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- What do CPUs use? Volatile memory!

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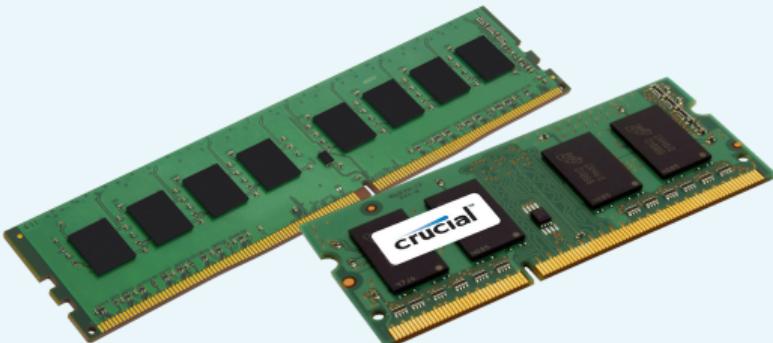
Static Random-access Memory
(SRAM)

How Does Computer Memory Work?

- What do CPUs use? Volatile memory!

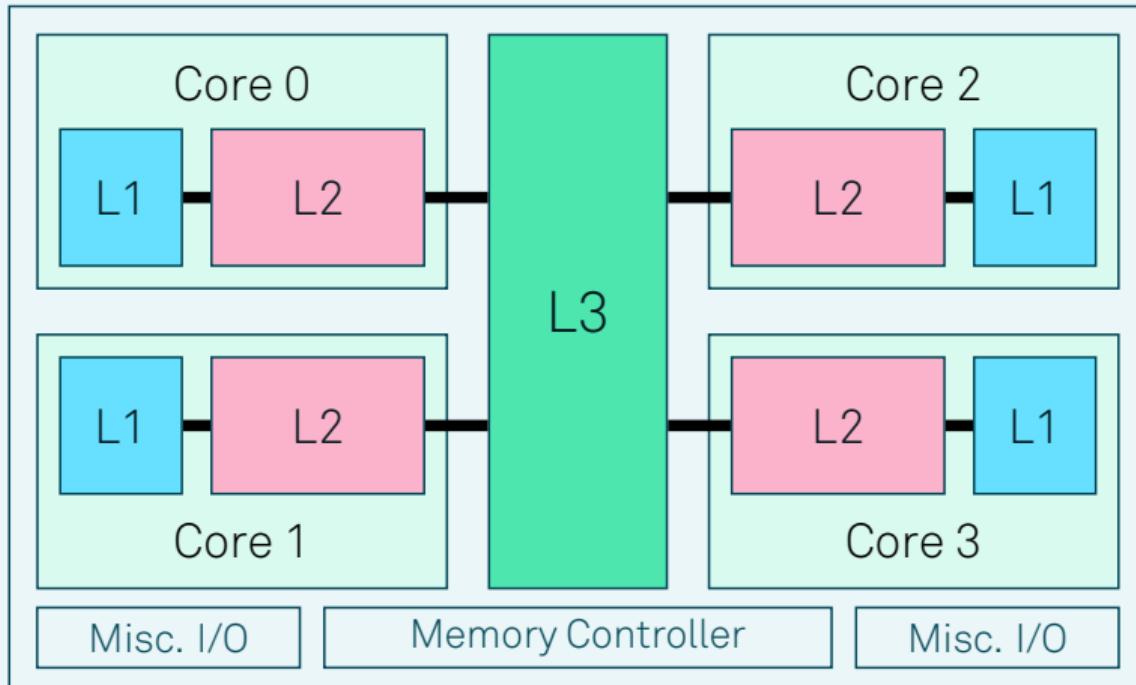


Static Random-access Memory
(SRAM)



Dynamic Random-access Memory
(DRAM)

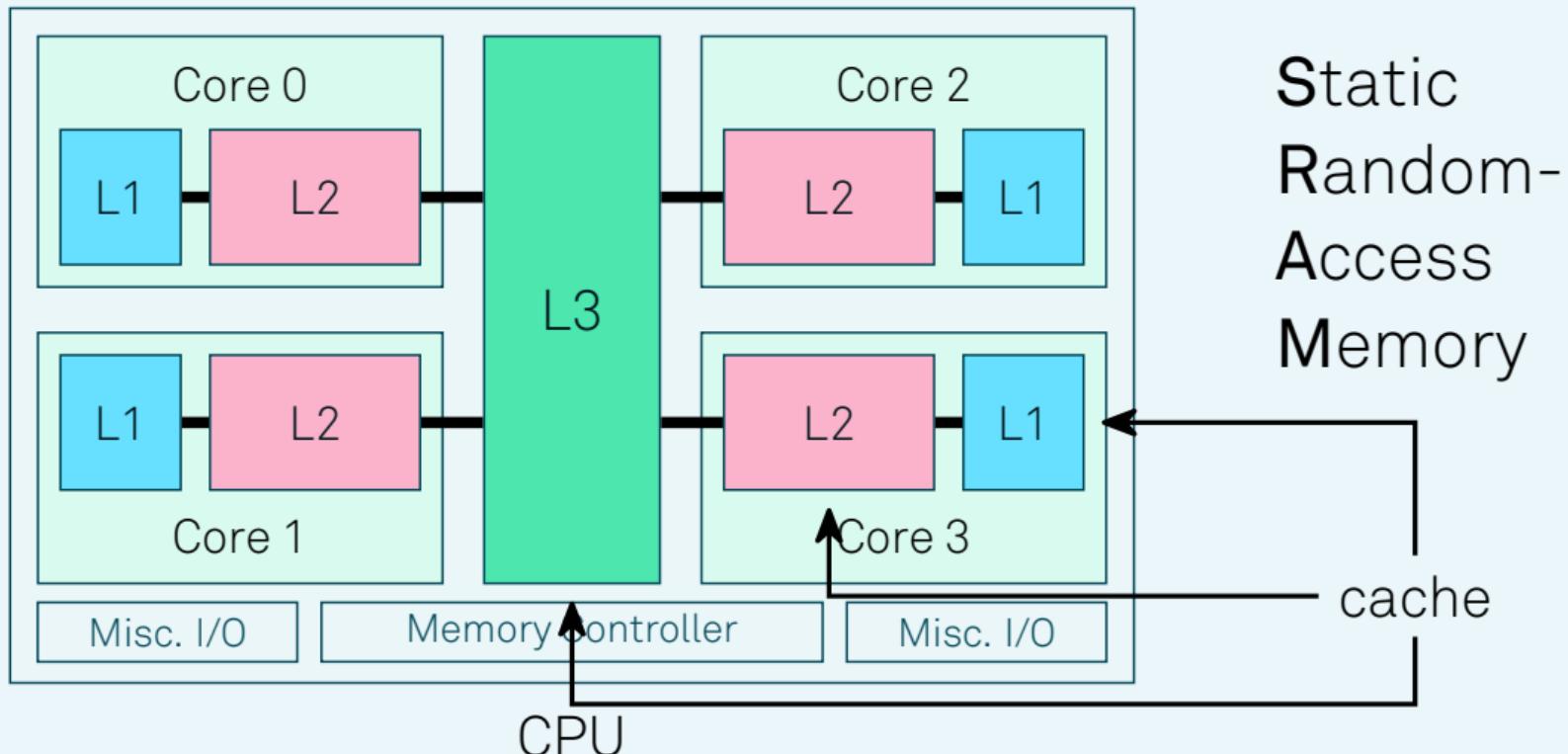
How Does Computer Memory Work?



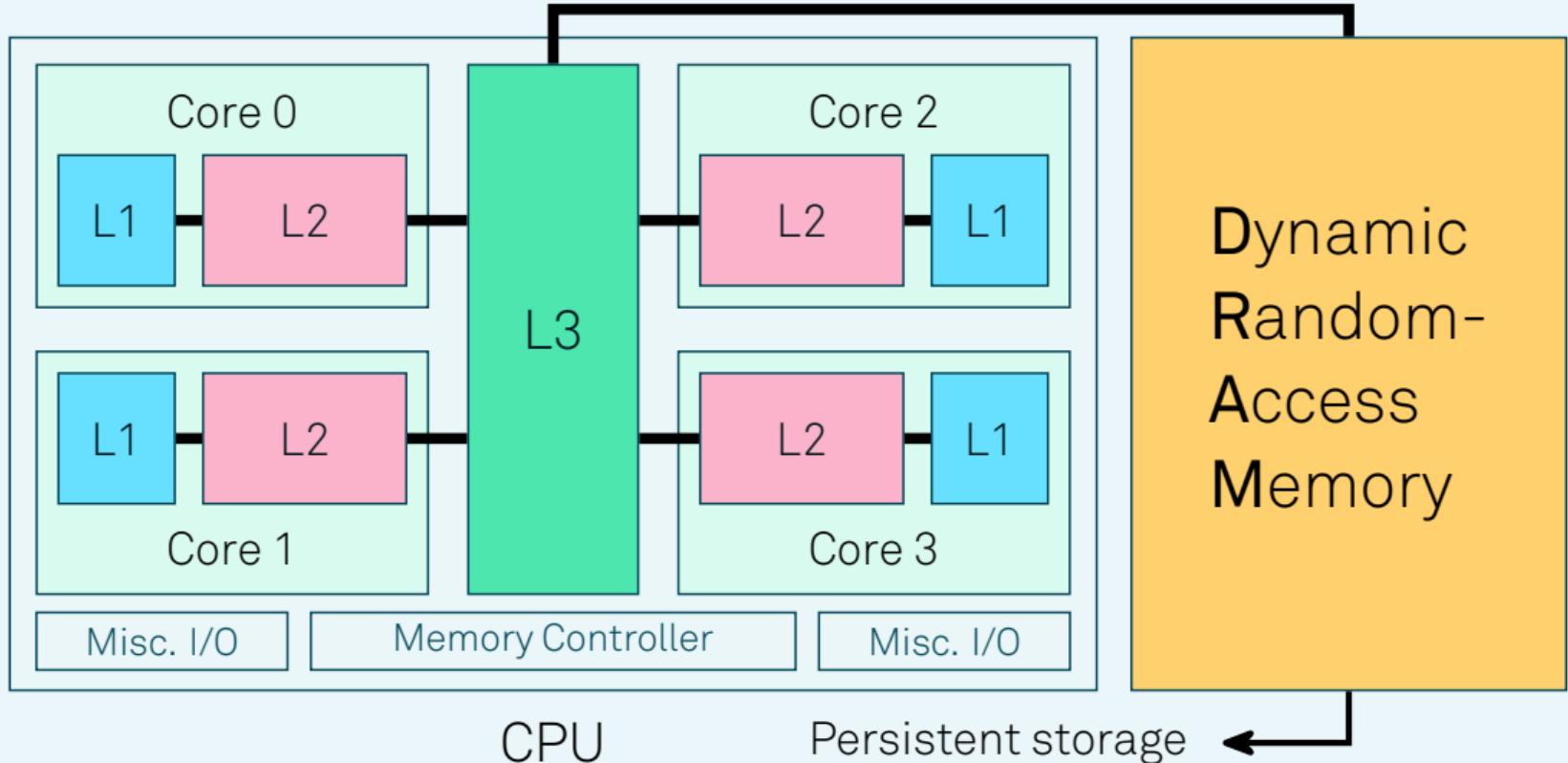
Static
Random-
Access
Memory

CPU

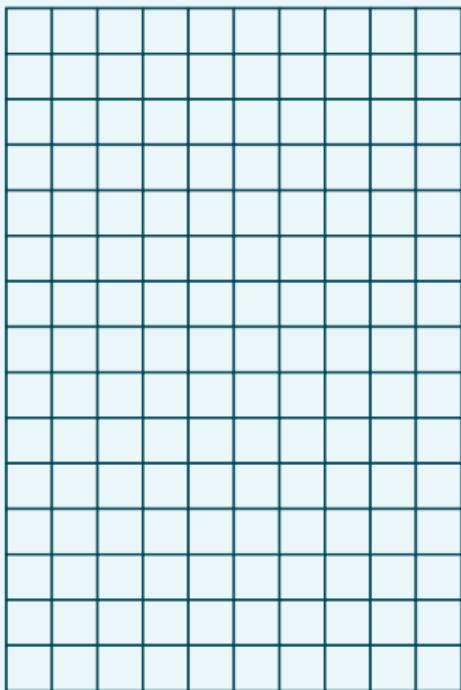
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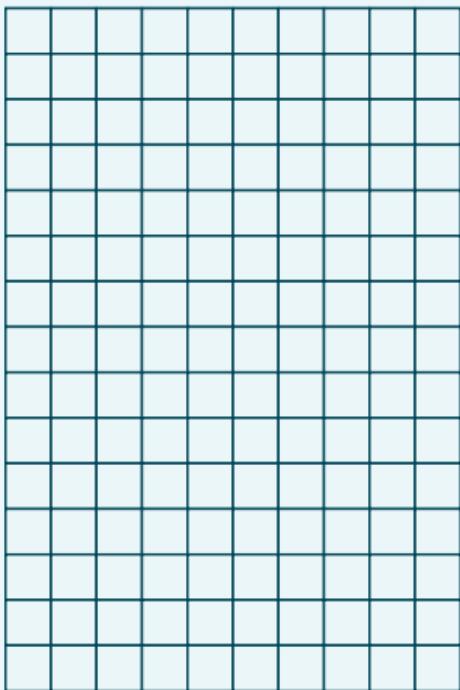
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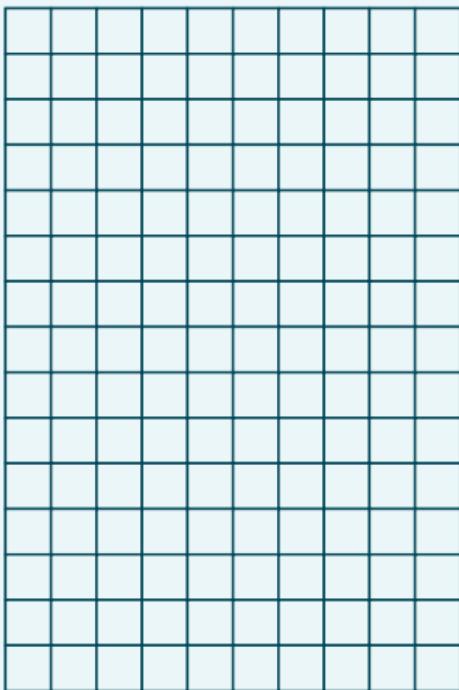
How Do Computers Look Up Data?



Page 0

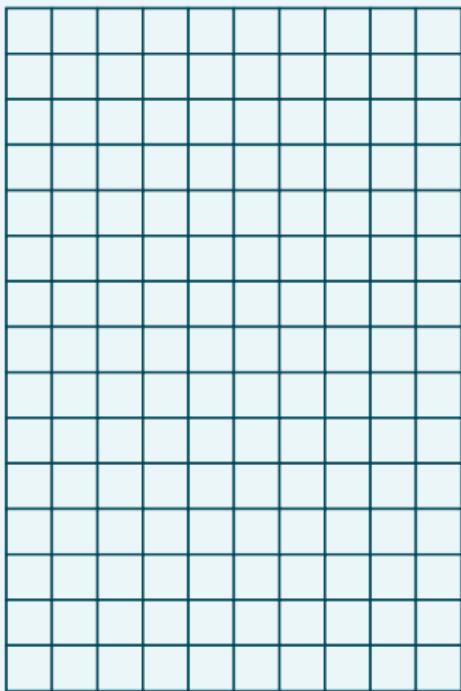


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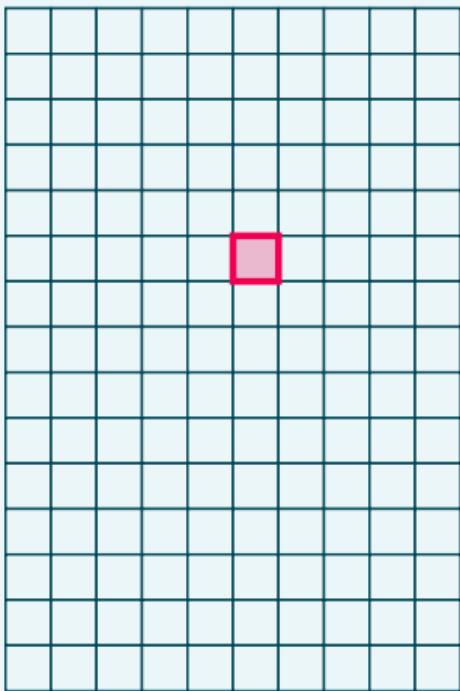


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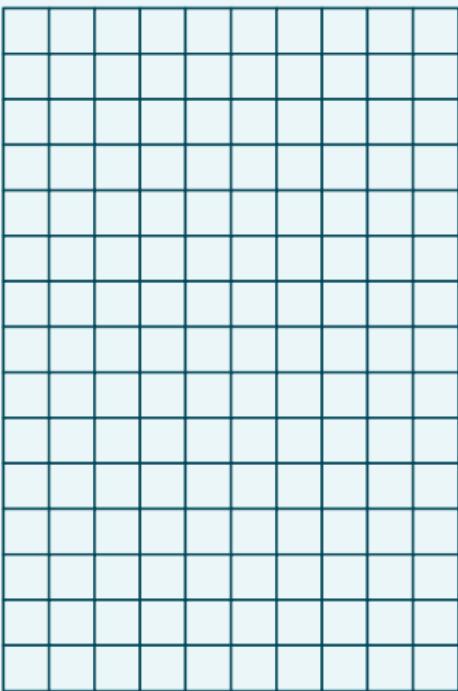
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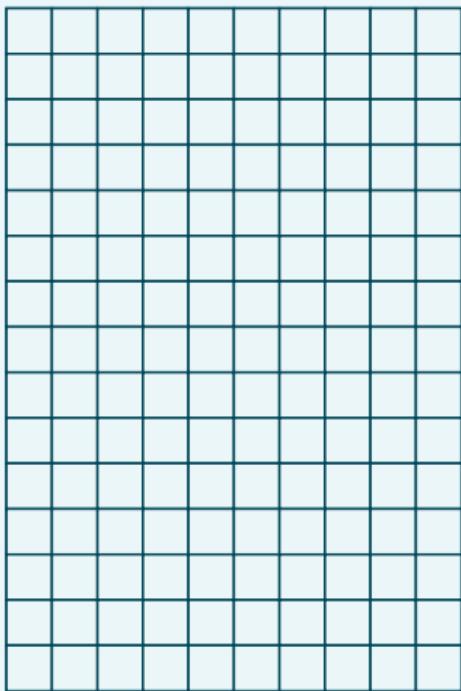


Page 1

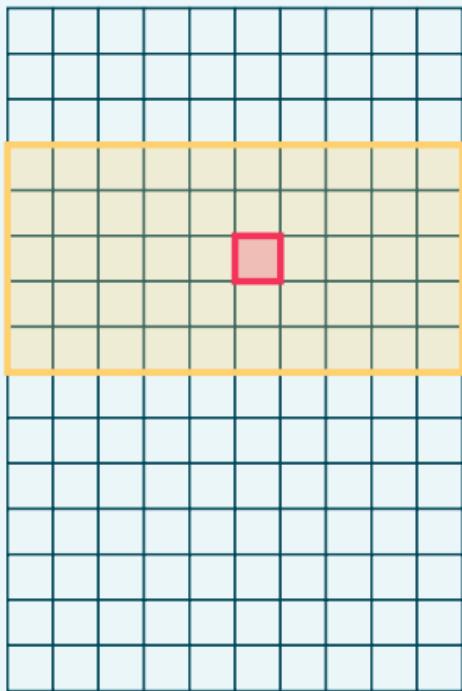


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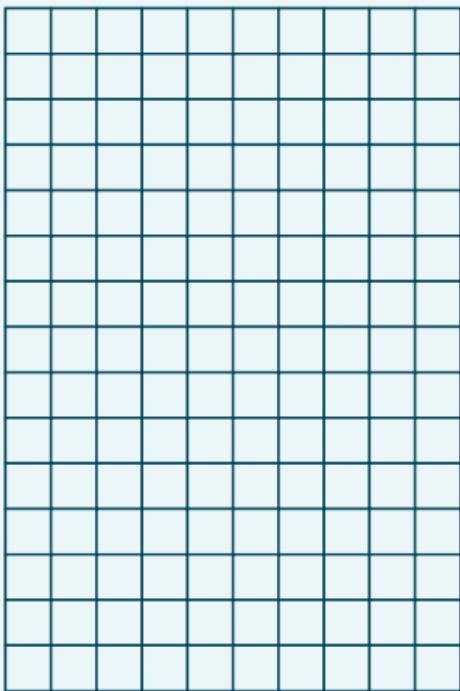
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Page 0



Page 1



Page 2

Why do arrays have good
cache locality?

Working with Arrays

Array Operations

- What operations do arrays have?

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 - Size (constant time)

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- What operations do arrays have?
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 - Get (constant time)

Array Operations

- What operations do arrays have?
 - Size (constant time)
 - Get (constant time)
 - Set (constant time)

Accessing Elements

- Array elements are *indexed*

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What is an index?

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An index is a way of enumerating the elements of a sequence so they can be accessed by number

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- The last index value is the size minus one

Accessing Elements

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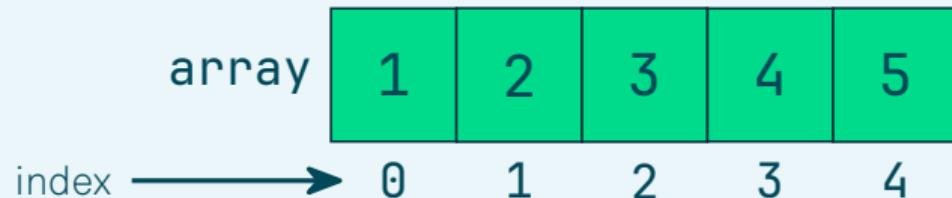
An index is a way of enumerating the elements of a sequence so they can be accessed by number

- Indices start from zero and count up
- The last index value is the size minus one
- Some languages allow negative index values (e.g., Python), but C++ is not one of them

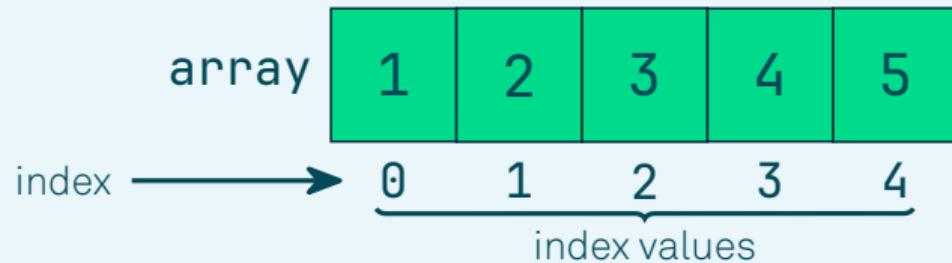
Accessing Elements

array	1	2	3	4	5
	0	1	2	3	4

Accessing Elements



Accessing Elements



Array Syntax: Creation

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

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

Diagram illustrating the components of the C++ array syntax:

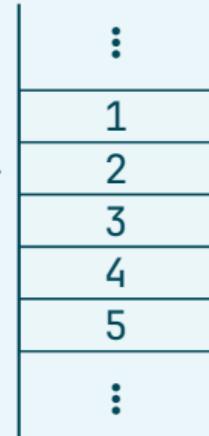
- C++ array type (from `<array>`)**: `std::array`
- element type**: `std::int32_t`
- variable name**: `array`
- size**: `5`
- elements**: `{ 1, 2, 3, 4, 5 }`

Array Syntax: Creation

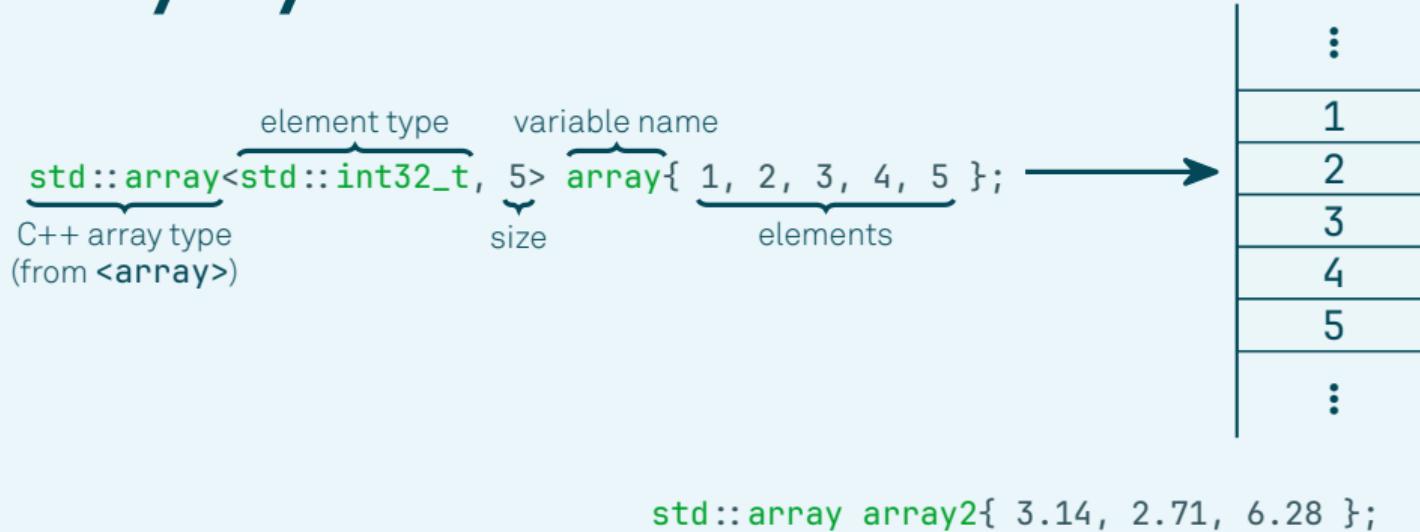
`std::array<std::int32_t, 5> array{ 1, 2, 3, 4, 5 };`

element type
variable name
size
elements

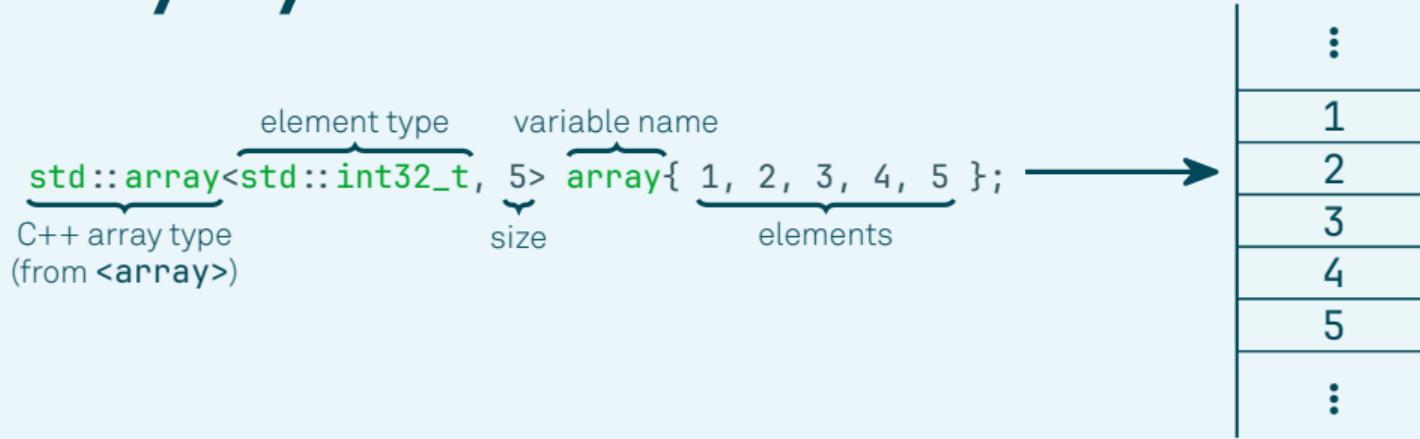
C++ array type
(from `<array>`)



Array Syntax: Creation



Array Syntax: Creation

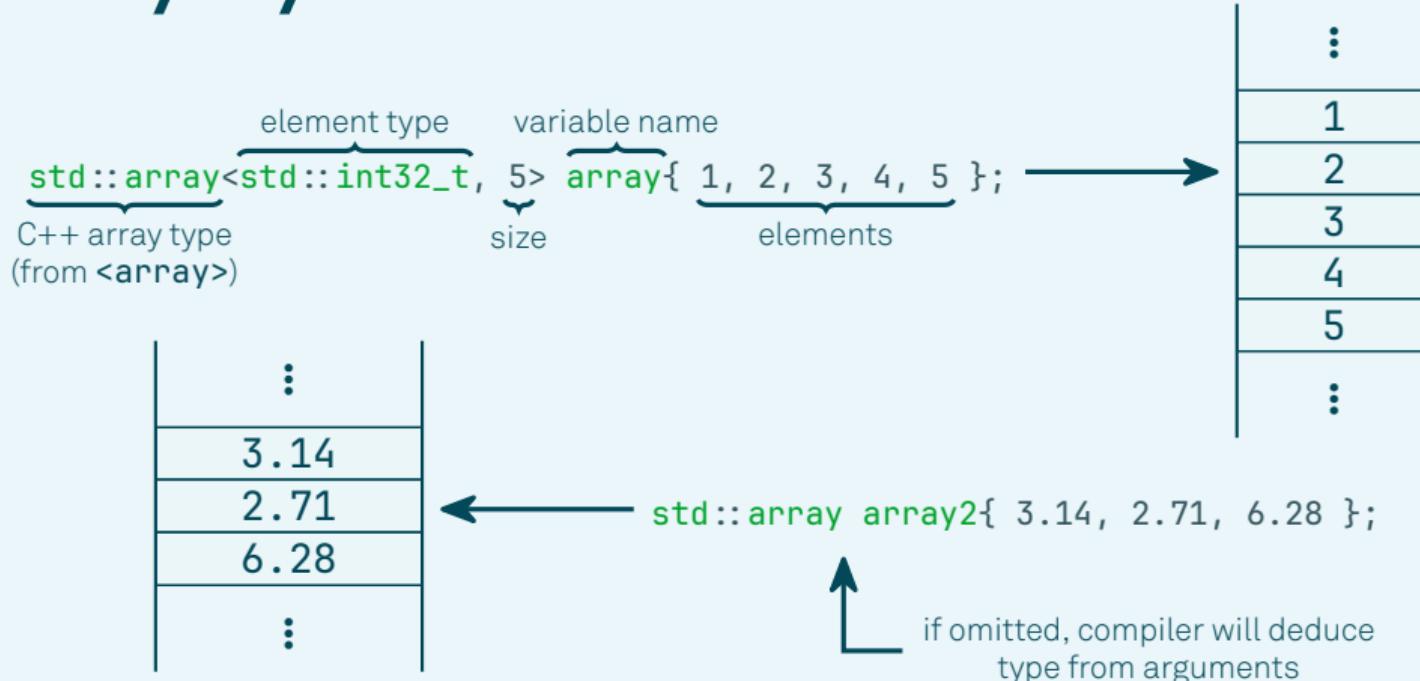


```
std::array array2{ 3.14, 2.71, 6.28 };
```



if omitted, compiler will deduce
type from arguments

Array Syntax: Creation



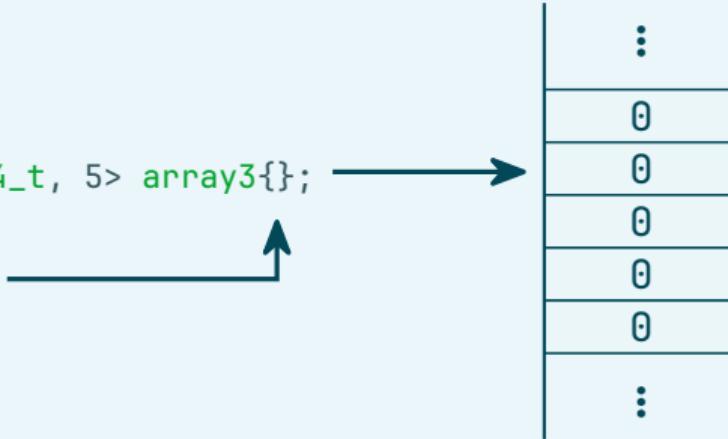
Array Syntax: Creation

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

Array Syntax: Creation

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```

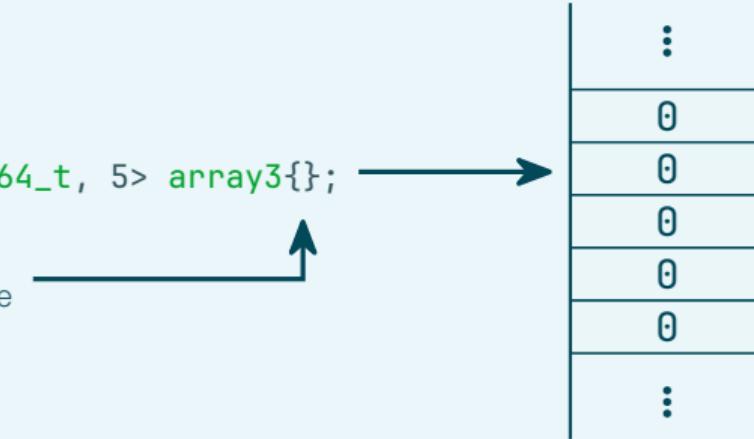
perform zero-initialization
array will be uninitialized without these



Array Syntax: Creation

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

perform zero-initialization
array will be uninitialized without these



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

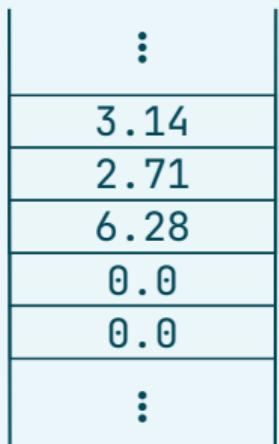
Array Syntax: Creation

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

perform zero-initialization
array will be uninitialized without these



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



Array Syntax: Creation

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

Array Syntax: Creation

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

/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';
```

Array Syntax: Accessing

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

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

```
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

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

Array Syntax: Accessing

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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

```
4 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

```
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
```

```
7 cout << "nums: ";
8 for (std::size_t i{nums.size()}; i > 0U; --i) {
9     cout << nums.at(i - 1U) << ' ';
10 }
11 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

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- 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<<(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

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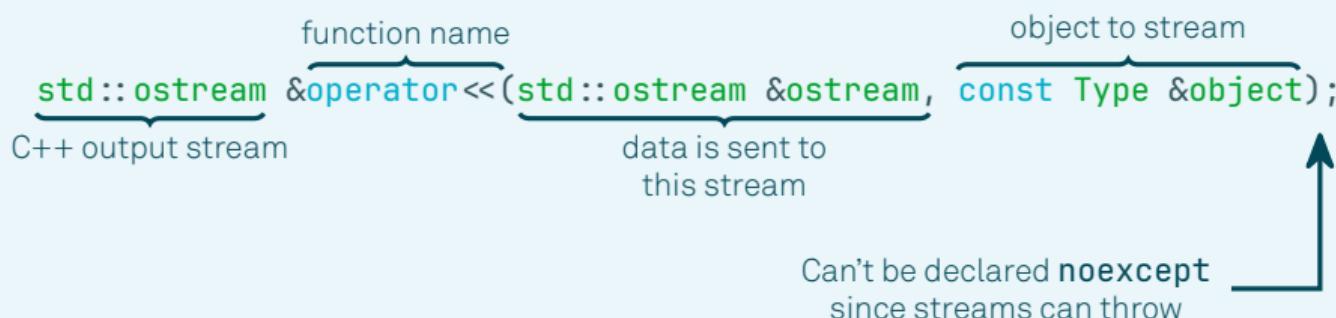
```
function name  
std::ostream &operator<<(std::ostream &ostream,  
                           const Type &object);  
C++ output stream          data is sent to  
                           this stream          object to stream
```

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Can't be declared **noexcept**
since streams can throw



Array Syntax: Printing

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```
function name  
std::ostream &operator<<(std::ostream &ostream,  
                           const Type &object);  
  
C++ output stream          data is sent to  
                           this stream          object to stream  
  
argument is returned to     Can't be declared noexcept  
allow for pipelining         since streams can throw
```

The diagram shows the signature of the insertion operator: `function name std::ostream &operator<<(std::ostream &ostream, const Type &object);`. Annotations with arrows point to specific parts of the code:

- An arrow from the left points to `std::ostream`, labeled "C++ output stream".
- An arrow from the top points to `&operator<<`, labeled "function name".
- An arrow from the middle points to `ostream` in the second parameter, labeled "data is sent to this stream".
- An arrow from the right points to `const Type &object`, labeled "object to stream".
- An arrow from the bottom left points to the closing parenthesis of the first parameter, labeled "argument is returned to allow for pipelining".
- An arrow from the bottom right points to the `&` before `noexcept`, labeled "Can't be declared noexcept since streams can throw".

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

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std::int32_t add(const std::int32_t a, const std::int32_t b) noexcept {  
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- 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 parameters

template <typename T>

```
T add(const T &a, const T &b) { return a + b; }
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Array Syntax: Printing

declares a template parameters

`template <typename T>`

`T add(const T &a, const T &b) { return a + b; }`

The diagram consists of three parts: 1) A bracket above the word 'template' with the text 'declares a template'. 2) A bracket above the type name 'T' in '`<typename T>`' with the text 'parameters'. 3) Three arrows pointing from the two occurrences of 'T' in the code snippet below to the single 'T' in the sentence 'act as placeholders for some type T'.

act as placeholders for some type T

Array Syntax: Printing

declares a template parameters

`template <typename T>`

`T add(const T &a, const T &b) { return a + b; }`

act as placeholders for some type T

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

Array Syntax: Printing

declares a template parameters

`template <typename T>`

`T add(const T &a, const T &b) { return a + b; }`

act as placeholders for some type `T`



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

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add(3, 5) = 8  
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```

- How do templates work?

Array Syntax: Printing

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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';
```

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:

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

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

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

```
template <>
std::string add(const std::string &a, const std::string &b) {
    return a + b;
}
```

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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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

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 - How might templates negatively affect compilation, if at all?

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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

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std::ostream &operator<<(std::ostream &ostream,  
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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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```
template <typename T>  
std::ostream &operator<<(std::ostream &ostream,  
                           const std::array<T, 5> &array);
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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 &os, 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';
```

The diagram illustrates the flow of code execution. A box encloses the user's code at the top, with two arrows pointing downwards to the implementations in the standard library. One arrow points to the implementation for `std::array<double, 3>`, and the other points to the implementation for `std::array<std::int32_t, 2>`.

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

```
template <>
std::ostream &operator<<(std::ostream &os, 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 };
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```

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 };
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```
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?

Undefined Behavior

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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?

Undefined Behavior

```
1 constexpr std::array chars{ 'a', 'b', 'c' };
2 cout << chars.front() << '\n'; // UB if `chars` is empty
3 cout << chars.back() << '\n'; // UB if `chars` is empty
```

Multi-dimensional Arrays

Two-dimensional Arrays

- Arrays of arrays

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

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1 std::array<std::array<std::int32_t, 3>, 3> grid{{  
2     { 1, 2, 3 },  
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note the double curly brackets
needed for multi-dimensional arrays

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4     { 7, 8, 9 },  
5 }};
```

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

note the double curly brackets
needed for multi-dimensional arrays

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;
```

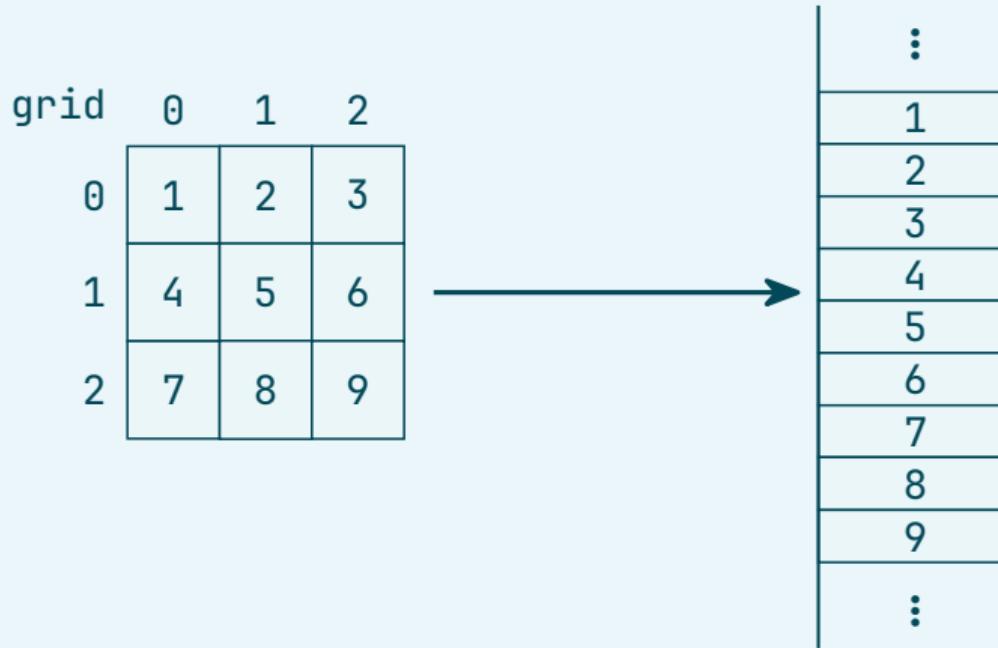
```
grid: [[1, 2, 3], [4, 5, 6], [7, 8, 9]]
center value: 5
grid: [[1, 2, 3], [40, 50, 60], [7, 8, 9]]
```

Two-dimensional Arrays

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

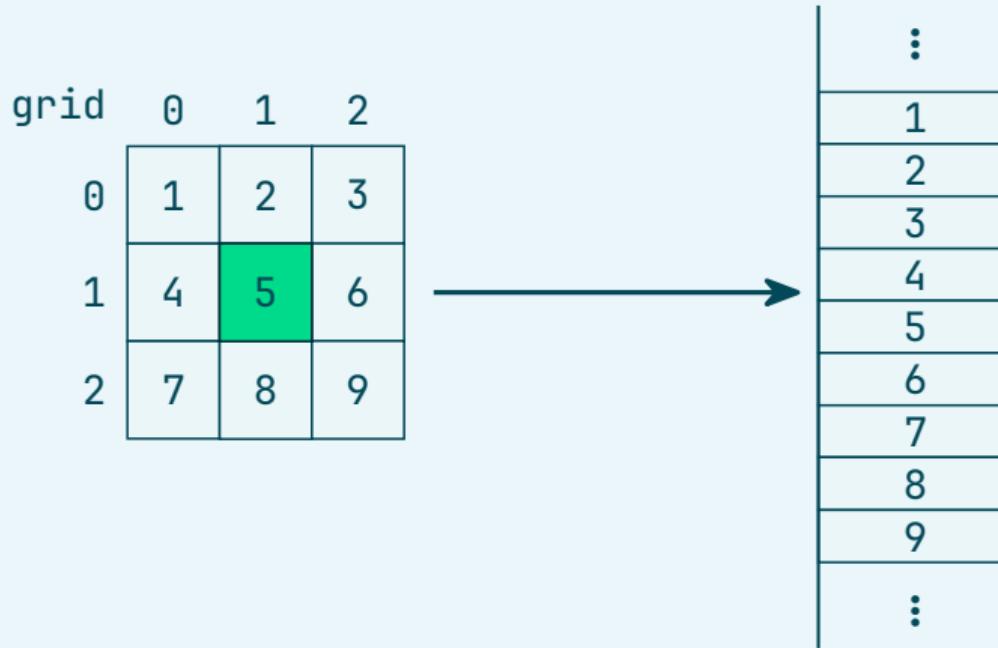
Two-dimensional Arrays

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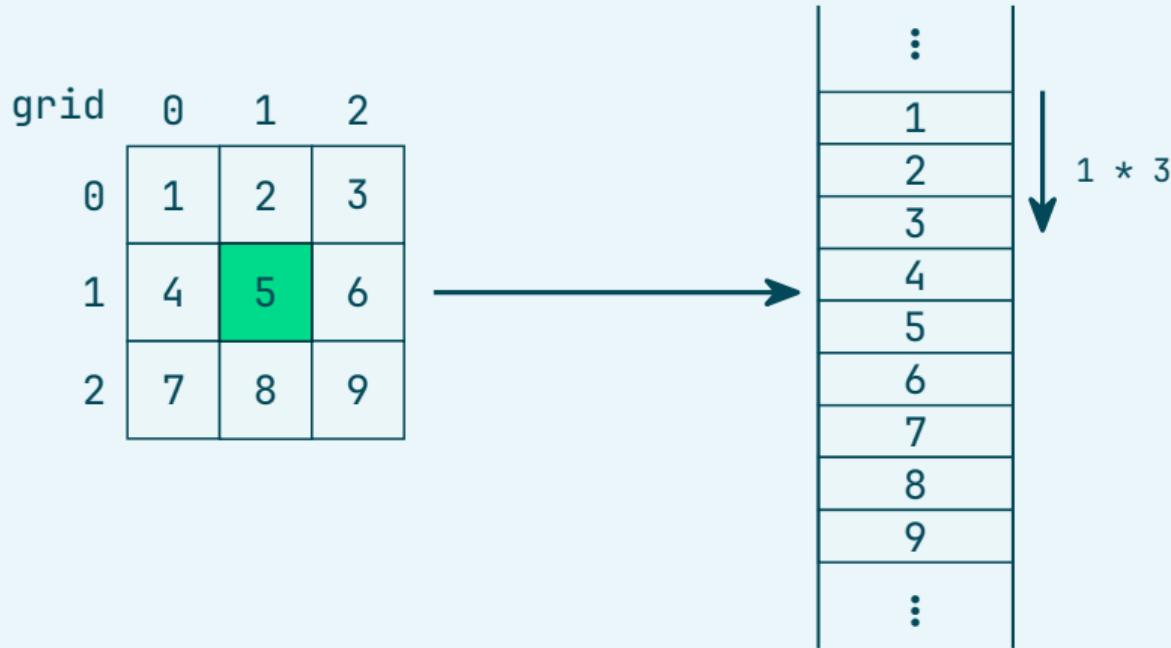
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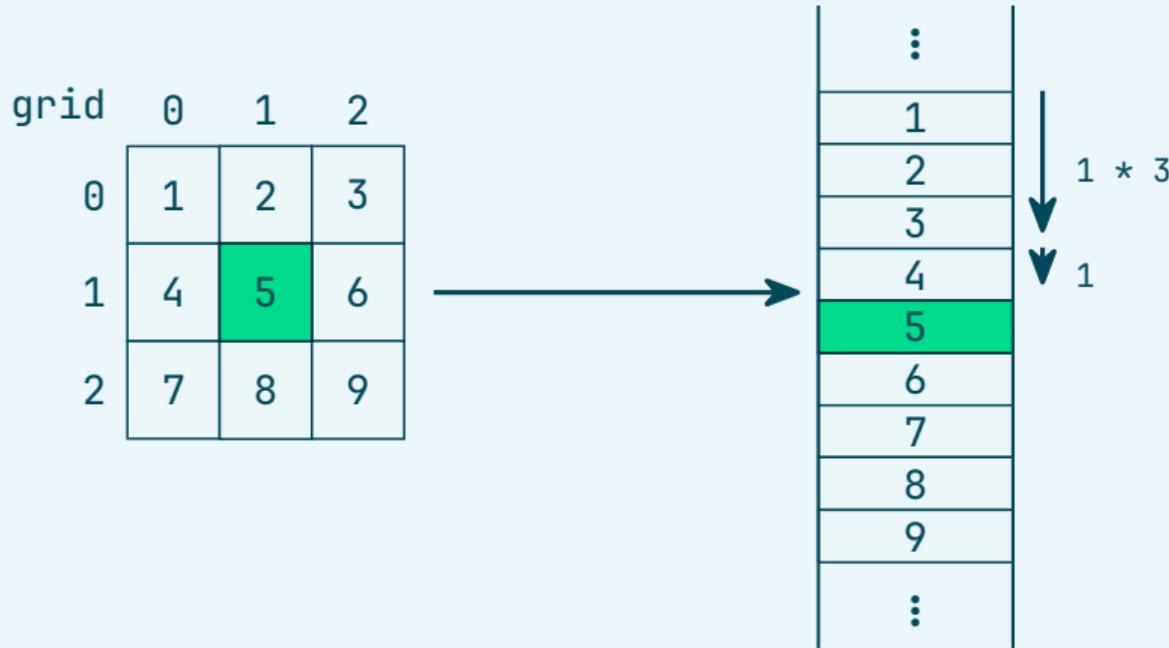
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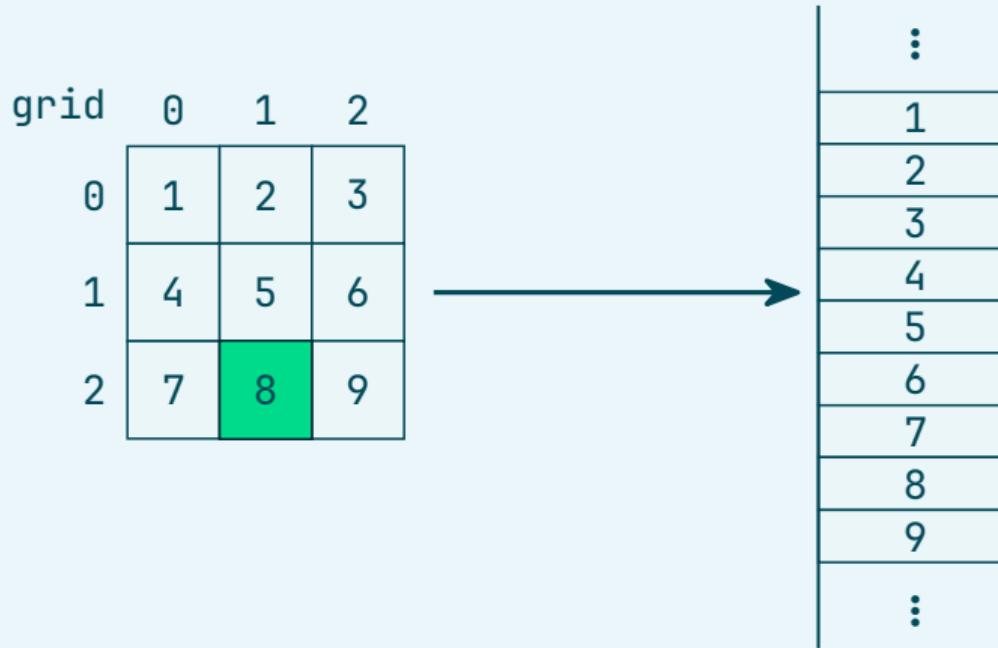
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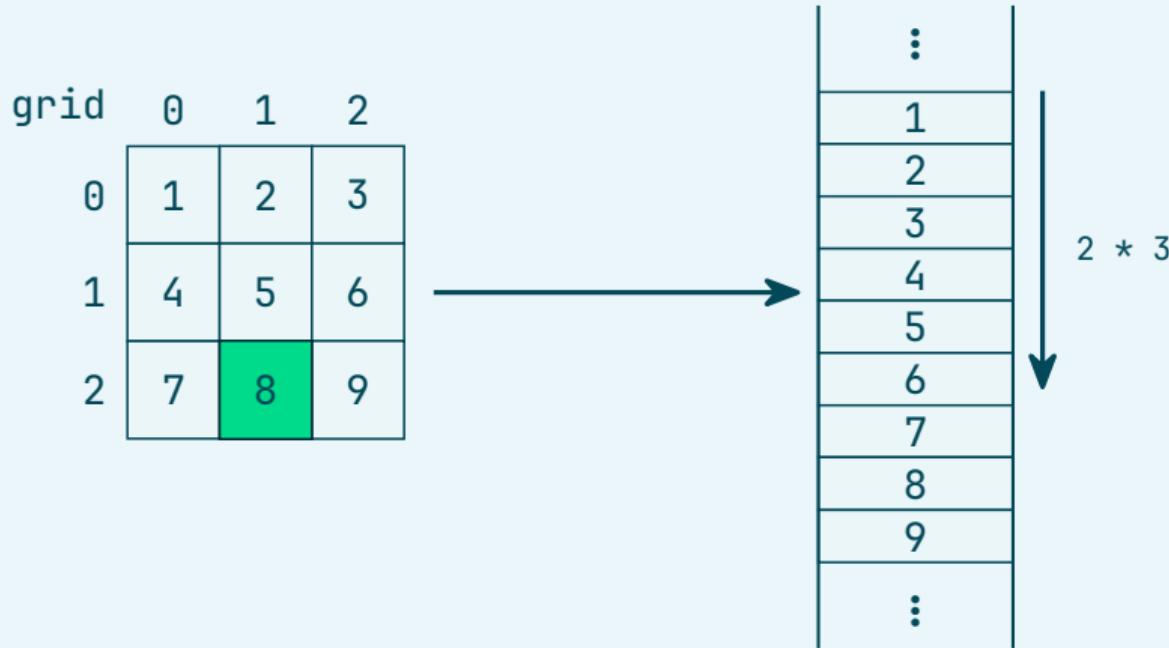
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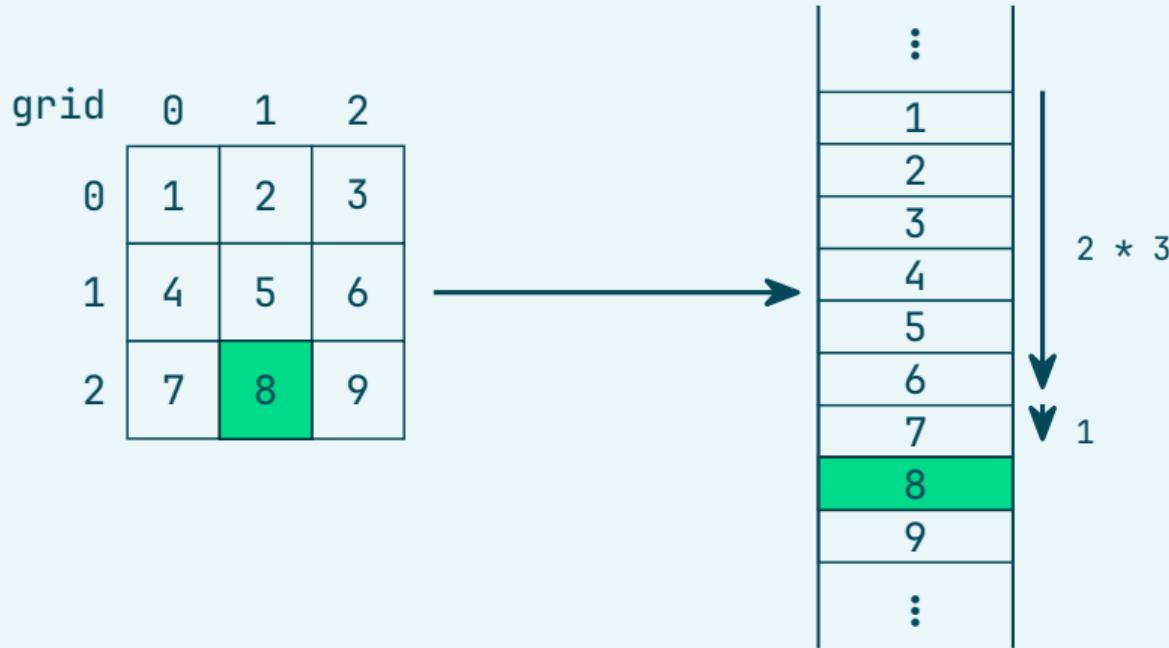
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- These concepts extend to more than two dimensions

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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?