C++ PROGRAMMING

Lecture 1

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CONTENTS

1. More on data types
2. Expressions
3. `const` & `constexpr`
4. Statements
5. Control flow
6. Recap

More on data types: built-in arrays

- A variable can hold a value of a certain type
  - Example

```
int i = 42;
```

- What if I need 10 integers to solve a given task?

```
int one = 1;
int two = 2;
...
```

and if I need 1000 integers or more?

- Use arrays
  - Built-in **static** arrays can store N objects of the same type
  - Stored in one contiguous block of memory (one after another)

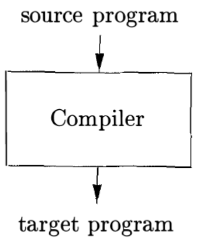


Figure 1.1: A compiler

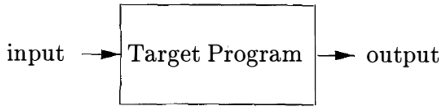


Figure 1.2: Running the target program

- **Static:** at compile time
- **Dynamic**: at runtime
- More on memory later on

Compilers: Principles, Techniques, & Tools, Aho, Lam, Sethi, Ullman 2007

More on data types: built-in arrays

- Create an array of 4 integers

  ```
  int array[4];
  array[0] = 10;
  array[1] = 20;
  array[2] = 30;
  array[3] = 40;
  std::cout << array[0] << '\n';
  std::cout << array[3] << '\n';
  int number = array[2];
  ```

  - What does this print?

- Problems
  - An array does not know its size
    - Increases probability for out-of-bounds
- Use `std::array` or `std::vector` instead
  - Next time
- Caution
  - Never ever try something like

    `array[-3] = 12;` or `array[5] = 13;`

    - If indices are out-of-bounds we have undefined behavior
    - At best
      - Program crashes
    - At worst
      - Program continues execution
      - Results are non-sense and you are not even aware of that

Multi-dimensional arrays

- Arrays can have multiple dimensions
- Example: a 2D array (which is a matrix)

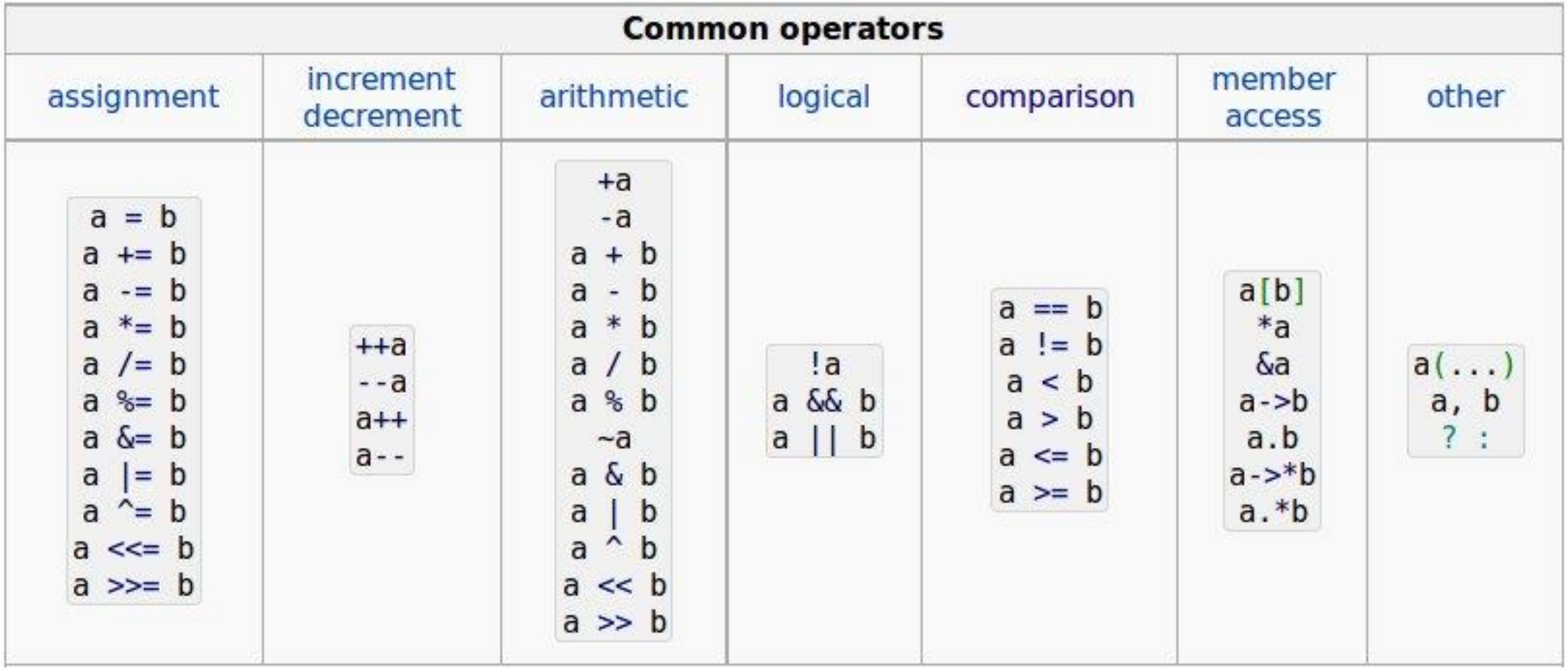
```
int matrix[2][2];
matrix[0][0] = 1;
matrix[0][1] = 2;
matrix[1][0] = 3;
matrix[1][1] = 4;
int n = matrix[1][0]; // What is n's content?
```

- You can create arrays of arbitrary dimensions

- Analog to
  - $matrix = \begin{pmatrix} 1 & 2 \\ 3 & 4 \end{pmatrix}, \; matrix \in \mathbb{Z}^{2\times 2}$

Expressions

- “An expression is a sequence of operators and their operands, that specifies a computation. …”
- “… Expression evaluation may produce a result and may generate side-effects.” [en.cppreference.com]
- Operands can be variables or literals
- Operators



<table>
<tr><th colspan="7">Common operators</th></tr>
<tr><th>assignment</th><th>increment
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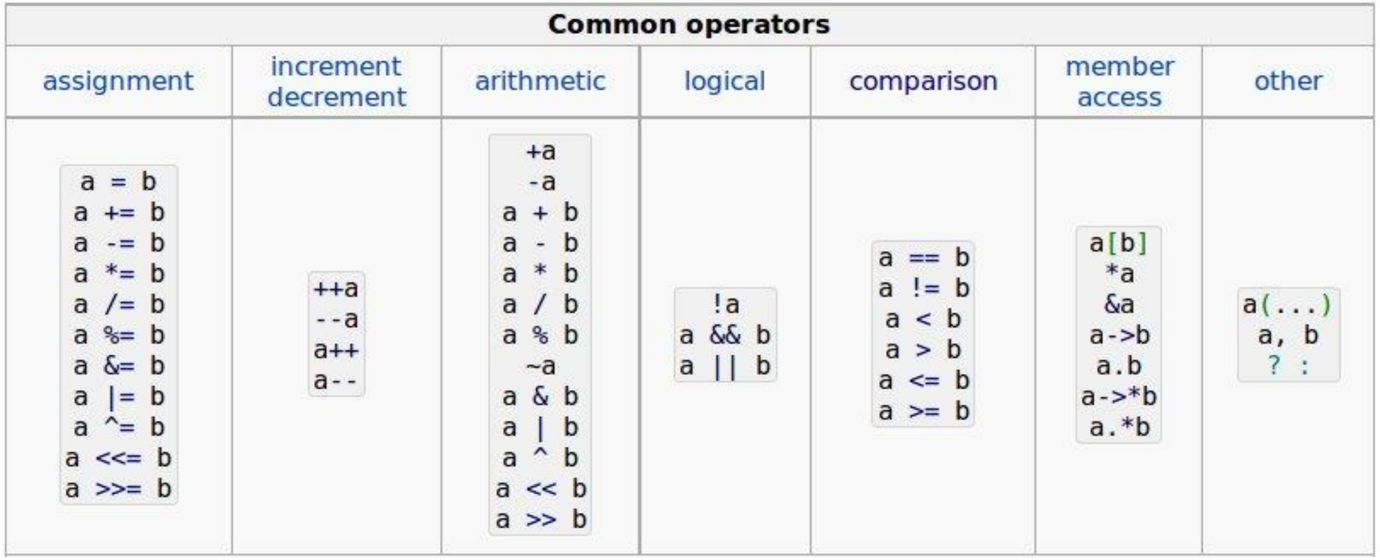
<tr>
<td>a = b
a += b
a -= b
a *= b
a /= b
a %= b
a &= b
a |= b
a ^= b
a <<= b
a >>= b</td>
<td>++a
--a
a++
a--</td>
<td>+a
-a
a + b
a - b
a * b
a / b
a % b
~a
a & b
a | b
a ^ b
a << b
a >> b</td>
<td>!a
a && b
a || b</td>
<td>a == b
a != b
a < b
a > b
a <= b
a >= b</td>
<td>a[b]
*a
&a
a->b
a.b
a->*b
a.*b</td>
<td>a(...)
a, b
? :</td>
</tr>
</table>

Expressions

▪ Examples: arithmetic, consider `int i = 5;`	▪ Evaluates to
▪ `-i`	`-5`
▪ `i + 10`	`15`
▪ `i - 5 * 2 * 2`	`-15`
▪ `6 * 6`	`36`
▪ `--i`	`4`
▪ `11 % i`	`1`



Common operators

assignment	increment decrement	arithmetic	logical	comparison	member access	other

`a = b`
`a += b`
`a -= b`
`a *= b`
`a /= b`
`a %= b`
`a &= b`
`a |= b`
`a ^= b`
`a <<= b`
`a >>= b`
	`++a`
	`--a`
	`a++`
	`a--`
		`+a`
		`-a`
		`a + b`
		`a - b`
		`a * b`
		`a / b`
		`a % b`
		`~a`
		`a & b`
		`a | b`
		`a ^ b`
		`a << b`
		`a >> b`
			`!a`
			`a && b`
			`a || b`
				`a == b`
				`a != b`
				`a < b`
				`a > b`
				`a <= b`
				`a >= b`
					`a[b]`
					`*a`
					`&a`
					`a->b`
					`a.b`
					`a->*b`
					`a.*b`
						`a(...)`
						`a, b`
						`? :`

Expressions

- Examples: comparison, consider `int i = 5;`
  - `i == 5`
  - `i > 100`
  - `i <= 5`
  - `100 >= 99`

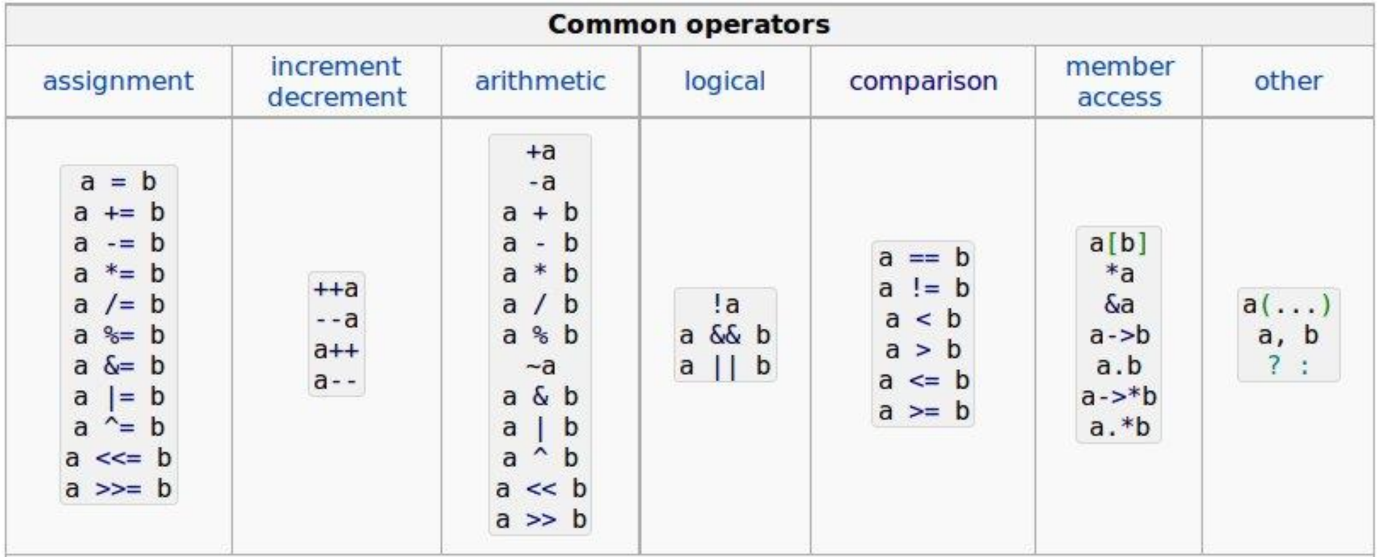
- Evaluates to

`1 or true`

`0 or false`

`1 or true`

`1 or true`



Common operators						
assignment	increment decrement	arithmetic	logical	comparison	member access	other
a = b a += b a -= b a *= b a /= b a %= b a &= b a |= b a ^= b a <<= b a >>= b	++a --a a++ a--	+a -a a + b a - b a * b a / b a % b ~a a & b a | b a ^ b a << b a >> b	!a a && b a || b	a == b a != b a < b a > b a <= b a >= b	a[b] *a &a a->b a.b a->*b a.*b	a(...) a, b ? :

Expressions

- Examples: comparison & logic, consider `int i = 5;`
  - `!(i == 5)`
  - `(i > 100) || (i == 5)`
  - `(i <= 5) && (-10 <= 1)`
  - `false || true`

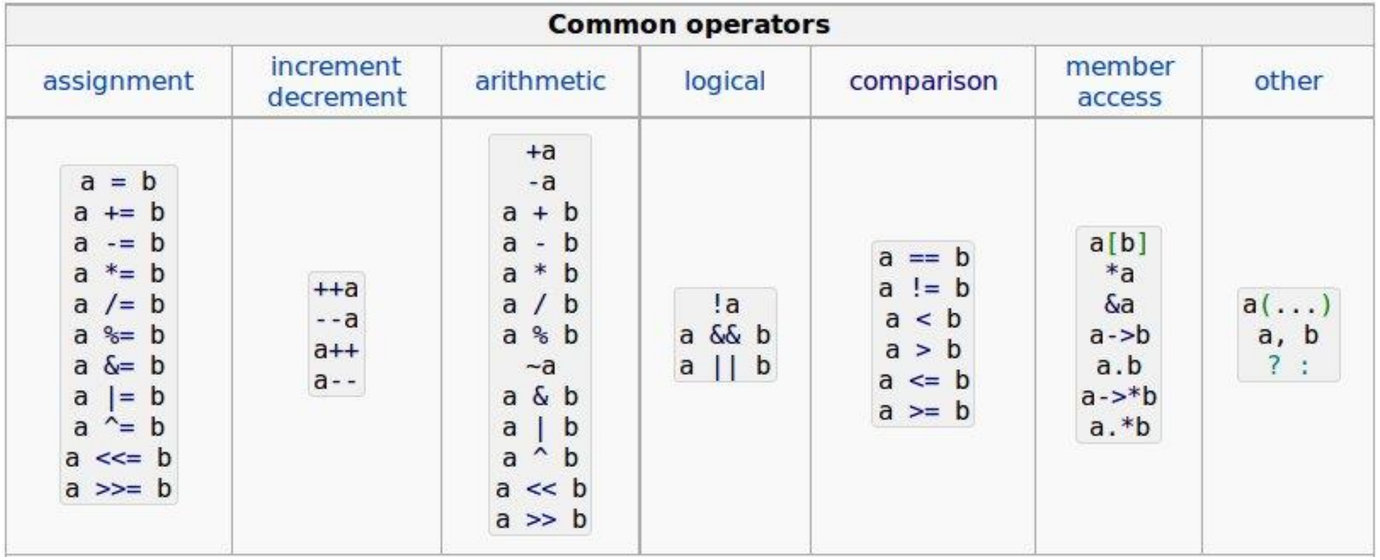
- Evaluates to

`0 or false`

`1 or true`

`1 or true`

`1 or true`



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assignment	increment decrement	arithmetic	logical	comparison	member access	other

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`a >>= b`
	`++a`
	`--a`
	`a++`
	`a--`
		`+a`
		`-a`
		`a + b`
		`a - b`
		`a * b`
		`a / b`
		`a % b`
		`~a`
		`a & b`
		`a | b`
		`a ^ b`
		`a << b`
		`a >> b`
			`!a`
			`a && b`
			`a || b`
				`a == b`
				`a != b`
				`a < b`
				`a > b`
				`a <= b`
				`a >= b`
					`a[b]`
					`*a`
					`&a`
					`a->b`
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						`a(...)`
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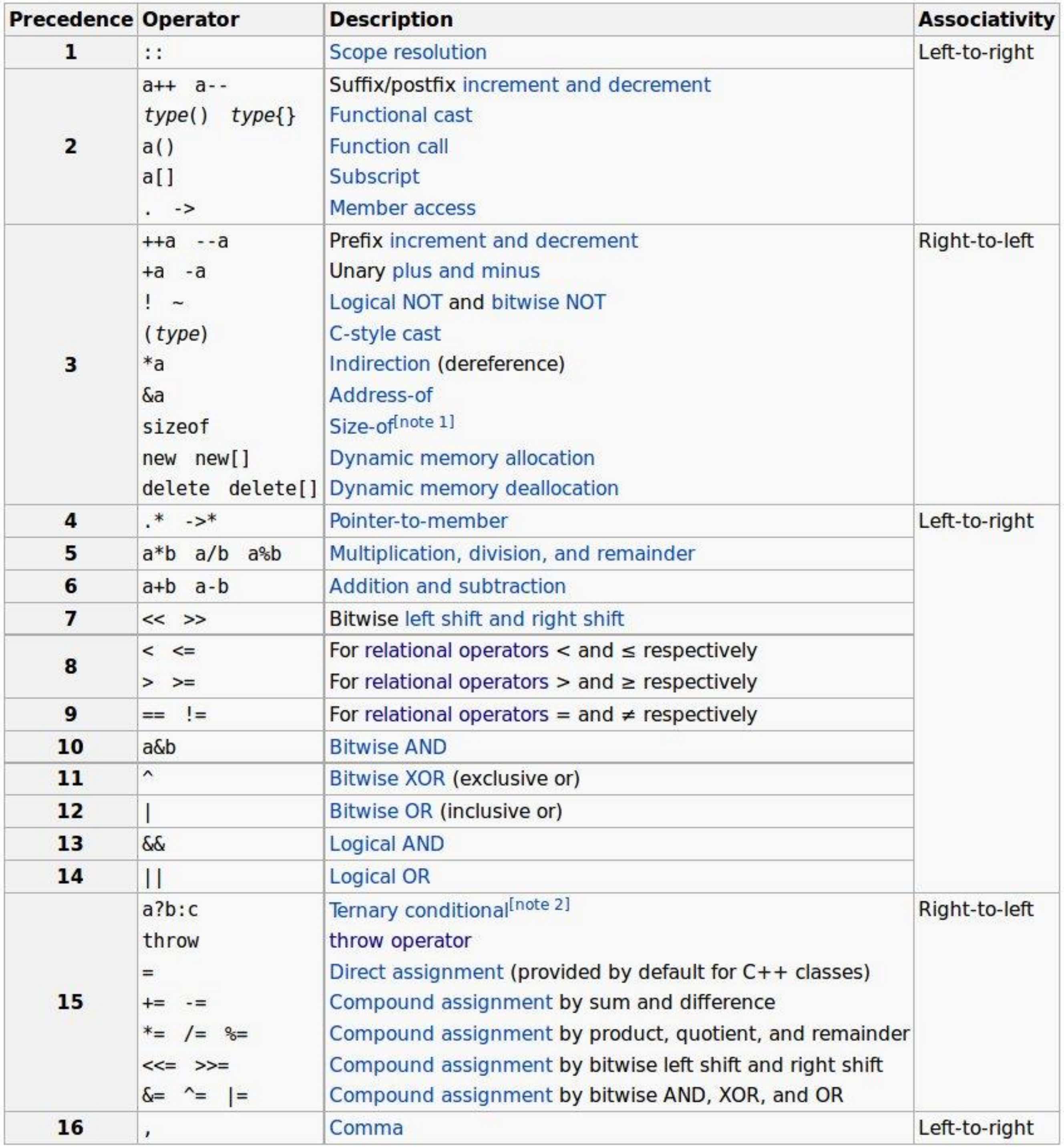
						`? :`

Expressions

- Keep operators' precedence in mind
- In doubt always use parentheses: `( expr )`
  - `expr` then gets evaluated first



Precedence	Operator	Description	Associativity
1	`::`	Scope resolution	Left-to-right
2	`a++ a--`	Suffix/postfix increment and decrement	
	type`()` *type*`{}`	Functional cast	
	`a()`	Function call	
	`a[]`	Subscript	
	`. ->`	Member access	
3	`++a --a`	Prefix increment and decrement	Right-to-left
	`+a -a`	Unary plus and minus	
	`! ~`	Logical NOT and bitwise NOT	
	`(`*type*`)`	C-style cast	
	`*a`	Indirection (dereference)	
	`&a`	Address-of	
	`sizeof`	Size-of[note 1]	
	`new new[]`	Dynamic memory allocation	
	`delete delete[]`	Dynamic memory deallocation	
4	`.* ->*`	Pointer-to-member	Left-to-right
5	`a*b a/b a%b`	Multiplication, division, and remainder	
6	`a+b a-b`	Addition and subtraction	
7	`<< >>`	Bitwise left shift and right shift	
8	`< <=`	For relational operators < and ≤ respectively	
	`> >=`	For relational operators > and ≥ respectively	
9	`== !=`	For relational operators = and ≠ respectively	
10	`a&b`	Bitwise AND	
11	`^`	Bitwise XOR (exclusive or)	
12	`|`	Bitwise OR (inclusive or)	
13	`&&`	Logical AND	
14	`||`	Logical OR	
15	`a?b:c`	Ternary conditional[note 2]	Right-to-left
	`throw`	throw operator	
	`=`	Direct assignment (provided by default for C++ classes)	
	`+= -=`	Compound assignment by sum and difference	
	`*= /= %=`	Compound assignment by product, quotient, and remainder	
	`<<= >>=`	Compound assignment by bitwise left shift and right shift	
	`&= ^= |=`	Compound assignment by bitwise AND, XOR, and OR	
16	`,`	Comma	Left-to-right

Operator `=` (assign) revisited

- `=` is the assignment operator
  - Not the mathematical equals (check for equality would be `==`)
- Example

```
int value = 10;
```

  - In words: evaluate the expression on the right side and shove the result into the variable specified on the left hand side!

```
int other = 2 * 2 + 3; // after this assignment other stores the value 7
```

- An assignment has a “left-hand side” and a “right-hand side”
  - Lvalue and Rvalue
  - An lvalue is an address (variable, reference, or pointer)
  - An rvalue is an expression that can be evaluated (to a value)

Variables revisited: `const` qualifier

- Variables can be qualified with `const`
- Do qualify constant variables with `const`!
- Examples

```
const double PI = 3.1415926535;            // ok: initialized at compile time
const int fortytwo = 21 + 21;              // ok: initialized at compile time
const double value = calculateValue();     // ok: initialized at run time
const int i;                               // error: i is uninitialized const
PI = 3;                                    // error: PI is const
fortytwo = 12;                             // error: fortytwo is const
double a = PI * 2;                         // ok: PI is only read
std::cout << fortytwo << '\n';             // ok: fortytwo is only read
```

- Constant variables can be read, but “*never*” written to after initialization
- Use `const` as much as possible
  - It will prevent you from making mistakes

[Figure taken from http://www.the007dossier.com/007dossier/page/Never-Say-Never-Again-Wallpaper]

Variables revisited: `const` qualifier

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```
const double PI = 3.1415926535;
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const double value = calculateValue();
const int i;
PI = 3;
fortytwo = 12;
double a = PI * 2;
std::cout << fortytwo << '\n';
```

- Constant variables can be read, but "*never*" written to after initialization
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Computing ahead of time: constexpr (at compile time)

- Use constexpr for constant expressions
- Variables can be constexpr

```
constexpr double d = 2.5 * 6.8 + 120;
constexpr int i = 12 * 12;
```

- Functions can be constexpr as well // next lecture
- Note: constexpr produces constant values (d and i cannot be changed, d and i are const)
- C++'s workflow

1. compile source code to executable program
2. run the executable

- Constant expressions are (may be) evaluated at compile time!
  - Effectively: pre-computation of values
  - Leads to increased performance (but slows down compile time)
- constexpr similar to const but may be evaluated at compile time

Statements

- “Statements are fragments of the C++ program that are executed in sequence. The body of any function is a sequence of statements.” [en.cpp.reference.com]
- Example

```
int i = 2 * 3 + 10;           // this is a statement
int j = 10;                   // j is 10
i = j;                        // content of i is overwritten with j’s content
std::cout << i << '\n';       // prints 10
```

  - Note that `i = j;` overrides `i`’s content with whatever `j`’s content is
  - Order of execution matters

Mathematical formulas and functions

- Use `#include <cmath>` to include mathematical functions
  - `pow(), sqrt(), abs(), sin(), cos(), …`
  - Have a look at http://en.cppreference.com/w/cpp/header/cmath
  - We will talk about functions in detail next time
  - For now just use them
    - What is the C++ equivalent to $x = \sqrt{2},\ x \in \mathbb{R}$

      ```
      double x = sqrt(2);
      ```

    - What is the C++ equivalent to $\mathrm{y} = \frac{1}{4}e^3,\ y \in \mathbb{R}$

      ```
      double y = 1 / 4 * exp(3);
      ```

Statements

- C++ includes the following types of statements

1. Expression statements	// e.g. `n = n + 1;`
2. Compound statements (*blocks*)	// next
3. Selection statements	// today
4. Iteration statements	// today
5. Jump statements	// e.g. `return 0;` in our main(), later on
6. Declaration statements	// e.g. `int i;`
7. Try blocks	// later on
8. Atomic and synchronized blocks	// later on

Compound Statements

- Compound statements or *blocks* are brace-enclosed sequences of statements
- Example

```
{
    int i = 42;
    int j = i + 10;
}
```

- Scopes: note that something like this is possible

```
int i = 1;
{
    std::cout << i << '\n';
    int i = 2;
    std::cout << i << '\n';
    {
        int i = 3;
        std::cout << i << '\n';
    }
}
std::cout << i << '\n';
```

Scopes: { and }

- A variable can be defined multiple times with the same name (usually don’t do it)
- Each name that appears in a C++ program is only valid in some portion of the source code called its scope!

```
{
    int i = 42;
    int j = i + 10;
}
```

- If a variable goes out of scope it can no longer be accessed
- Example

```
{
    int i = 42;
    // i can be used in this block (its scope)
}   // i goes out of scope at this point
i = 13;    // error: i can no longer be used
```

Statements

- C++ includes the following types of statements

1. Expression statements	// e.g. n = n + 1;
2. Compound statements (*blocks*)	// done!
3. Selection statements	// next!
4. Iteration statements	// today
5. Jump statements	// e.g. ´return 0;´ in our main(), later on
6. Declaration statements	// e.g. int i = 10;
7. Try blocks	// later on
8. Atomic and synchronized blocks	// later on

Selection statements aka control flow

- Just a bunch of statements in sequence is not expressive enough
  - How to express: “You pass if you achieve more than 50% in the exercises, otherwise you fail.”
  - We need conditional code execution
  - Three kinds of selection statements exist

- Selection statements or control flow constructs in C++ are
  - if (condition) statement
  - if (condition) statement else statement
  - switch (condition) statement
  - Note: a statement can also be a compound statement / block
  - A condition is an expression that can be evaluated to `true` or `false`

If statement

- if (condition) statement
  - Example

```
int i = 10;
if (i < 100) {
  std::cout << "i is smaller than 100\n";
}
```

- If statements allow to execute specific code depending on a condition!
- If only a “single” statement should be executed one can omit the braces { and }

```
int i = 10;
if (i < 100)
  std::cout << "i is smaller than 100\n";
```

If statement with else branch

- if (condition) statement else statement
  - Example

```
int i = 10;
if (i < 100) {
  std::cout << "i is smaller than 100\n";
} else {
  std::cout << "i is bigger than 100\n";
}
```

- Braces not needed here: only one statement should be executed in each branch

```
int i = 10;
if (i < 100)
  std::cout << "i is smaller than 100\n"; // the IF branch
else
  std::cout << "i is bigger than 100\n"; // the ELSE branch
```

If statement

- There may be more than two branches
  - Example

```
int i = 3;
if (i == 1) {
  std::cout << "i is 1\n";
} else if (i == 2) {
  std::cout << "i is 2\n";
} else if (i == 3) {
  std::cout << "i is 3\n";
} else {
  std::cout << "i is something else\n";
}
```

Switch statement

- switch (condition) statement
- Similar to the if statement
- More convenient if many conditions need to be checked
    - switch is optimized for this purpose

```
switch ( expression ) {
    case expression:
        // branch
    break;
        …
    default:
        // default branch
    break;
}
```

Switch statement

- Switch in action
  - Example on the right
- What number will be printed?
- What will be printed if `c` is `'X'`?
- C/C++: switch only works if the condition can be evaluated to an integer

```
char c = 'D';
switch (c) {
  case 'A':
    std::cout << 1 << '\n';
  break;
  case 'B':
    std::cout << 2 << '\n';
  break;
  case 'C':
    std::cout << 3 << '\n';
  break;
  case 'D':
    std::cout << 4 << '\n';
  break;
  default:
    std::cout << -1 << '\n';
  break;
}
```

Statements

- C++ includes the following types of statements

1. Expression statements	// e.g. n = n + 1;
2. Compound statements (*blocks*)	// done!
3. Selection statements	// done!
4. Iteration statements	// next!
5. Jump statements	// e.g. ´return 0;´ in our main(), later on
6. Declaration statements	// e.g. int i = 10;
7. Try blocks	// later on
8. Atomic and synchronized blocks	// later on

Iteration statements aka loops

- The previous types of statements are still not quite expressive enough
  - Example calculate sum from 1 to 100
    - `int i = 1 + 2 + 3 + ... + 100;`
  - But if we want to sum from 1 to 10 or from 1 to 1000000?
  - What if your user can choose the upper end?
    - You cannot write an infinite number of programs up-frond!
- Iteration statements or loop constructs in C++
  - while (condition) statement
  - do statement while (expression);
  - for (init-statement (optional); condition (“optional”) ; expression (optional)) statement
  - for (for-range-decl : for-range-init) statement
  - Note a statement can be a compound statement / block

for loop

- Problem: sum up the numbers from 1 to 100.

  ```
  int sum = 1 + 2 + 3 + ... + 100;
  std::cout << "result: " << sum << '\n';
  ```

  - Better use a loop
  - Structure of a for loop
  - for (init-statement (optional);

    condition (optional) ;

    expression (optional)) statement

    ```
    int sum = 0;
    for (size_t i = 1; i <= 100; ++i) {
        sum += i; // means: sum = sum + i;
    }
    ```

- What is going on?

1. i is initialized (only once)
2. condition is checked
   - I. If true
     - I. execute loop body
     - II. execute expression (usually increases loop counter), go to 2.
   - II. If false
     - I. skip the loop

for loops

- Problem: sum up the numbers from $1^2\ to\ 100^2$!

```
int sum = 0;
for (size_t i = 1; i <= 100; ++i) {
    sum += i * i;
}
```

- Observe: we can use the counter variable inside the loop!
- Loops can have arbitrary step widths

```
int sum = 0;
for (int i = 10; i < 4; i += 10) {
    sum += i;
}
std::cout << sum << '\n';
```

Caution

- *“Stupid is as stupid does.”*
  - What does this print?

```
int sum = 0;
for (int i = 1; i < 3; ++i) {
  sum += i;
  --i;
}
std::cout << sum << '\n';
```

Another kind of for loop

- for loop
- for (init-statement (optional);

  Condition (optional) ;

  expression (optional)) statement
- Example

```
int sum = 0;
for (size_t i = 1; i <= 100; ++i) {
    sum += i;
}
```

- Ubiquitous

- range for loop (or range for)
- for (for-range-decl : for-range-init) statement
- Example

```
int sum = 0;
std::vector<int> vec = {1, 2 , 3};
for (int i : vec) {
    sum += i;
}
```

- Useful when using containers // later on!
- Detail: container has to implement
  - begin() and end() // later on!

While loops

- while loop
- while (condition) statement
- Example

```
int sum = 0;
int i = 1;
while (i <= 100) {
    sum += i;
    i++;
}
```

- Rejecting while loop

While loops

- Same as for for-loop: *"Stupid is as stupid does.“*

```
int i = 1;
while (i < 2) {
    std::cout << "not wise\n";
}
```

- One needs to leave the loop at some point
- Condition (usually) needs to be evaluated to false at some point
  - Sometimes a infinite loop is what you want
    - Infinite for loop

      ```
      for (;;) { // do stuff }
      ```

    - Infinite while loop

      ```
      while (true) { // do more stuff }
      ```

Another kind of while loop

- while loop
- while (condition) statement
- Example

```
int sum = 0;
int i = 1;
while (i <= 100) {
    sum += i;
    i++;
}
```

- Rejecting while loop
- Body might not be executed

- do while loop
- do statement while (expression);
- Example

```
int sum = 0;
int i = 300;
do {
    sum += i;
} while (i <= 100);
```

- Non-rejecting while loop!
- Body is executed at least once

4 basic loops

- For
- Range for
- While
- Do while
- **All loops are equivalent**
  - Can be transformed into each other
  - Use the most natural one for each situation!

Breaking loops

- Loops can be broken
  - Use `break` keyword
  - Break leaves the loop it is used in
  - Example

```
int i = 1;
while (i > 0) {
  i += 1;
  break;
}
```

[Image from http://matrix.wikia.com/]

Breaking loops

- Loops can be broken
  - Use `break` keyword
  - Break leaves the loop it is used in
  - Very useful when combined with an if statement
    - Example

```
int sensor_value;
while (true) {
  // do measurements
  sensor_value = getSensorValue();
  if (sensor_value == 0) {
    break;
  }
}
// do other stuff
```

[Image from http://matrix.wikia.com/]

Skipping loop iterations

- Loop iterations can be skipped
- Use `continue` keyword
  - Causes a jump to the end of loop body
  - Very useful when combined with an if statement
    - Example

```
for (int i = 0; i < 10; i++) {
  if (i != 5) {
    continue;
  }
  std::cout << i << ' ';
}
```

- What will be printed?

[Image from images.google.de]

- `break` would have landed on the other roof

A note on nesting

- You can nest loops and if statements
- Example

```
for (int i = 0; i < 5; ++i) {
    for (int j = 0; j < 5; ++j) {
        std::cout << '#';
    }
    std::cout << '\n';
}
```

- What does this code print?

```
#####
#####
#####
#####
#####
```

A note on nesting

- You can nest loops and if statements
- Example

```
int i = 15;
if (i >= 10) {
  if ((i % 5) == 0) {
    std::cout << "i is greater than 9 and dividable by 5\n";
  } else {
    std::cout << "i is greater than 9\n";
  }
} else {
  cout << "i is smaller than 10\n";
}
```

- What does this code print?

Algorithm and program

- You now have a Turing-Complete language (we will discover more, later on)
  - That is, you can compute everything that a Turing-Machine can compute
    - That is, you can compute “everything” that is intuitively computable!
  - https://de.wikipedia.org/wiki/Alan_Turing
  - https://en.wikipedia.org/wiki/Turing_machine
  - “The Imitation Game”: http://www.imdb.com/title/tt2084970/
- Algorithm versus program
  - An algorithm is a description on how to solve a problem
  - A program is an algorithm formulated for the computer
  - C++ programs are algorithms described using a bunch of statements

- You now have the first tools to formulate algorithms in C++

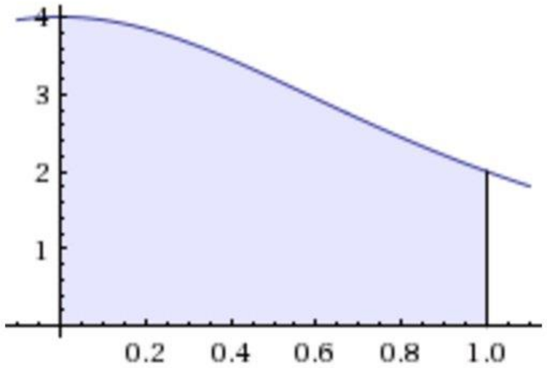
Algorithms, Maths & C++

- You can almost always translate mathematics to C++
- How to obtain a solution for a given task?
- Usually:
  I. Start with a problem
  II. Abstract the problem and find an algorithm to solve the problem)
  III. Formulate algorithm in mathematics
  IV. Formulate mathematical algorithm in a programming language (e.g. C++)
  V. The resulting program then solves the problem
- I will try to make links between mathematics and C++ whenever possible
- Mathematics and computer science / programming are very similar
  - “Computer science is mathematics with electricity!”, Dirk Frettlöh

A fun example: calculating an integral

- Calculate $\int_0^1 \frac{4}{1+x^2} dx$
- Assumption:
  - We don’t know how to calculate an antiderivative of $f(x) = \frac{4}{1+x^2}$
- Solution: use numerical integration **18 lines**
  - Use simple arithmetic
  - A computer is very fast at arithmetic

Visual representation of the integral:



```
#include <iostream>
#include <cmath>
int main() {
  long double integral_val = 0.0;
  long double x = 0.0;
  const size_t N = 1000000;
  long double step_width =
      std::abs(0-1) /
      static_cast<long double>(N);
  for (size_t n = 0; n < N; ++n) {
    // evaluate function a point x
    integral_val += 4 / (1 + x * x);
    x += step_width;
  }
  integral_val /= N;
  std::cout << integral_val << '\n';
  return 0;
}
```

Recap

- Built-in arrays
- Expressions
- Assignments
- Qualifiers
- Simple statements
- Mathematical formulas
- Scopes
- Statements
  - Selection: `if` and `switch`
  - Iteration: `for` and `while`
  - Nesting
- Algorithms, mathematics and computer science

Thank you for your attention
Questions?