CS100 Lecture 3

Operators (1) and Control Flow (1)

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- Operators
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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.

```c
#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);
```

```c
  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
`+`	unary plus	`+a`	the value of **a** after promotions
`-`	unary minus	`-a`	the negative of **a**
`+`	addition	`a + b`	the addition of **a** and **b**
`-`	subtraction	`a - b`	the subtraction of **b** from **a**
`*`	product	`a * b`	the product of **a** and **b**
`/`	division	`a / b`	the division of **a** by **b**
`%`	remainder	`a % b`	the remainder of **a** divided by **b**
`~`	bitwise NOT	`~a`	the bitwise NOT of **a**
`&`	bitwise AND	`a & b`	the bitwise AND of **a** and **b**
`|`	bitwise OR	`a | b`	the bitwise OR of **a** and **b**
`^`	bitwise XOR	`a ^ b`	the bitwise XOR of **a** and **b**
`<<`	bitwise left shift	`a << b`	**a** left shifted by **b**
`>>`	bitwise right shift	`a >> b`	**a** right shifted by **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:

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

  $\Rightarrow$ 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:

```cpp
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`. [1]

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) [2].
  - 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) [2].
- 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 $\dfrac{a}{b}$. 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) $\left(10^5\right)^2 = 10^{10} > 2^{31} - 1.$

(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.

$\Rightarrow$ 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.

e.g. For `unsigned int`, adding one to $2^{32}-1$ gives 0, and subtracting one from 0 gives $2^{32}-1$ (assuming `unsigned int` is 32-bit).

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**.

*** What does "result" mean?**

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**.

```c
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

`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.

$\Rightarrow$ 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 `{}`.

```c
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 `{}`.

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

The calculator example

```c
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.

```c
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`.

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

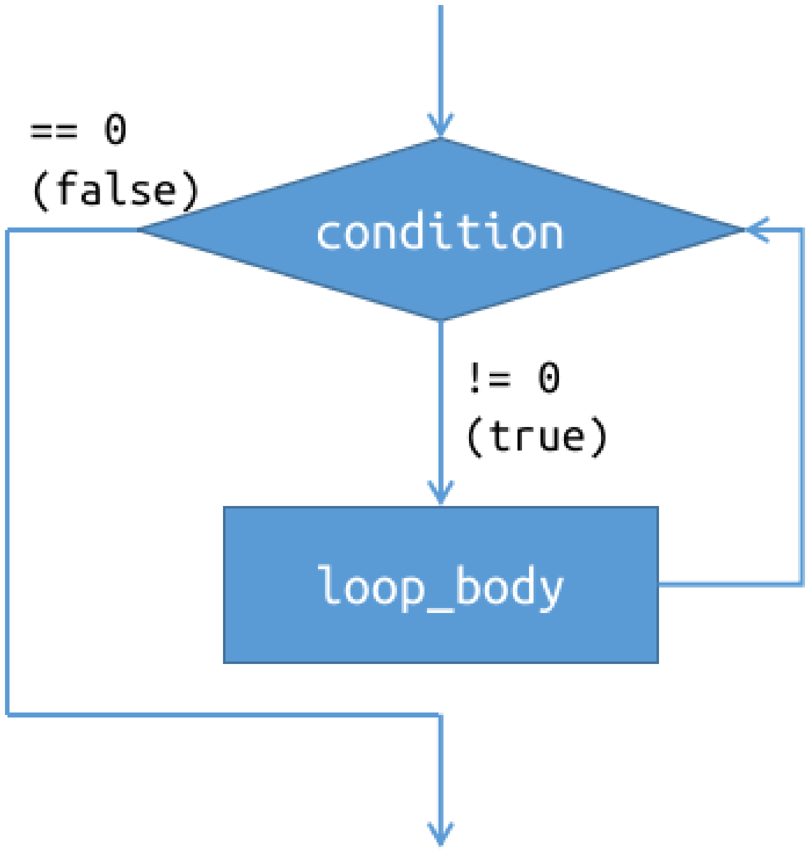
`while`

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.

```c
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 enclosing 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 enclosing loop body to be skipped.

```
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`: terminates the loop.

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

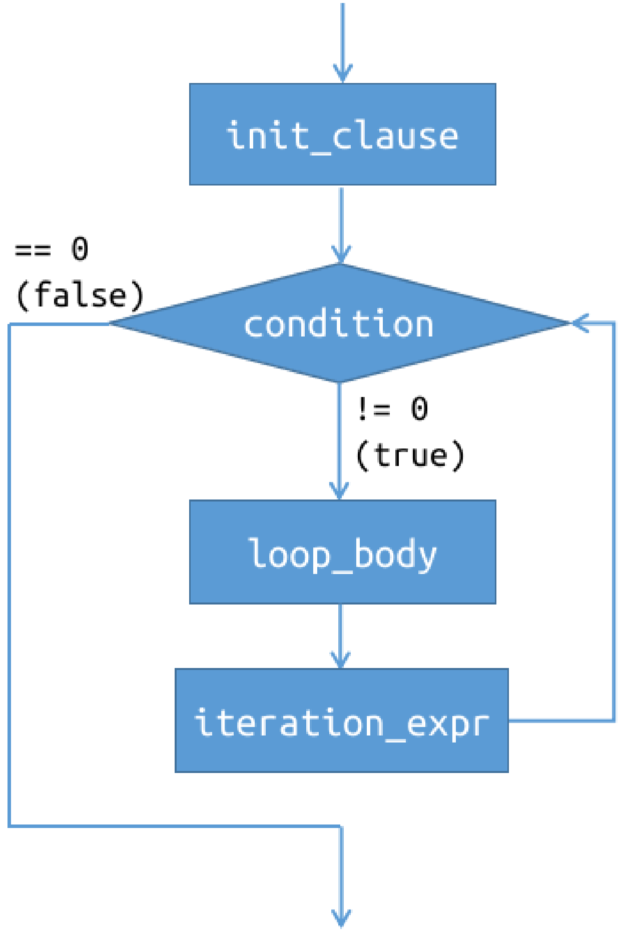
`continue`: skips the rest of the loop body.

```
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 the body for `n` times.

The following are equivalent.

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

```c
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?

```c
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:

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

Write it in a modern, standard way:

```c
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

[1] 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.

[2] Before C99 and C++11, the result of integer division is rounded in an implementation-defined direction.