

# CS100 Lecture 3

## Operators and Control Flow I

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# Operators

# The calculator

Accept input of the form `x op y`, where `x` and `y` are floating-point numbers and `op`  $\in \{ '+', '-', '*', '/' \}$ . Print the result.

```
#include <stdio.h>

int main(void) {
    double x, y;
    char op;
    scanf("%lf %c %lf", &x, &op, &y);
    if (op == '+')
        printf("%lf\n", x + y);
    else if (op == '-')
        printf("%lf\n", x - y);
```

```
    else if (op == '*')
        printf("%lf\n", x * y);
    else if (op == '/')
        printf("%lf\n", x / y);
    else
        printf("Invalid operator.\n");
    return 0;
}
```

# Overview of arithmetic operators

Operator	Operator name	Example	Result
<code>+</code>	unary plus	<code>+a</code>	the value of <b>a</b> after promotions
<code>-</code>	unary minus	<code>-a</code>	the negative of <b>a</b>
<code>+</code>	addition	<code>a + b</code>	the addition of <b>a</b> and <b>b</b>
<code>-</code>	subtraction	<code>a - b</code>	the subtraction of <b>b</b> from <b>a</b>
<code>*</code>	product	<code>a * b</code>	the product of <b>a</b> and <b>b</b>
<code>/</code>	division	<code>a / b</code>	the division of <b>a</b> by <b>b</b>
<code>%</code>	remainder	<code>a % b</code>	the remainder of <b>a</b> divided by <b>b</b>
<code>~</code>	bitwise NOT	<code>~a</code>	the bitwise NOT of <b>a</b>
<code>&amp;</code>	bitwise AND	<code>a &amp; b</code>	the bitwise AND of <b>a</b> and <b>b</b>
<code> </code>	bitwise OR	<code>a   b</code>	the bitwise OR of <b>a</b> and <b>b</b>
<code>^</code>	bitwise XOR	<code>a ^ b</code>	the bitwise XOR of <b>a</b> and <b>b</b>
<code>&lt;&lt;</code>	bitwise left shift	<code>a &lt;&lt; b</code>	<b>a</b> left shifted by <b>b</b>
<code>&gt;&gt;</code>	bitwise right shift	<code>a &gt;&gt; b</code>	<b>a</b> right shifted by <b>b</b>

**+**, **-**, **\***, **/**, **%**

- **+** and **-** have two versions: unary (**+a**, **-a**) and binary (**a+b**, **a-b**).
  - The unary **+** / **-** and binary **+** / **-** are **different operators**, although they use the same notation.

- Operator precedence:

$\{ \text{unary } +, \text{unary } - \} > \{ *, /, \% \} > \{ \text{binary } +, \text{binary } - \}$

e.g. **a + b \* c** is interpreted as **a + (b \* c)**, instead of **(a + b) \* c**.

⇒ We will talk more about operator precedence later.

## Binary `+`, `-` and `*`, `/`

`a + b`, `a - b`, `a * b`, `a / b`

Before the evaluation of such an expression, the operands (`a`, `b`) undergo a sequence of **type conversions**.

- The [detailed rules of the conversions](#) are very complex,
  - including *promotions*, conversions between `signed` and `unsigned` types, conversions between integers and floating-point types, etc.
  - We only need to remember some common ones.
- In the end, the operands will be converted to a **same type**, denoted `T`. **The result type is also `T`.**

## Binary `+`, `-` and `*`, `/`

`a + b`, `a - b`, `a * b`, `a / b`

If any one operand is of floating-point type and the other is an integer, **the integer will be implicitly converted to that floating-point type.**

Example:

```
double pi = 3.14;  
int diameter = 20;  
WhatType c = pi * diameter; // What is the type of this result?
```



## Binary `+`, `-` and `*`, `/`

`a + b`, `a - b`, `a * b`, `a / b`

If any one operand is of floating-point type and the other is an integer, **the integer will be implicitly converted to that floating-point type.**

Example:

```
double pi = 3.14;  
int diameter = 20;  
double c = pi * diameter; // 62.8
```

The value of `diameter` is implicitly converted to a value of type `double`. Then, a floating-point multiplication is performed, yielding a result of type `double`.

\* Does this rule make sense?

## Binary `+`, `-` and `*`, `/`

`a + b`, `a - b`, `a * b`, `a / b`

If any one operand is of floating-point type and the other is an integer, **the integer will be implicitly converted to that floating-point type.**

Example:

```
double pi = 3.14;  
int diameter = 20;  
double c = pi * diameter; // 62.8
```

The value of `diameter` is implicitly converted to a value of type `double`. Then, a floating-point multiplication is performed, yielding a result of type `double`.

\* Does this rule make sense? - Yes, because  $\mathbb{Z} \subseteq \mathbb{R}$ .

## Binary `+`, `-` and `*`, `/`

`a + b`, `a - b`, `a * b`, `a / b`

If any one operand is of floating-point type and the other is an integer, **the integer will be implicitly converted to that floating-point type**, and the result type is that floating-point type.

Similarly, if the operands are of types `int` and `long long`, the `int` value will be implicitly converted to `long long`, and the result type is `long long`.<sup>1</sup>

## Division: $a / b$

Assume  $a$  and  $b$  are of the same type  $T$  (after conversions as mentioned above).

- Then, the result type is also  $T$ .

Two cases:

- If  $T$  is a floating-point type, this is a floating-point division.
- If  $T$  is an integer type, this is an integer division.

## Division: `a / b`

Two cases:

- If `T` is a floating-point type, this is a floating-point division.
  - The result is no surprising.
- If `T` is an integer type, this is an integer division.
  - The result is **truncated towards zero** (since C99 and C++11) <sup>2</sup>.
  - What is the result of `3 / -2`?

Let `a` and `b` be two integers.

- What is the difference between `a / 2` and `a / 2.0`?
- What does `(a + 0.0) / b` mean? What about `1.0 * a / b`?

## Division: `a / b`

If `T` is an integer type, this is an integer division.

- The result is **truncated towards zero** (since C99 and C++11) <sup>2</sup>.
- What is the result of `3 / -2`?
  - `-1.5` truncated towards zero, which is `-1`.

What is the difference between `a / 2` and `a / 2.0`?

- `a / 2` yields an integer, while `a / 2.0` yields a `double`.

What does `(a + 0.0) / b` mean? What about `1.0 * a / b`?

- Both use floating-point division to compute  $\frac{a}{b}$ . The floating-point numbers `0.0` and `1.0` here cause the conversion of the other operands.

Remainder: `a % b`

Example: `15 % 4 == 3`.

`a` and `b` must have integer types.

If `a` is negative, is the result negative? What if `b` is negative? What if both are negative?

## Remainder: `a % b`

Example: `15 % 4 == 3`.

`a` and `b` must have integer types.

~~If `a` is negative, is the result negative? What if `b` is negative? What if both are negative?~~

For any integers `a` and `b`, the following always holds:

$$(a / b) * b + (a \% b) == a$$



## Compound assignment operators

`+=` , `-=` , `*=` , `/=` , `%=`

- `a op= b` is equivalent to `a = a op b` .
- e.g. `x *= 2` is equivalent to `x = x * 2` .
- **[Best practice]** Learn to use these operators, to make your code clear and simple.

## Signed integer overflow

If a **signed integer type** holds a value that is not in the valid range, **overflow** is caused.

Suppose `int` is 32-bit and `long long` is 64-bit.

Do the following computations cause overflow?

```
int ival = 100000; long long llval = ival;  
int result1 = ival * ival;  
long long result2 = ival * ival;  
long long result3 = llval * ival;  
long long result4 = llval * ival * ival;
```

# Signed integer overflow

Suppose `int` is 32-bit and `long long` is 64-bit.

Do the following computations cause overflow?

```
int ival = 100000; long long llval = ival;
int result1 = ival * ival;           // (1) overflow
long long result2 = ival * ival;     // (2) overflow
long long result3 = llval * ival;    // (3) not overflow
long long result4 = llval * ival * ival; // (4) not overflow
```

(1)  $(10^5)^2 = 10^{10} > 2^{31} - 1$ .

(2) The result type of the multiplication `ival * ival` is `int`, which causes overflow. This is not affected by the type of `result2`.

# Signed integer overflow

Suppose `int` is 32-bit and `long long` is 64-bit.

Do the following computations cause overflow?

```
int ival = 100000; long long llval = ival;  
int result1 = ival * ival;           // (1) overflow  
long long result2 = ival * ival;      // (2) overflow  
long long result3 = llval * ival;     // (3) not overflow  
long long result4 = llval * ival * ival; // (4) not overflow
```

(3) Since `llval` is of type `long long`, the value of `ival` will be implicitly converted to `long long`, and then the multiplication yields a `long long` value.

(4) `*` is **left-associative**, so the expression `a * b * c` is interpreted as `(a * b) * c`.

⇒ We will talk about associativity in later lectures.

# Undefined behavior

Signed integer overflow is **undefined behavior**: There are no restrictions on the **behavior of the program**. Compilers are not required to diagnose undefined behavior (although many simple situations are diagnosed), and the compiled program is not required to do anything meaningful.

- It may yield some garbage values, or zero, or anything else;
- or, this statement may be removed if the compiler is clever enough;
- or, the program may crash;
- or, any other results beyond imagination.

⇒ More on undefined behaviors in recitations.

## Unsigned integers never overflow

Unsigned integer arithmetic is always performed *modulo*  $2^n$ , where  $n$  is the number of bits in that integer type.

For example, for `unsigned int` (assuming it is 32-bit)

- adding one to  $2^{32} - 1$  gives 0 because  $2^{32} \bmod 2^{32} = 0$ , and
- subtracting one from 0 gives  $2^{32} - 1$  because  $-1 \bmod 2^{32} = 2^{32} - 1$ .

\* "wrap-around"

## Increment/decrement operators

Unary operators that increment/decrement the value of a variable by `1`.

Postfix form: `a++`, `a--`

Prefix form: `++a`, `--a`

- `a++` and `++a` increment the value of `a` by `1`.
- `a--` and `--a` decrement the value of `a` by `1`.

## Increment/decrement operators

Unary operators that increment/decrement the value of a variable by `1`.

Postfix form: `a++`, `a--`

The result of the **postfix** increment/decrement operators is the value of `a` **before** incrementation/decrementation.



# Increment/decrement operators

Unary operators that increment/decrement the value of a variable by `1`.

Postfix form: `a++`, `a--`

The result of the **postfix** increment/decrement operators is the value of `a` **before** incrementation/decrementation.

```
int x = 42;
printf("%d\n", x++); // x becomes 43, but 42 is printed.
int y = x++; // y is initialized with 43. x becomes 44.
```

# Increment/decrement operators

Unary operators that increment/decrement the value of a variable by `1`.

Prefix form: `++a`, `--a`

The result of the **prefix** increment/decrement operators is the value of `a` **after** incrementation/decrementation.

```
int x = 42;
printf("%d\n", ++x); // x becomes 43, and 43 is printed.
int y = ++x; // y is initialized with 44. x becomes 44.
```

# Control flow

# Control statements

**Control flow** refers to the path along which instructions are executed in a program.

**Control statements** are used to direct the control flow of a program, allowing you to make decisions, repeat actions, and jump to different locations of the program.

## if - else

Conditionally executes some code.

Syntax:

- (1) `if (condition) statementT`
- (2) `if (condition) statementT else statementF`

where `condition` is an expression of arithmetic type or pointer type.

⇒ We will talk about pointers in later lectures.

If `condition` compares not equal to the integer zero, `statementT` is executed.

In (2), if `condition` compares equal to the integer zero, `statementF` is executed.

## if - else

- (1) `if (condition) statementT`
- (2) `if (condition) statementT else statementF`

`statementT` , `statementF` : Either a **statement** or a **block** (any number of statements surrounded by `{}` ).

- If more than one statements are to be executed, they must be surrounded with a pair of braces `{}` .

```
int i = 42;
if (i == 42)
    printf("hello");
    printf("world\n"); // This is NOT a part of statementT!
                        // This code is incorrectly indented.
```

## if - else

- (1) `if (condition) statementT`
- (2) `if (condition) statementT else statementF`

`statementT` , `statementF` : Either a **statement** or a **block** (any number of statements surrounded by `{}` ).

- If more than one statements are to be executed, they must be surrounded with a pair of braces `{}` .

```
int i = 42;
if (i == 42) {
    printf("hello");
    printf("world\n");
}
```

# The calculator example

```
double x, y;
char op;
scanf("%lf %c %lf", &x, &op, &y);
if (op == '+') {
    printf("%lf + %lf == %lf\n", x, y, x + y);
} else if (op == '-') {
    printf("%lf - %lf == %lf\n", x, y, x - y);
} else if (op == '*') {
    printf("%lf * %lf == %lf\n", x, y, x * y);
} else if (op == '/') {
    printf("%lf / %lf == %lf\n", x, y, x / y);
} else {
    printf("Unknown operator!\n");
}
```



# The calculator example

If there is only one statement, the braces can be omitted.

```
double x, y;  
char op;  
scanf("%lf %c %lf", &x, &op, &y);  
if (op == '+')  
    printf("%lf + %lf == %lf\n", x, y, x + y);  
else if (op == '-')  
    printf("%lf - %lf == %lf\n", x, y, x - y);  
else if (op == '*')  
    printf("%lf * %lf == %lf\n", x, y, x * y);  
else if (op == '/')  
    printf("%lf / %lf == %lf\n", x, y, x / y);  
else  
    printf("Unknown operator!\n");
```

# The calculator example

Nested `if` statements are possible:

```
double x, y;
char op;
scanf("%lf %c %lf", &x, &op, &y);
if (op == '+')
    printf("%lf + %lf == %lf\n", x, y, x + y);
else if (op == '-')
    printf("%lf - %lf == %lf\n", x, y, x - y);
else if (op == '*')
    printf("%lf * %lf == %lf\n", x, y, x * y);
else if (op == '/') {
    if (y == 0)
        printf("Error: division by zero.\n");
    else
        printf("%lf / %lf == %lf\n", x, y, x / y);
} else
    printf("Unknown operator!\n");
```

## Dangling `else`

The `else` is always associated with the closest preceding `if`.

```
if (i == 1)
    if (j == 2)
        printf("aaa\n");
else // Incorrectly indented! This `else` is associated with `if (j == 2)`.
    printf("bbb\n");
```

If you want this `else` to be associated with `if (i == 1)`, add a pair of braces.

```
if (i == 1) {
    if (j == 2)
        printf("aaa\n");
} else
    printf("bbb\n");
```

## The formatter tells you the truth.

Unlike Python, indentations are not part of the C syntax. The following code is completely legal, but with extremely low readability.

```
int a,b;scanf("%d%d",&a,&b);int s=a+b;printf("%d\n",s);if(a==1)if(b==2)printf("aaa\n");else printf("b\n");
```

**[Best practice]** Use a formatter! If you use VSCode, press Shift+Alt+F (Windows), ⌘⇧F (MacOS) or Ctrl+Shift+I (Linux) to format the code.

- Other editors may also have this functionality.

The formats are customizable. Explore it on your own if you are interested.

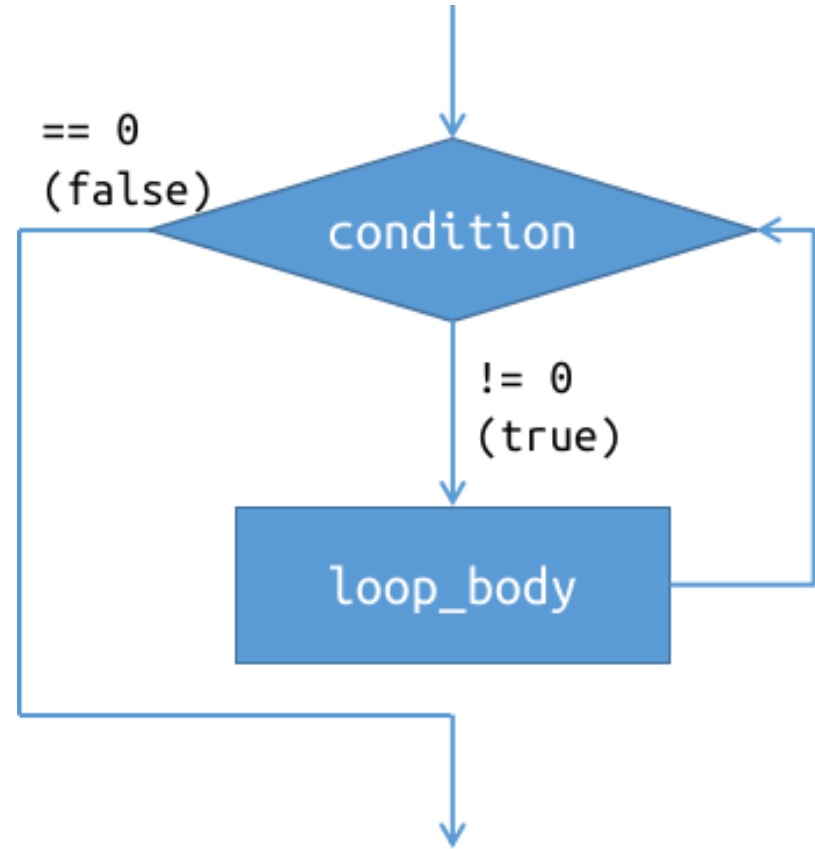
# while

Executes some code repeatedly under certain condition.

Syntax:

```
while (condition) loop_body
```

where `condition` is an expression of arithmetic type or pointer type, and `loop_body` is a statement or a block.



## while

Read an integer `n`, followed by `n` integers. Print the sum of the `n` integers.

```
int n;  
scanf("%d", &n);  
int sum = 0;  
while (n > 0) {  
    int x;  
    scanf("%d", &x);  
    sum += x;  
    --n;  
}  
printf("%d\n", sum);
```

## while

```
while (n > 0) {  
    // loop body  
    --n;  
}
```

How many times is this loop body executed?

After the loop, what is the value of `n`?

## while

```
while (n > 0) {  
    // loop body  
    --n;  
}
```

How many times is this loop body executed?

- `n`.

After the loop, what is the value of `n`?

- `0`, which makes `n > 0` not satisfied.



## while

A simpler and common way to write this loop:

```
while (n--) {  
    // loop body  
}
```

How many times is this loop body executed?

After the loop, what is the value of `n`?

## while

A simpler and common way to write this loop:

```
while (n--) {  
    // loop body  
}
```

How many times is this loop body executed?

- `n`.

After the loop, what is the value of `n`?

- `-1`. When `n == 0`, the result of `n--` is `0`, which not only makes the loop terminated but also decrements `n` by `1`.

## break

`break;` causes the loop to terminate.

```
while (n--) {  
    int x;  
    scanf("%d", &x);  
    // If x == 42, the loop is terminated and control goes to (*).  
    if (x == 42)  
        break;  
    sum += x;  
}  
// (*)  
printf("%d\n", sum);
```

## continue

`continue;` causes the remaining portion of the loop body to be skipped (in the current iteration).

```
while (n--) {  
    int x;  
    scanf("%d", &x);  
    // If x == 42, the rest of the loop body is skipped and control goes to (*).  
    if (x == 42)  
        continue;  
    sum += x;  
    // (*)  
}  
printf("%d\n", sum);
```

## break vs continue

**break** : terminate the loop.

```
while (n--) {  
    int x;  
    scanf("%d", &x);  
    if (x == 42)  
        break; // goto (*)  
    sum += x;  
}  
// (*)  
printf("%d\n", sum);
```

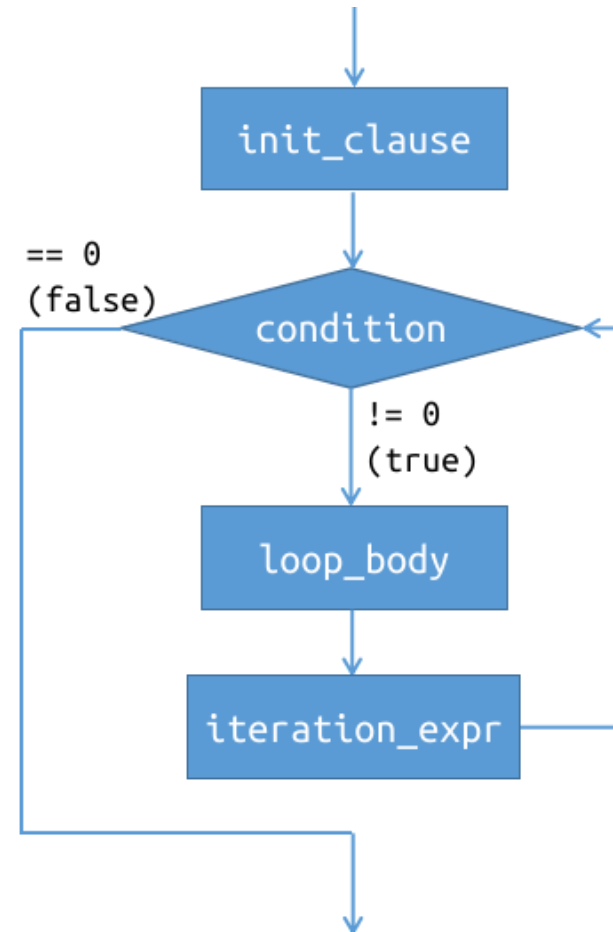
**continue** : skip the rest of the loop body.

```
while (n--) {  
    int x;  
    scanf("%d", &x);  
    if (x == 42)  
        continue; // goto (*)  
    sum += x;  
    // (*)  
}  
printf("%d\n", sum);
```

# for

Syntax: `for (init_clause; condition; iteration_expr) loop_body`

- `init_clause` may be an expression or a declaration (since C99).
- `condition` is an expression of arithmetic type or pointer type. It is evaluated before the loop body.
- `iteration_expr` is an expression evaluated after the loop body.
- `loop_body` is either a statement or a block.



## for

Typical usage: execute a loop body for `n` times.

The following are equivalent.

```
while (n--> 0) {  
    int x;  
    scanf("%d", &x);  
    sum += x;  
}
```

```
for (int i = 0; i < n; ++i) {  
    int x;  
    scanf("%d", &x);  
    sum += x;  
}
```

## for

Syntax: `for (init_clause; condition; iteration_expr) loop_body`

It is equivalent to

```
{
    init_clause;
    while (condition) {
        loop_body
        iteration_expr;
    }
}
```



## for

A loop with iteration variable `i` incremented by `2` every time:

```
for (int i = 0; i < n; i += 2)
    // ...
```

Loop until  $\lfloor \sqrt{n} \rfloor$ :

```
for (int i = 0; i * i <= n; ++i) // We don't need sqrt.
    // ...
```

A loop with iteration variable `i` going downward from `n` to `0`:

```
for (int i = n; i >= 0; --i)
    // ...
```

\* Can we use `unsigned` here?

**for**

What will happen?

```
for (unsigned i = n; i >= 0; --i)  
    // ...
```

## for

What will happen?

```
for (unsigned i = n; i >= 0; --i)  
    // ...
```

`i` is an `unsigned` integer, so `i >= 0` holds forever.

- When `i == 0`, `--i` makes the value of `i` become `4294967295` (if `unsigned` is 32-bit).
- An unsigned integer never overflows. Unsigned integer arithmetic is performed modulo  $2^n$ .

## for

**[Best practice]** Always declare and initialize the iteration variable inside the `for` statement, if possible.

Do not write code of the last century:

```
main() {  
    int i, j;  
    /* ... */  
    for (i = 0; i < n; ++i)  
        for (j = 0; j < m; ++j)  
            /* ... */  
}
```

Write it in a modern, standard way:

```
int main(void) {  
    // ...  
    for (int i = 0; i < n; ++i)  
        for (int j = 0; j < m; ++j)  
            // ...  
}
```

# Summary

## Operators

- `a + b`, `a - b`, `a * b`, `a / b`: `a` and `b` are converted to a common type `T` according to some rules, and the result type is also `T`.
- Integer division: The result is truncated towards zero.
- Remainder: `(a / b) * b + (a % b) == a` always holds.
- `+=`, `-=`, `*=`, `/=`, `%=`: `a op= b`  $\Leftrightarrow$  `a = a op b`
- Signed integer overflow: **undefined behavior**.
- Unsigned integer arithmetic: modulo  $2^n$ , never overflows.
- `a++` and `a--` return the original value. `++a` and `--a` return the new value.

# Summary

## Control flow

- `if - else`
- `while` , `break` , `continue`
- `for`

## Exercises

1. Write a program that reads **an unknown number** of integers from input until `0` is entered. Print the sum of these integers.
2. Make the calculator a loop that runs repeatedly, instead of handling only one input.

## Notes

<sup>1</sup> Similar conversions also happen for operands with types `int` + `long`, `long` + `long long`, `unsigned` + `unsigned long long`, etc. However, if any operand is of type with *rank* less than *rank* of `int`, **integer promotion** is first applied. For example, if `a` is of type `signed char` and `b` is of type `short`, both of them are converted to `int` first and the result type is `int`, not `short`.

Integer promotion is also applied to the operand of unary `+` and `-`. For example, `+x` is of type `int` if `x` is a `short` variable.

<sup>2</sup> Before C99 and C++11, the result of integer division is rounded in an implementation-defined direction.