



DARK CORNERS OF C

ALL NOTES

BY

0xLeo (github.com/0xleo)

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1 Preprocessor tricks

1.1 Macros vs functions

TAKEAWAY 1.1 (Macros vs functions). *Macros textually replace a name with its definition at compile time. Functions induce an overhead to manipulate the stack while macros do not.*

Macros in C are preprocessor fragments of code that define a name (e.g. function). That name is textually replaced by its definition at compile time, and particularly by the preprocessor. Therefore they do not make any function calls. That eliminates the overhead to call a function but has potential side-effects.

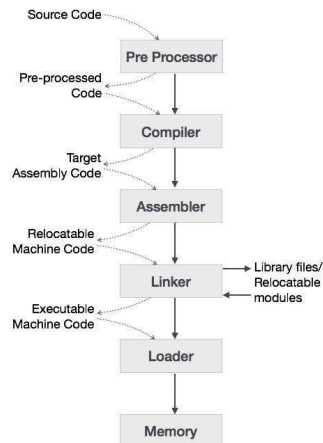


Fig. 1. Language processing system.

Let's see the difference in practice.

Listing 1: Computing the max (src/preprocessor_tricks/preprocessor_01.c)

```
1 #define MAX(a,b) (((a)>(b))?(a):(b))
2
3 int max(int a, int b) {
4     return a > b ? a : b;
5 }
6
7 int main() {
8     int a = 0, b = 1;
9     int c = MAX(a, b);
10    int d = max(a, b);
11    printf("%d", c);
12 }
```

In Listing 1, local variables `a` and `b` are mapped to the following stack location in assembly (`#` denotes an inline comment):

```
mov     DWORD PTR [ebp-12], 0 # a
mov     DWORD PTR [ebp-16], 1 # b
```

Finding the maximum by calling the macro `MAX` simply adds more branches to the generated code. The C line below:

```
int c = MAX(a, b);
```

generates the following code:

```
mov     eax, DWORD PTR [ebp-12]
cmp     eax, DWORD PTR [ebp-16]
jle     .L6
mov     eax, DWORD PTR [ebp-12]
jmp     .L7
.L6:
```

```

    mov     eax, DWORD PTR [ebp-16]
.L7:
    mov     DWORD PTR [ebp-20], eax

```

This is translated into the following pseudocode, where [...] denote memory location:

```

[ebp=12] = 0 # a
[ebp-16] = 1 # b
eax = a
if eax <= b:
    goto .L6
goto .L7

.L6:
    eax = b
.L7
    [ebp-20] = eax # address ebp-20 stores c

```

On the other hand, calling the max function:

```
int d = max(a, b);
```

requires pushing the local variables a, b in the stack before the function is called and then popping (add esp, 4 pops 4 bytes - one integer) the stack:

```

mov     DWORD PTR [ebp-20], eax
push    DWORD PTR [ebp-16]
push    DWORD PTR [ebp-12]
call    max(int, int)
add     esp, 8
mov     DWORD PTR [ebp-24], eax

```

1.2 The double evaluation problem of macros

Passing expressions to macros, such as the output of function, e.g. foo() may hinder the performance of the code due to double evaluation.

TAKEAWAY 1.2 (double evaluation problem of macros). *Passing an expression as an argument to a function-like macro will potentially evaluate that expression twice. That is because the expression will be repeated where ever the macro parameter it takes on, is used in the macro's definition.*

This can be remedied by passing values into the macro.

Supposed we have defined a macro for the maximum of two numbers and we want to evaluate by calling two functions:

```

1 #include <stdio.h>
2
3 #define MAX(a,b) (((a)>(b))?(a):(b))
4
5 int x() { puts("x"); return 0; }
6 int y() { puts("y"); return 1; }
7
8 int main() {
9     MAX(x(), y());
10 }

```

MAX in this case will expand to:

```
#define MAX(a,b) ((x() > y()) ? x() : y())
```

When running the C code for \texttt{MAX}, \texttt{x()}, y() are both called once at the test condition

```

x
y
y

```

Obviously the remedy is to store their returns in local variables and pass the local variables in the macro.

1.3 Multi-line macros

Before multi-line are defined, it is important to know about control flow statements not followed by curly braces (“naked” if, else, while, for).

TAKEAWAY 1.3 (naked control flow statements). *A control flow statement that is not followed by is considered as a block with the next statement that follows it.*

For instance:

```
if (condition)
int a = 1; int b = 2;
```

is equivalent to:

```
if (condition) {
int a = 1;
}
int b = 2;
```

Back to the main problem – suppose we want to write a multi-line macro, e.g. a F00 function-like macro that subsequently calls two functions foo, bar.

Attempt 1:

One naive attempt would be the following:

Listing 2: First attempt for multi-line macro (src/preprocessor_tricks/preprocessor/preprocessor_tricks_02.c)

```
1 #include <stdio.h>
2
3 #define F001(val) foo(val); bar();
4
5 void foo(int val) {
6     puts("foo");
7 }
8
9 void bar() {
10    puts("bar");
11 }
12
13
14 int main() {
15     if (2 + 2 == 5)
16         F001(42); // foo(42); bar()
17 }
```

This expands the macro to two statements – foo(42) and bar() and since “naked” if is only followed by one statement, bar() will be executed regardless of the condition.

Attempt 2:

One can try wrapping the two statements in curly braces.

Listing 3: Third attempt for multi-line macro (src/preprocessor_tricks/preprocessor/preprocessor_tricks_03.c)

```
1 #include <stdio.h>
2
3 #define F002(val) { foo(val); bar(); }
4
5 void foo(int val) {
6     puts("foo");
7 }
8
9 void bar() {
10    puts("bar");
11 }
```

```

11 }
12
13
14 int main() {
15     if (2 + 2 == 4)
16         F002(42);
17 }

```

This will be expanded to two statements wrapped in curly braces followed by ;:

```

if (2 + 2 == 4)
{ foo(42); bar() };

```

This is an invalid syntax in C so it will not compile.

Attempt 4:

We can try removing the semicolon after the function-line macro F002(42) is called to turn this into a valid if statement:

Listing 4: Fourth attempt for multi-line macro (src/preprocessor_tricks/preprocessor/preprocessor_tricks_04.c)

```

1 #include <stdio.h>
2
3 #define F002(val) { foo(val); bar(); }
4
5 void foo(int val) {
6     puts("foo");
7 }
8
9 void bar() {
10    puts("bar");
11 }
12
13
14 int main() {
15     if (2 + 2 == 4)
16         F002(42) // { foo(42); bar() };
17     else
18         foo(43);
19 }

```

It prints:

```

foo
bar

```

This approach works but it's unconventional as C statements are normally followed by semicolon.

Attempt 5:

One way to consistently define function-line macros that are followed by a semicolon is by wrapping them in a do-while block as follows:

Listing 5: Fifth attempt for multi-line macro (src/preprocessor_tricks/preprocessor/preprocessor_tricks_05.c)

```

1 #include <stdio.h>
2
3 #define F003(val) do { foo(val); bar(); } while(0)
4
5 void foo(int val) {
6     puts("foo");
7 }
8
9 void bar() {
10    puts("bar");
11 }
12

```

```

13
14 int main() {
15     if (2 + 2 == 4)
16         F003(42); // { foo(42); bar(); }
17     else
18         foo(43);
19 }

```

The above program prints the desired output:

```

foo
bar

```

The do-while block ensures the commands inside it will be executed only once. Furthermore, do-while as always followed by a semicolon. Therefore this idiom not only executes multi-line preprocessor commands, but also must be followed by a semicolon, which makes it consistent with other statements such as function calls. For code maintainability purposes, it's a good practice to wrap *any* macro in do-while – even single-line ones.

TAKEAWAY 1.4 (multi-line macros). *To define a multiple statements `statement1; statement2; ...` in a macro, they can be wrapped in a do-while block as follows:*

```
#define F00(arg1, arg2, ...) do { statement1; statement2; ... } while(0)
```

2 Integer promotions and signed conversions in C

2.1 Mixing floats with ints

Consider the following program. What will be the output?

```
1 double d = 3.33;
2 if (d*3 < 10L)
3     puts("true");
```

Confirming the maths, the output is true, but why? Which value gets converted to which type? Let's look at the main part of the clang disassembly:

```
1 movsd    xmm0, qword ptr [.LCPIO_0] # xmm0 = double 10
2 movsd    xmm1, qword ptr [.LCPIO_1] # xmm1 = double 3
3 movsd    xmm2, qword ptr [.LCPIO_2] # xmm2 = double 3.33
4 movsd    qword ptr [ebp - 16], xmm2
5 mulsd    xmm1, qword ptr [ebp - 16] # xmm1 = xmm1 * 3.33
6 ucomisd  xmm0, xmm1
7 jbe      .LBB0_2 # if 10 below or equal to xmm1 jump to return (.LBB0_2)
8 <-- omitted -->
9 call     puts # if xmm0 > xmm1
```

So 10L gets converted to double, which makes sense as the other way would make operand `d*3` lose its precision. A similar conversion occurs in the following snippet too.

```
1 int i = 1;
2 if (i + 1.5 < i + 2)
3     puts("correct!");
```

In this case, In this case `i` gets stored at an int register (e.g. `eax` register) and when the compiler sees the addition with 1.5 it copies `eax` to a floating pointer register (e.g. `xmm1`) and performs the addition with both operands as doubles. The result of `i+2` also in the end gets stored at a floating point register and the comparison between doubles is made, printing `correct!`.

According the C ISO [1], the following rules apply when an operator operating on double or float and another type¹:

TAKEAWAY 2.1 (conversion between double/ float and another type – C ISO 2007, 6.3.1.8/1).

1. First, if the type of either operand is long double, the other operand is converted, without change of type domain, to long double.
2. Otherwise, if the type of either operand is double, the other operand is converted, without change of type domain, to double.
3. Otherwise, if the type of either operand is float, the other operand is converted, without change of type domain, to float.

To sum up:

long double > double > float > int types

2.2 Integer sub-types and ranges

Sometimes integer types and its their sub-types need to be converted from one to another. Such a conversion is called integer promotion, for example when a `char` gets converted to `int`. As a reminder, the table below shows the size of `int` and its sub-types for most 32-bit machines.

Types	Bits	Naming	Min	Max
char (signed char)	8	byte	-2^7	$2^7 - 1$
unsigned char	8	byte	0	$2^8 - 1$
short (signed short)	16	word	-2^{15}	$2^{15} - 1$
unsigned short	16	word	0	$2^{16} - 1$
int (signed int)	32	double word	-2^{31}	$2^{31} - 1$
unsigned int	32	double word	0	$2^{32} - 1$

¹We don't take into account imaginary numbers for simplicity.

Note that the sizes in the table are common among many systems but not universal. For example, OpenBSD systems use different numbers of bits. Another integer type, which is *not* a sub-type of `int` but a super-type of it, is `long`. It is guaranteed to be at least 32 bits. On Linux Intel architecture, which is used in these notes, its size is the following.

Types	Architecture	Bits	Naming	Min	Max
<code>long</code> (signed <code>long</code>)	Linux IA-32	32	quad word	-2^{31}	$2^{31} - 1$
<code>unsigned long</code>	Linux IA-32	32	quad word	0	$2^{32} - 1$
<code>long</code> (signed <code>long</code>)	Linux IA/Intel-64	64	quad word	-2^{63}	$2^{63} - 1$
<code>unsigned long</code>	Linux IA/Intel-64	64	quad word	0	$2^{64} - 1$

2.3 Integer promotion

Integer promotion occurs implicitly when we operate on integer sub-types or integers. If an `int` can represent all values of the original type, the value is converted to an `int` (and its value is preserved), otherwise it is converted to an `unsigned int`. Bear in mind integer promotion is not the same as integer conversion, which is studied in another section. The following examples make it clear.

EXAMPLE 2.1 (Integer promotion – signed chars). Let's take a look at what happens when we operate on integer sub-types together, for example two (signed) `char` variables.

```
1 char c1 = 100, c2 = 3;
2 if (c1*c2 > 299)
3     puts("Now I know 1st grade maths!");
```

The snippet above prints `Now I know 1st grade maths!`, as it should. But what's the type of `c1`, `c2`, `c1*c2` and `299` when the comparison is made? The gcc disassembly shows that initially `c1` and `c2` are stored in byte (`char`)-wide local variables but have been copied to 4-byte registers as signed integers². Next, they are multiplied as signed integers (`imul`) and then the comparison takes place:

```
1 mov     BYTE PTR [ebp-9], 100
2 mov     BYTE PTR [ebp-10], 3
3 movsx   edx, BYTE PTR [ebp-9]
4 movsx   eax, BYTE PTR [ebp-10]
5 imul    eax, edx
6 cmp     eax, 299
```

■

EXAMPLE 2.2 (Integer promotion – signed char and unsigned char). We introduce a subtle change to the previous example, defining one signed `char` and one unsigned `char` instead, so the snippet looks like:

```
1 char c1 = 100;
2 unsigned char c2 = 3;
3 if (c1*c2 > 299)
4     puts("Now I know 1st grade maths!");
```

Then `c1` is zero-extended when copied to a 4-byte general register to store local variable `c2` as unsigned but the final result, i.e. `c1*c2` is treated as a signed `int`, as indicated by the `imul`:

```
1 movsx   eax, byte ptr [ebp - 5]
2 movzx   ecx, byte ptr [ebp - 6]
3 imul    eax, ecx
```

The compiler would prefer to represent expression `c1*c2` as signed `int` even if both `c1`, `c2` were defined unsigned `char`! ■

EXAMPLE 2.3 (Integer promotion – unsigned char and unsigned char). In this case, have define `c1` and `c2` as unsigned `char`. However, we assign `-6` to one of them. What gets printed?

²`movsx` means move and sign-extend

```

1 unsigned char c1 = 100;
2 unsigned char c2 = -6;
3 printf("%d\n", c1*c2);

```

The gcc disassembly sheds some light.

```

1 mov     BYTE PTR [ebp-0xa],0x64
2 mov     BYTE PTR [ebp-0x9],0xfa
3 movzx   edx,BYTE PTR [ebp-0xa]
4 movzx   eax,BYTE PTR [ebp-0x9]
5 imul    eax,edx

```

So what actually gets stored in c2 (local variable [ebp-0x9]) is 0xfa = 250, therefore the compiler mapped -6 to the unsigned char range [0,255]³, doing what the type of c2 defined. Although c1 and c2 are correctly represented by unsigned values (movzx instruction), the expression c1*c2 is once again treated as signed integer, as indicated by imul. ■

We've seen what happens when operations between int sub-types are performed. But what if two (signed) ints are operated and the result is not small enough to fit in the signed int range?

EXAMPLE 2.4 (When result doesn't fit in signed int.). In this example, we have the maximum integer than can be represented by the 32-bit range, i.e. $2^{31} - 1$. We want to double it and compare it to zero, which should of course be true. But we want the operation to be performed between unsigned integers, as signed cannot represent the result. If we simply compared:

In C, integers are signed by default.

```

1 2*i > 0

```

, then 2, i, 0 are all signed and we'd end up comparing -2 to 0. The way to make the compiler understand that the result should be performed in unsigned if it doesn't fit in signed would be to make at least of the operands unsigned, e.g. as follows:

```

1 #include <stdio.h>
2 #include <limits.h>
3
4 void main(int argc, char *argv[])
5 {
6     signed int i = INT_MAX; // 2^31 - 1 for 32b systems
7     if (2U*i > 0)
8         printf("correct! unsigned result = %u" , 2U*i);
9 }

```

Then

correct! unsigned result = 4294967294

is printed (i.e. $2^{32} - 2$, or 0xffffffff), as it should. As a final note, notice again that the expression 2*i > 0 operates on unsigned int if either of 2 (e.g. 2U), i, or 0 is unsigned (0U). The next section explains such conversions. ■

The last 4 examples can be justified by the following C ISO standard [1].

TAKEAWAY 2.2 (integer promotion definition – C ISO 2007, 6.3.1.1/2). *If an int can represent all values of the original type or int sub-type, the value is converted to an int; otherwise, it is converted to an unsigned int. These are called integer promotions. All other types are unchanged by integer promotions.*

Integer promotions occur every time we operate with integer sub-types.

2.4 IEEE priority (rank) rules

When operating on both signed and unsigned, there are a few things that C takes into account to determine the result, in order of priority:

1. The width of each type (e.g. 256 for signed char and unsigned char etc. The width of each type can be mapped to the “rank” in the C ISO. Integer rank defines which type will be converted to what.

³When mapping from one range of equal width to another, the byte representation doesn't change, only the way we interpret the bytes does.

2. Whether the operands are signed or unsigned, and whether they're different or not.

Regarding the rank, the ISO[1] defines the following:

TAKEAWAY 2.3 (integer rank – C ISO 2007 6.3.1.1/2).

```
1 rank(long long) > rank(long) > rank(int) > rank(short) > rank(char)
```

The rank of any unsigned integer type shall equal the rank of the corresponding signed integer type, if any. Rank is essentially the width a type can represent.

Here are some typical cases. Try to guess what rules apply given the rank and the signedness. Following the examples, the rule from C ISO is quoted.

EXAMPLE 2.5 (Mixing smaller int sub-type with larger sub-type). `signed char sc = -1;`

```
2 unsigned short ush = 0;
3 (sc + ush < ush)? puts("-1 < 0"): puts("-1 >= 0");
```

In this case, we operate on int sub-types `signed char` and `unsigned short`. First, `+` takes place. According to the promotions, `sc` and `ush` are both promoted to `int` before the addition, both obtaining the same rank and yielding `-1`. So we compare the latter result to `ush`, which is zero. `ush` is also promoted to `int` before the comparison, resulting in the condition printing `-1 < 0`. ■

EXAMPLE 2.6 (Mixing int sub-type with signed int). This is similar to the previous, except `si` does not have to be promoted to `int` as it already is – only `ssh` will, maintaining its value.

```
1 signed short ssh = -1;
2 int si = 0;
3 (ssh + si < si)? puts("-1 < 0"): puts("-1 >= 0");
```

The result is `-1 < 0`.

EXAMPLE 2.7 (mixing signed int with unsigned int). We have the same code with the previous example, except now we compare `ssh + si` to unsigned zero (`0U`).

```
1 signed short ssh = -1;
2 int si = 0;
3 (ssh + si < 0U)? puts("-1 < 0"): puts("-1 >= 0");
```

The result is `-1 > 0` so `ssh + si` must have been converted to unsigned `int`. Indeed, `printf("n%u", ssh + si)` gives 4294967295, which is $2^{32} - 1$, which is the upper limit of unsigned `int` for 32-bit systems. To summarise, the bottom to top order is:

```
ssh => int
(ssh + si) => int
(ssh + si < 0U) => ssh + si => unsigned int
```

It seems that if we have operate on two types with the same rank and different sign, the compiler prefers to convert signed to unsigned. ■

EXAMPLE 2.8 (Mixing long with int). Now we have two types with different rank – unsigned `long` and `int`.

```
1 int si = -1;
2 unsigned long ul = 0;
3 (si + ul < ul)? puts("[4]: -1 < 0"): puts("[4]: -1 >= 0");
```

On a 32-bit system, unsigned `long` and `int` have the same width of 4 bytes therefore the same rank, therefore the output would depend on signedness; we've seen that signed is preferred to be converted to unsigned when the rank is the same so the result is `-1 >= 0`.

On a 64-bit system, the result would also be `-1 <= 0`. The rank of unsigned `long` is same the rank of `long` and is greater than the rank of `int`. So `si` would be converted to unsigned `long` etc.

The disassembly shows how the comparison is implemented in the generated code. The relevant parts are the following, and especially the `jbe` instruction.

```

1 mov DWORD PTR [rbp-0xc],0xffffffff ; int si = -1
2 mov QWORD PTR [rbp-0x8],0x0        ; unsigned long ul = 0
3 mov eax,DWORD PTR [rbp-0xc]
4 movsxd rdx,eax                    ; eax = 0xffffffffffffff
5 mov rax,QWORD PTR [rbp-0x8]        ; rax = ul = 0
6 add rax,rdx                        ; rax += si
7 cmp QWORD PTR [rbp-0x8],rax
8 jbe 0x1178 <main+63>              ; if (PTR[rbp-0x8] <= rax)...
```

The instruction `jbe` treats the comparison operands as unsigned.

On the other hand, consider defining `ul` as `long`. Then `si` wouldn't have to be converted to unsigned `long` (in fact not even to `long` as it's simply compared to zero, hence the `DWORD`!). We'd end up with:

```

1 mov DWORD PTR [rbp-0xc],0xffffffff
2 cmp DWORD PTR [rbp-0xc],0x0
3 jns 0x116b <main+50>
```

`cmp` compares `si` to zero. `jns` (Jump if Not Sign) checks its sign, i.e. its first bit, and branches accordingly.

EXAMPLE 2.9 (signed char to unsigned char). `char sc = -2;`

```

2 unsigned char uc = 1;
3 (sc + uc == -1)? puts("[5] -1"): puts("[5] != -1");
```

In this case, both `sc` and `uc` are promoted to integer before the addition and the sign and values are preserved:

```

1 movsx  edx,BYTE PTR [rbp-0x2]
2 movsx  eax,BYTE PTR [rbp-0x1]
3 add     eax,edx
4 cmp     eax,0xffffffff
5 jne     0x117d <main+52>
```

`[5] -1` is printed. The result would also be true in the following cases:

```

1 (sc + uc == -1U)
2 (sc + uc == UINT_MAX)
3 (sc + uc == 0xffffffff)
```

EXAMPLE 2.10 (signed int to unsigned int). `signed int si = -5; unsigned int ui = 2; (si + ui == -3)? puts("[6]: -5+2== -3"): puts("[6]: -5+2!= -3");` In this case, `si` and `ui` have the same rank but different sign. Because `int` can represent both, no conversion is necessary therefore `[6] : -5+2== -3` is printed.

The code for all examples is found in `src/int_conv/conversions.c`. The following C ISO extract applies to the above examples. Note that when we operate on signed and unsigned it is *not always* the case that signed will be converted to unsigned (paragraph 4).

TAKEAWAY 2.4 (C ISO 2007 – 6.3.1.8/1).

1. If both operands have the same type, then no further conversion is needed.
2. Otherwise, if both operands have signed integer types or both have unsigned integer types, the operand with the type of lesser integer conversion rank is converted to the type of the operand with greater rank.
3. Otherwise, if the operand that has unsigned integer type has rank greater or equal to the rank of the type of the other operand, then the operand with signed integer type is converted to the type of the operand with unsigned integer type.
4. Otherwise, if the type of the operand with signed integer type can represent all of the values of the type of the operand with unsigned integer type, then the operand with unsigned integer type is converted to the type of the operand with signed integer type.
5. Otherwise, both operands are converted to the unsigned integer type corresponding to the type of the

operand with signed integer type.

Finally, if it's not clear yet, to convert a negative signed to unsigned we do the following:

```
while (number < 0) {  
    number += MAX_UNSIGNED_INT + 1  
}
```

This does not change the binary representation of the number – only the way it's interpreted. In binary, negative numbers are represented by 2's complement. For example, on a 4-bit machine, we have the signed

$-2 = 1110b$

Adding $MAX_UNSIGNED_INT = 16$ does not change the bits of the number. Using the magnitude representation instead of 2's complement, we have

$-2 + MAX_UNSIGNED_INT = 14 = 1110b$

These are the basics of how integers are handled by the compiler in C.

3 Inline functions in C

3.1 Why use them?

Functions in C can be declared as `inline` to *hint* (but not force) the compiler to optimise the speed of the code where they are used. Although many compilers know when to inline a function, it's a good practice to declare them in the source code.

Making a function `inline` means that instead of calling it, its body is copied by the compiler to the caller line. This eliminates the overhead of calling a function (creating stack space, arguments and local variables, and jumping to its definition, push variables to stack, pop etc.). It's a good practice for short functions that are called a few times in the code, otherwise it increases the code size (each call, one copy is added to the code).

TAKEAWAY 3.1. *inline is nothing but a hint to the compiler to try to replace a function call with its definition code wherever it's called.*

It may seem that inline functions are similar to macros. They are, but there are two key differences:

- Macros are expanded by the preprocessor before compilation and they *always* substitute the caller text with the body text.
- `inline` functions are type-checked but macros are not since macros are just text.

Let's create an inline function, call it and see what happens. If we try to compile the code below (without optimisations), i.e.

```
gcc inline_error.c -o inline_error
```

we get the linker error:

Listing 6: Attempting to declare an inline function (src/inline_error.c).

```
1 inline int foo()  
2 {  
3     return 0xaa;  
4 }  
5  
6 int main(int argc, char *argv[])  
7 {  
8     int ret;  
9  
10    ret = foo();  
11    return 0;  
12 }
```

```
inline_error.c:(.text+0x12): undefined reference to `foo'  
collect2: error: ld returned 1 exit status
```

In this case, the compiler has chosen *not to* inline `foo`, searches its definition symbol and cannot find it. However, if we compile with optimisations, i.e.

```
gcc -O inline_error.c -o inline_error
```

, then everything will work. `foo` will be inlined and so the linker will not need the “regular” definition.

3.2 Linkage issues – static inline vs extern inline

The C ISO, section 6.7.4⁴, defines the following regarding the linkage of inline functions.

“Any function with internal linkage can be an inline function. For a function with external linkage, the following restrictions apply:

If a function is declared with an inline function specifier, then it shall also be defined in the same translation unit.

⁴ <http://www.open-std.org/jtc1/sc22/wg14/www/docs/n1256.pdf>

If all of the file scope declarations for a function in a translation unit (TU) ⁵ include the inline function specifier without `extern`, then the definition in that TU is an inline definition. An inline definition does not provide an external definition for the function, and does not forbid an external definition in another TU. An inline definition provides an alternative to an external definition, which a translator may use to implement any call to the function in the same TU. It is unspecified whether a call to the function uses the inline definition or the external definition. ”

The key part of this specification is “an inline definition does not provide an external definition for the function, and does not forbid an external definition in another TU.” When we defined function `foo()` in Listing 7 and used it, although it was in the same file, the call to that function is resolved by the linker not the compiler, because it is implicitly `extern`. But this definition alone does not provide an external definition of the function. That’s how inline functions differ from regular ones. Also, note the part “it is unspecified whether a call to the function uses the inline definition or the external definition.”. That means that if let’s say, we have defined a function `inline int foo()`. When the function is called, it’s up to the compiler to choose whether to inline it or not. If it chooses not to, it will call `int foo()`. But the symbol for `int foo()` is not defined, hence the error. If it chooses to inline it, it will of course find it and link it so no error.

TAKEAWAY 3.2. *The definition of an inline function must be present in the TU where it is accessed.*

To resolve the missing definition behaviour it is recommended that linkage always be resolved by declaring them as `static inline` or `extern inline`. Which one is preferred though?

When we inline a function, we want to have both the “regular” and inline def’s available.

`inline` functions in gcc should be declared `static` or `extern`.

3.2.1 static inline

If the function is declared to be a `static inline` then, as before the compiler may choose to inline the function. In addition the compiler may emit a locally scoped version of the function in the object file if necessary. There can be one static version per object file, so you may end up with multiple definitions of the same function, so if the function is long this can be very space inefficient. The reason for this is that the compiler will generate the function definition (body) in every TU that calls the inline function.

TAKEAWAY 3.3. *`static` means “compile the function only with the current TU and then link it only with it”.*

Listing 7 demonstrates a case where both the “regular” and inline definitions are needed. In this case, the compiler will inline the code to compute `x*x`. However, next, it will search for the address of the (regular) square function. In square was only inlined, the address would not be found as the definition symbol would not exist.

`static inline` means “We have to have this function. If you use it but don’t inline it then make a static version of it in this TU.” – Linus

Listing 7: static inline demonstration (src/inline_static.c).

```
1 #include <stdio.h>
2
3 static inline unsigned int square(int x)
4 {
5     return x*x;
6 }
7
8 int main(int argc, char *argv[])
9 {
10     unsigned int i = square(5);
11     printf("address = 0x%x, return = 0x%x\n", (unsigned int) &square, i);
12     return 0;
13 }
```

Create the object file with optimisations⁶:

```
gcc -g -O -c inline_static.c -o inline_static.o
```

View the symbol table for the object file:

```
objdump -t -M intel inline_static.o
```

⁵translation unit (TU) = source file after it has been pre-processed - i.e. after all the `#ifdef`, `#define` etc. have been resolved.

⁶Code highlighted in grey indicates it has been entered in the command line.

```

inline_static.o:      file format elf32-i386
SYMBOL TABLE:
00000000 1      df *ABS* 00000000 inline_static.c
00000000 1      d  .text 00000000 .text
00000000 1      d  .data 00000000 .data
00000000 1      d  .bss 00000000 .bss
00000000 1      F .text 00000008 square
<-- omitted -->
00000008 g      F .text 00000032 main
00000000      *UND* 00000000 __printf_chk

```

Next, observe how both the inlined body and the function call (at printf) co-exist in the executable. Create the executable with optimisations:

```
gcc -g -O inline_static.c -o inline_static
```

View the disassembly:

```
gdb -q inline_static
```

Reading symbols from inline_static...done.

```
(gdb) disas square
```

```

Dump of assembler code for function square:
0x0804842b <+0>: mov     eax,DWORD PTR [esp+0x4]
0x0804842f <+4>: imul    eax,eax
0x08048432 <+7>: ret
End of assembler dump.

```

```
(gdb) print &square
```

```
$1 = (int (*)(int)) 0x804842b <square>
```

```
(gdb) disas main
```

```

<-- omitted -->
0x08048444 <+17>: push    0x19
0x08048446 <+19>: push    0x804842b
0x0804844b <+24>: push    0x80484f0
0x08048450 <+29>: push    0x1
0x08048452 <+31>: call    0x8048310 <__printf_chk@plt>
0x08048457 <+36>: add     esp,0x10
<-- omitted -->

```

To print $5 \times 5 = 0x19$, the compiler directly pushes it in the stack instead of calling square, avoiding all the call overhead. At the same time, the function definition exists in the file since its address (0x804842b) had to be printed. The takeaway here is that:

TAKEAWAY 3.4. *The compiler will generate function code for a static inline only if its address is used.*

The listing below demonstrates it.

Listing 8: In this case, function code for square will not be generated. (src/inline_static_no_code.c).

```

1 #include <stdio.h>
2
3 static inline unsigned int square(int x)
4 {
5     return x*x;
6 }
7
8 int main(int argc, char *argv[])
9 {
10     unsigned int i = square(5);

```

Functions are more likely to be inlined when the TU is compiled with optimisations.


```

11     printf("return = 0x%x\n", i);
12     return 0;
13 }

```

If we compile it with optimisations and search for the symbol of the square function, nothing will be found. It is used solely as inlined. This can also be confirmed by gdb.

```

gcc -c -O -g inline_static_no_code.c -o inline_static_no_code.o
objdump -t -M intel inline_static_no_code.o | grep square

```

TAKEAWAY 3.5. *Short, simple functions are OK to be defined as `static inline` in the TU that calls them as long as they don't generate too much bloat.*

3.3 extern inline

In C, all functions are extern by default, i.e. visible to other TUs, so for regular functions there's no need to use it.

Declaring a function as extern tells the compiler that the storage for this function is defined somewhere and if you haven't seen its definition that's OK – it will be connected with the linker. Thus extends the visibility of a function (or variable). It is useful when an inline function is defined in a header. Then it can be declared extern in the .c file that wants to call it. The linker will link it to the one in the header and depending on whether the compiler has decided to optimise or not, it will use either the function call or the inline code.

Since the declaration can be done any number of times and definition can be done only once, we notice that declaration of a function can be added in several TUs. But the definition only exists in one TU and it might contain. And as the extern extends the visibility to the whole file, the function with extended visibility can be called anywhere in any TU provided the declaration of the function is known. This way we avoid defining a function with the same body again and again.

A good practice is to declare a function defined somewhere else as extern.

TAKEAWAY 3.6. *So the best practice when we want to make an inline function external is:*

```

// .h file - regular definition
void foo(void)
{
    ...
}

// .c caller file - declaration
extern inline void foo(void);
...
foo();

```

EXAMPLE 3.1. We have our simple regular function to inline in a header.

Listing 9: Definition of foo() (src/foo.h).

```

1 #ifndef FOO_H
2 #define FOO_H
3
4 #include <stdio.h>
5
6 unsigned int foo(void)
7 {
8     return 0xaa;
9 }
10 #endif /* FOO_H */

```

We want our .c caller to see it and potentially inline it. As mentioned before, the way to do this is by adding extern inline in front of the declaration (Listing 10).

Listing 10: Telling the compiler to use the external def'n of foo (src/extern_call_foo.c).

```

1 #include <stdio.h>

```

```

2 #include "foo.h"
3
4 extern inline unsigned int foo(void);
5
6 int main(int argc, char *argv[])
7 {
8     printf("address = 0x%x, ret = 0x%x\n", &foo, foo());
9     return 0;
10 }

```

The following caller, although it does not explicitly declares `foo` as external, would also work since all functions in modern C are external by default. The code produced with or without `extern` is the same. However it's a good practice to use the `extern` keyword to make it clear.

Listing 11: Implicitly telling the compiler to use the external def'n of `foo` (`src/extern_call_foo2.c`).

```

1 #include <stdio.h>
2 #include "foo.h"
3
4 inline unsigned int foo(void);
5
6 int main(int argc, char *argv[])
7 {
8     printf("address = 0x%x, ret = 0x%x\n", &foo, foo());
9     return 0;
10 }

```

Both of the last two listings work with or without the `-O` flag - i.e. the compiler is free to choose either the inline or regular version of `foo`. In this case, it will inline `foo()` with `-O`. For the address, it of course needs the full definition.

code	gcc	gcc -O
Listing 10	✓	✓
Listing 11	✓	✓

EXAMPLE 3.2.

In this example, we show how to call the *same* external inline function (address and body) in multiple `.c` files.

When we want to inline a function, its body must be present in the header where it's defined. As usual, the function we want to inline is `foo`. That's a rare case where we define a function in the header itself as regular functions as declared in `func.h` but defined in `func.c`.

We don't normally define functions in headers but functions we will later declare as extern inline are an exception.

Listing 12: Definition of `foo()` that we want to inline (`src/foo.h`).

```

1 #ifndef FOO_H
2 #define FOO_H
3
4 #include <stdio.h>
5
6 unsigned int foo(void)
7 {
8     return 0xaa;
9 }
10 #endif /* FOO_H */

```

Let's say that we have a function `foo_caller` that marks `foo` as inline, calls it, and prints its address and return declared in `foo_caller.h` and defined in `foo_caller.c`.

Listing 13: Declaration of `foo_caller()` (`src/foo_caller.h`).

```

1 #ifndef FOO_CALLER_H
2 #define FOO_CALLER_H
3
4 void foo_caller(void);

```

```

5
6 #endif /* FOO_CALLER_H */

```

Listing 14: Declaration of `foo_caller()` (`src/foo_caller.c`).

```

1 #include <stdio.h>
2 #include "foo_caller.h"
3 #include "foo.h"
4
5 extern inline unsigned int foo(void);
6
7 void foo_caller(void)
8 {
9     printf("foo_caller called foo at 0x%x, ret = 0x%x\n", &foo, foo());
10 }

```

Finally, we have the main function that will mark `foo` as `extern inline` (i.e. tells the compiler its definition is found elsewhere), and call it directly and through `foo_caller`. There's one important detail to note when including `foo`'s header. The header contains its definition. `foo_caller.c` includes `foo.h`, therefore contains one definition of `foo`. `main.c` includes `foo_caller.h`, therefore already contains one definition of `foo`. If we include `foo.h` in `main`, we'll end up with a multiple definition error emitted by the linker. This wouldn't be a problem with regular functions, as they only contain the declaration in the header and a function can be declared infinite times, but it is a problem when a function is defined in the header, e.g. a function we want to inline. In this case, the programmer must manually make sure to include the header only once!

When we define a function in a header, its header must only be included once in the main!

Listing 15: main function calling `foo` through two different files (`src/main_ext_foo.c`).

```

1 #include <stdio.h>
2 #include "foo_caller.h"
3
4 extern inline unsigned int foo(void);
5
6 int main(int argc, char *argv[])
7 {
8     foo_caller();
9     printf("foo called from main at 0x%x, ret = 0x%x\n", &foo, foo());
10     return 0;
11 }

```

This compiles either without or without optimisations and the output is:

```

foo_caller called foo at 0x400526, ret = 0xaa
foo called from main at 0x400526, ret = 0xaa

```

Therefore both `main` and `foo_caller` use the same definition. The compiler is free to choose the inline or regular version of `foo` depending on the optimisation flag. For the address, it will of course always use the regular version as it needs the definition. We can do the usual checks with `gdb` and `objdump` to confirm the disassembly looks as expected. Some final notes regarding this example.

We have been talking about extern functions, but extern variables also behave the same way.

3.3.1 Force the GNU C compiler to inline a function

In GNU C, we can force inlining of a function by setting its so-called attribute.

In GNU C (and C++), we can use function attributes to specify certain function properties that may help the compiler optimise calls or check code more carefully for correctness. Function attributes are introduced by the `__attribute__` keyword in the declaration of a function, followed by an attribute specification enclosed in double parentheses.

We can specify multiple attributes in a declaration by separating them by commas within the double parentheses or by immediately following one attribute specification with another.

To get to the point, the particular attribute to force inlining is `always_inline`. According to `gcc` docs:

“ Generally, functions are not inlined unless optimization is specified. For functions declared inline, this attribute inlines the function even if no optimization level was specified. ”

Therefore we can force inlining, e.g. for a static function, as follows:

```
static void foo(void)
{
    // ...
}
```

```
static inline void foo(void) __attribute__((always_inline));
```

We will experiment with the usual foo function:

Listing 16: Force foo to be inlined, with or without optimisations (src/force_inline.c).

```
1 #include <stdio.h>
2
3 static unsigned int foo(void)
4 {
5     return 0xaa;
6 }
7
8 static inline unsigned int foo(void) __attribute__((always_inline));
9
10 int main(int argc, char *argv[])
11 {
12     int i = foo();
13     printf("ret = 0x%x\n", i);
14     return 0;
15 }
```

Compiling without optimisations and debugging:

```
gcc -g force_inline.c -o force_inline
gdb force_inline
(gdb) set disassembly-flavor intel
(gdb) disas main
```

We see that the call to printf, which prints the return of foo is disassembled to the following snippet, which shows that our call has been inlined.

```
0x08048426 <+17>: mov     eax,0xaa
0x0804842b <+22>: mov     DWORD PTR [ebp-0xc],eax
0x0804842e <+25>: sub     esp,0x8
0x08048431 <+28>: push    DWORD PTR [ebp-0xc]
0x08048434 <+31>: push    0x80484d0
0x08048439 <+36>: call    0x80482e0 <printf@plt>
```

3.4 Conclusion – When to use the inline keyword?

static inline works in both ISO C and GNU C (see A.1), it's natural that people ended up settling for that and seeing that it appeared to work without giving errors. So static inline gives portability, although it may result in code bloat.

With the exception of tight loops and trivial functions, inlining is the sort of optimisation that should usually be used only when a performance bottleneck has been discovered through profiling. People suggest that:

- Don't use inline unless you know what they do and all of the implications.
- Choosing to use the inline code or not doing carries no guarantees but may improve performance.
- “Premature optimisation is the root of all evil.” – D. Knuth.

4 Operator precedence

4.1 Associativity and precedence

Associativity and precedence defined how operations are evaluated when there are multiple in a line.

- **Associativity** defines the order in which operations of the same precedence are evaluated in an expression. It can be left to right (\rightarrow) or right to left (\leftarrow).
- **Precedence** determines the grouping of terms in an expression and decides how an expression is evaluated. Certain operators have higher precedence than others.

4.2 Precedence table

If more than one operators are involved in an expression, C language has a predefined rule of priority for the operators. This rule of priority of operators is called operator precedence.

Rank	Operator	Type of operation	Associativity
1	()	Parentheses or function call	\rightarrow
1	[]	Brackets or array subscript	\rightarrow
1	.	Dot or member selection operator	\rightarrow
1	->	Arrow operator	\rightarrow
1	++ or --	Postfix increment/ decrement	\rightarrow
2	++ or --	Prefix increment/ decrement	\leftarrow
2	+ or -	Unary plus or minus	\leftarrow
2	!, ~	not operator, bitwise complement	\leftarrow
2	(type), e.g. (double)	2 type cast	\leftarrow
2	*	Indirection or dereference	\leftarrow
2	&	address of	\leftarrow
2	sizeof	Determine size in bytes	\leftarrow
3	* . %	Multiplication, division, modulus	\rightarrow
4	+ -	Addition and subtraction	\rightarrow
5	<< >>	Bitwise left shift and right shift	\rightarrow
6	< <=	relational less/ less than or equal to	\rightarrow
6	> >=	relational greater/ greater than or equal to	\rightarrow
7	== !=	relational equal or not equal to	\rightarrow
8	&&	bitwise AND	\rightarrow
9	^	bitwise XOR	\rightarrow
10		bitwise OR	\rightarrow
11	&&	Logical AND	\rightarrow
12		Logical OR	\rightarrow
13	?:	Ternary operator	\leftarrow
14	=	Assignment	\leftarrow
14	+= -=	Add/ subtract and assign	\leftarrow
14	*= /=	Multiply/ divide and assign	\leftarrow
14	%= &=	Modulus and assign/ bitwise AND and assign	\leftarrow
14	^= =	Bitwise XOR/ bitwise OR and assign	\leftarrow
14	<<= >>=	Shift left/ shift right and assign	\leftarrow
15	,	comma operator ⁷	\rightarrow

One in the table above that is not used often is the comma. (,).

TAKEAWAY 4.1. Comma operator returns the rightmost operand in the expression and evaluates the rest, rejecting their return value.

⁷<https://stackoverflow.com/a/52558>

EXAMPLE 4.1. The left column shows some examples of the , operator and the right their output.

It is no way implied that the following are good code practices, they simply test the understanding of operators!

```
1 #include <stdio.h>
2
3 int main(int argc, char *argv[])
4 {
5     int i;
6     i = 1, 2, 3;
7     printf("%d\n", i);
8 }
```

1

(= operation has highest precedence, therefore i = 1 gets evaluated first. Then, , 2, 3 gets evaluated, which does nothing.)

```
1 #include <stdio.h>
2
3 int main(int argc, char *argv[])
4 {
5     int i;
6     i = (1, 2, 3);
7     printf("%d\n", i);
8 }
```

1

(() have the highest priority, forcing what's inside them to get evaluated first, i.e. 1, 2, 3 to evaluate 3 (L to R). 3 gets assigned to i.)

```
1 #include <stdio.h>
2
3 int main(int argc, char *argv[])
4 {
5     int i = 1, 2, 3;
6     printf("%d\n", i);
7 }
```

(= has the highest priority, defining i as 1. Since the int type is multiplicative, int 2 and int 3 will also be attempted to be declared – compilation error.)

```
1 #include <stdio.h>
2
3 int main(int argc, char *argv[])
4 {
5     printf("%d bytes, %d bytes\n",
6           sizeof((double) (1,2,3)),
7           sizeof((int) (1.0, 2.0)));
8 }
```

8 bytes, 4 bytes

(Outer parens first. Then inner parens, evaluating 3 and 2.0 respectively. Then type casts, evaluating 3.0 and 2 respectively. sizeof operates on each outer paren, returning 8 and 4 respectively.)

```
1 #include <stdio.h>
2
3 int main(int argc, char *argv[])
4 {
5     int i = 0, j = 1, k = 2;
6     int *p_i = &i, p_j = &j, p_k = &k;
7     printf("%d %d %d\n", *p_i, *p_j, *
8     p_k);
9 }
```

(compilation error – int is multiplicative but dereference (*) is not. Pointer p_i will be defined properly but p_j, p_k are just int. The correct way would be *p_j = &j, *p_k = &k.)

```

1 #include <stdio.h>
2
3 int main(int argc, char *argv[])
4 {
5     int x = 0, y = 0;
6     int i = (1, x++, ++y);
7     printf("%d %d %d\n",
8           i, x++, ++y);
9     printf("%d %d %d\n",
10           i = 1337, x, y);
11 }

```

1 1 2
1337 2 2

(For explanation of the pre/post increment, see A.3.)

```

1 #include <stdio.h>
2
3 int main(int argc, char *argv[])
4 {
5     int i, j = (printf("Hello?\n"),
6                 1337);
7     printf("world!\n%d, %d\n",
8           i, j);
9 }

```

Hello?
world!
0, 1337

add double loop example here... how long does it run?

```

1 #include <stdio.h>
2
3 int main(int argc, char *argv[])
4 {
5     int i;
6     int arr[5] = {1, 2, 3, 4, 5};
7     int *p_arr = arr; // same as &arr[0]
8
9     // pr(++post) > pr(++pre) = pre(*deref)
10    // ++p_arr; *p_arr (L to R) => 2
11    printf("(1) %d\n", **p_arr);
12    // p_arr++, then *p_arr => 3
13    printf("(2) %d\n", *p_arr++); // *
14    // ++(*p_arr) => arr[2]++
15    printf("(3) %d\n", ++*p_arr);
16    // ++(*p_arr++)
17    printf("(4) %d\n", ++*p_arr++);
18    for (i = 0; i < sizeof(arr)/sizeof(arr[0]);
19         ++i)
20        printf("%d ", arr[i]);
21    return 0;
22 }

```

(1) 2, 0xf9933074
(2) 2, 0xf9933078
(3) 4, 0xf9933078
(4) 5, 0xf993307c
1 2 5 4 5

(1) Reading L to R, we evaluate `*(++p_arr)`. `p_arr` initially points at the 0-th element, so we print 2.

(2) Post-inc has the highest priority, however evaluates AFTER the whole expression is evaluated, therefore we compute `*p_arr = 2`, then increment the pointer.

(3) Equal priority, so we read L to R and evaluate `++`'s operand first. As we shifted the pointer before, result is `++(*p_arr) = 3+1`.

(4) Evaluated as `++(*p_arr++) = *p_arr++; ++p_arr`

```

1 #include <stdio.h>
2
3 int main(int argc, char *argv[])
4 {
5     int i = 0;
6     int arr[5] = {1, 2, 3, 4, 5};
7
8     printf("%d ", arr[++i]);
9     printf("%d ", arr[i]);
10    printf("%d ", arr[i++]);
11    printf("%d \n", arr[i]);
12    return 0;
13 }

```

```

\; \
2 2 2 3

```

(Pre-increment always happens before the expressions have been evaluated and post after – see A.3.)

```

1 #include <stdio.h>
2
3 void main(){
4     int intVar = 20, x;
5     x = ++intVar, intVar++, ++intVar;
6     printf("Value of intVar = %d, x = %d", intVar, x);
7 }

```

Value of intVar=23, x=21

(Since = operator has more precedence than , = operator will be evaluated first. Here, x = ++intVar, intVar++, ++intVar so x = ++intVar will be evaluated, assigning 21 to x. Then comma operator will be evaluated [2].)

```

1 #include <stdio.h>
2
3
4 void main()
5 {
6
7     // (1)
8     int x;
9     x = (printf("AA") || printf("BB"));
10    printf("%d\n", x);
11
12    // (2)
13    x = (printf("AA") && printf("BB"));
14    printf("%d\n", x);
15
16    // (3)
17    x = printf("1") && printf("3") ||
18        printf("3") && printf("7");
19    printf("\n%d\n", x);
20
21 }

```

```

AA1
AABB1
13
1

```

Adapted from [2]. Keep in mind that printf returns the number of characters to be printed.

(1) A logical OR (A || B) condition checks whether A or B is true and as soon as one of them is true, exits. printf("AA") is true and returns (int) true = 1 to x. In the end, prints AA1. (2) A && B checks whether both A and B are true and if so returns true, therefore runs the two printf commands and returns 2 && 2 = true to x. (3) Similar to others, but evaluation stops when the OR (||), is hit, which is when the compiler understands the expression is true and returns 1 to x, therefore 13 and 1 are printed.

```

1
2
3 void main()
4 {
5     char var = 10;
6     printf("var is = %d", ++var++);
7 }

```

lvalue required as increment operand

Question adapted from [2]. Will be evaluated as (++var)++. ++var will yield 11, which is an unnamed value – unnamed values cannot be the operand of ++ [2].


```

1 #include <stdio.h>
2
3 void main()
4 {
5     int a = 3, b = 2;
6     a = a == b == 0;
7     printf("%d,%d\n", a, b);
8 }

```

1, 2

= has the highest priority so the expression is evaluated as `a = (a == b == 0)`. Then L to R as `a = ((a == b) == 0)`, i.e. `a = (0 == 0)`, i.e. `a = 1` [2].

4.2.1 Application of using operators to write concise code – string manipulation

A basic string library has been written to demonstrate how operators can be used for denser code. By using them, less buffer variables are needed. Remember that in C, strings are terminated by '0', hence the conditions in the code. If precedence is correctly understood, then the code is easy to read too. Below are its functions. Prototypes are found in `sstr.h` and implementations at `sstr.c`.

Listing 17: String length implementation (src/sstrlib/sstr.c).

```

1 unsigned int sstrlen(const char* pSrc)
2 {
3     const char* start = pSrc;
4     while (*++pSrc);
5     return pSrc - start;
6 }

```

The following diagram shows how `sstrlen("abcd")` works assuming `pSrc` points to an imaginary address 0x800. First, we increment the pointer and then compare its value to 0.

```

+---+---+---+---+
|a|b|c|d|\0| (0x8001)
+---+---+---+---+
      |
      v
    True
+---+---+---+---+
|a|b|c|d|\0| (0x8002)
+---+---+---+---+
      |
      v
    True
+---+---+---+---+
|a|b|c|d|\0| (0x8003)
+---+---+---+---+
      |
      v
    True
+---+---+---+---+
|a|b|c|d|\0| (0x8004)
+---+---+---+---+
      |
      v
    False -----> 0x8004 - 0x8000

```

Listing 18: String copy implementation (src/sstrlib/sstr.c).

```

1 void sstrCpy(const char* pSrc, char* pDst)
2 {
3     while (*pDst++ = *pSrc++);
4 }

```

Listing 19: Reverse a string implementation (src/sstrlib/sstr.c).

```

1 void sstrrev(const char* pSrc, char* pDst)

```

```

2 {
3     pSrc += sstrlen(pSrc) - 1;
4     while (*pDst++ = *pSrc--);
5 }

```

Listing 20: Character to lowercase implementation (src/sstrlib/sstr.c).

```

1 char sstrLower(const char c)
2 {
3     return c + 32; // ASCII table
4 }

```

Listing 21: Check palindrome implementation (src/sstrlib/sstr.c).

```

1 unsigned int sstrPalin(const char* pSrc)
2 {
3     int len = sstrlen(pSrc);
4     // empty string or one letter
5     if (len == 1 || len == 0)
6         return 1;
7     const char *start = pSrc;
8     const char *end = pSrc + len - 1;
9     while (end-- >= start++)
10         if (*end != *start)
11             return 0;
12     return 1;
13 }

```

Listing 22: Print string implementation (src/sstrlib/sstr.c).

```

1 void sstrPrint(char* pSrc)
2 {
3     while (*pSrc)
4     {
5         printf("%c", *pSrc);
6         pSrc++;
7     }
8     printf("\n");
9 }

```

5 Advanced pointer usages

5.1 Const pointer vs pointer to const

In C, we often want to make a pointer point to a constant address or reference a constant. The syntax for both of these instructions is similar but there is a subtle difference. In this section, shed some light on this syntax difference to make it easy to remember.

5.1.1 Constant pointer

The syntax for constant point (constant address) is as follows:

```
int*    const    ptr;
```

This expression is read right from left. Let's read it step-by-step.

```
int*    const    ptr;
//              ~~~~
//              Define a pointer ptr
//              ~~~~~
//              that is constant
// ~~~~~
// and points to an integer variable
```

Therefore defines a constant point (the address it points to cannot change) to data of type int. Attempting to change the address results in a compilation error. A toy example is listed below.

Listing 23: DOs and DONTs of constant pointer (src/pointers/const_ptr.c)

```
1 #include <stdio.h>
2
3 int main(int argc, char *argv[])
4 {
5     int i = 0, j = 1;
6     int* const constPtr = &i;
7     *constPtr = 2; // <- OK
8     ++*constPtr; // <- OK
9     printf("\n%d\n", *constPtr);
10    //constPtr = &j; // <- not OK
11    return 0;
12 }
```

It prints 3.

5.1.2 Pointer to constant

The following pointer cannot have its value changed.

```
const    int    *ptr;
//              ~~~~
//              Define a pointer ptr
//              ~~~
//              that points to int data
// ~~~~~
// which data are constant
```

It's clear that the const specifier acts upon the value (int), therefore the pointer is of constant value (pointer to const). Attempting to dereference the pointer and change its value results in a compilation error. However, we can still change the data it points to. A toy example is also listed below.

Listing 24: DOs and DONTs of pointer to const (src/pointers/ptr_to_const.c)

```
1 #include <stdio.h>
2
3 int main(int argc, char *argv[])
4 {
5     int arr[2] = {0, 1};
6     const int* ptrToConst = arr; // a.k.a. &arr[0]
7     ptrToConst++; // <- OK
```

```
8   arr[1]++; // <- OK
9   //++*ptrToConst; // <- not OK - read-only variable is not assignable
10  //*ptrToConst = 2; // <- not OK - read-only variable is not assignable
11  printf("\n%d\n", *ptrToConst);
12  return 0;
13 }
```

The example code prints 2.

References

- [1] *C ISO/IEC 9899:TC3*. ANSI & ISO, Sep. 2007, pp. 43–45. [Online]. Available: <http://www.open-std.org/jtc1/sc22/wg14/www/docs/n1256.pdf>.
- [2] *C operators - aptitude questions & answers*, includehelp.com. [Online]. Available: <https://www.includehelp.com/c/operators-aptitude-questions-and-answers.aspx> (visited on 11/28/2019).

A Appendices

A.1 ANSI C vs GNU C

In the main text, we have used the terms “ISO C, ANSI C” and “GNU C”. They mean different things.

- GNU C: GNU is a unix like operating system (www.gnu.org) & somewhere GNU's project needs C programming language based on ANSI C standard. GNU use GCC (GNU Compiler Collection) compiler to compile the code. It has C library function which defines system calls such as malloc, calloc, exit...etc
- ANSI C is a standardised version of the C language. As with all such standards it was intended to promote compatibility between different compilers which tended to treat some things a little differently.
- standard specified in the ANSI X3.159-1989 document became known as ANSI C, but it was soon superseded as it was adopted as an international standard, ISO/IEC 9899:1990.

A.2 idiv and imul instructions

imul and idiv instructions are used in assembly to perform multiplication or division with signed integers. mul and div are their respective unsigned instructions. We'll be using Intel IA-32 instructions for convenience.

A.2.1 imul

The IMUL instruction takes one, two or three operands. It can be used for byte, word or dword operation. IMUL only works with signed numbers. The result is the correct sign to suit the signs of the multiplicand and the multiplier, therefore the if necessary (e.g. negative) is *sign extended* following the 2's complement rules. The size of the result maybe up to twice of the input size. Therefore when using a user-specified register as the destination (table below), the result is truncated to the register size and it's up to the user to prevent information loss. For 32-bit architectures, the result may be represented with up to 64 bits. Finally, remember that

- 32-bit signed range represents numbers $[-2^{31}, 2^{31} - 1]$,
- 32-bit unsigned range represents numbers $[0, 2^{32} - 1]$.

Listing 25: imul simple demonstration. (src/imul_only.asm).

```
1 ; imul_only.asm
2 ;
3 ; assemble: nasm -f elf -g -F stabs imul_only.asm
4 ; link:      ld -o imul_only imul_only.o -melf_i386
5
6 SECTION .data          ; data section
7     ; dd = double word (32 bits)
8     val1:  dd 10, 10          ; 10 = line end
9     val2:  dd -10, 10         ; 10 = line end
10
11 SECTION .text          ; code section
12 global _start          ; make label available to linker
13 _start:                ; standard nasm entry point
14     ;;; Example 1 - one operand
15     mov     ecx, 2
16     mov     eax, [val1]
17     ; edx:eax = eax * ecx
18     imul    ecx          ; stores the 64-bit result in (high:low) EDX:EAX
19
20     ;;; Example 2 - one operand
21     xor     eax, eax ; Clear eax register
22     mov     ecx, 2
23     mov     eax, [val2]
24     ; edx:eax = eax * ecx
25     imul    ecx          ; result edx:eax < 0 so sign extended
26
27     ;;; Example 3 - two operands
28     mov     eax, 2 ; Clear eax register
29     ; eax = eax * [val2]
30     imul    eax, [val2]
31
32     ;;; Example 4 - three operands
33     ; imul r, r/m32, const_value
34     ; eax = [val2] * 3
35     imul    eax, [val2], 3
36     nop
```

Note that when the result in EDX:EAX is negative, the whole double register is sign extended, to 64 bits, e.g. when we obtain -20, EDX:EAX stores 0xffffffff:0xfffffec.

Syntax	Description	Types
<code>imul src</code>	<code>EDX:EAX = EAX * src</code>	<code>src: r/m32</code>
<code>imul dst, src</code>	<code>dst = src * dst</code>	<code>dst: r32, src: r32/m32</code>
<code>imul dst, src1, src2</code>	<code>dst = src1 * src2</code>	<code>dst: r32, src1: r32/m32, src2: val32</code>

A.2.2 `idiv`

Assuming 32-bit architecture, `idiv src` performs signed division. It divides the 64-bit register pair `edx:eax` registers by the source operand `src` (divisor). It and stores the result in the the pair `edx:eax`. It stores the quotient in `eax` and the remainder in `edx`. Non-integral results are truncated (chopped) towards 0.

Syntax	Description	Types
<code>idiv src</code>	<code>EDX = EDX:EAX % src,</code> <code>EAX = EDX:EAX / src</code>	<code>src: r/m32</code>

However, we need to be careful before using `idiv`. Check out the following example.

At line 18, `edx = 0x20 = 32`. We pollute `eax` with `eax = 11 = 0xb` and want to divide by `ebx = 2` so the program will try to divide `edx:eax = 0x200000000b` by 2 and store the quotient `0x200000000b/2 = 68719476741` in `eax`. However, $68719476741 > 2^{32}$ so it cannot fit – the program will receive a SIGFPE (arithmetic exception) signal by the kernel and exit.

Always make sure that `eax` is zero before `idiv` (or `div`).

Listing 26: `idiv` demonstration for unsigned division. (src/`idiv_wrong1.asm`).

```

1 ; idiv_wrong1.asm
2 ;
3 ; assemble: nasm -f elf -g -F stabs idiv_wrong1.asm
4 ; link:      ld -o idiv_wrong1 idiv_wrong1.o -melf_i386
5
6 SECTION .data          ; data section
7
8 SECTION .text          ; code section
9 global _start          ; make label available to linker
10 _start:               ; standard nasm entry point
11     ;;; Example 1
12     xor     edx, edx    ; clear out edx
13     mov     eax, 21
14     mov     ebx, 2
15     idiv    ebx        ; eax = edx:eax / ebx, edx = edx:eax % ebx
16
17     ;;; Example 2 - forget to clear out edx before idiv
18     mov     edx, 0x20
19     mov     eax, 11
20     mov     ebx, 2      ; do we get eax = 5 and edx = 1?
21     idiv    ebx
22     nop

```

Let's examine what happens when we divide `EDX:EAX` by a negative number.

Listing 27: `idiv` demonstration for signed division. (src/`idiv_wrong2.asm`).

```

1 ; idiv_wrong1.asm
2 ;
3 ; assemble: nasm -f elf -g -F stabs idiv_wrong1.asm
4 ; link:      ld -o idiv_wrong1 idiv_wrong1.o -melf_i386
5
6 SECTION .data          ; data section
7
8 SECTION .text          ; code section
9 global _start          ; make label available to linker
10 _start:               ; standard nasm entry point
11
12     ;;; Example 1 - zeroing edx before division
13     xor     edx, edx    ; clear out edx

```

```

14     mov     eax, -21
15     mov     ebx, 2
16     idiv    ebx      ; eax = edx:eax / ebx, edx = edx:eax % ebx
17     nop
18
19     ;;; Example 2 - sign extend eax
20     mov     edx, 0xffffffff
21     mov     eax, -21
22     mov     ebx, 2      ; do we get eax = 5 and edx = 1?
23     idiv    ebx
24     nop

```

In the first example, we attempt to divide -21 by 2 so we move -21 to `eax`, which is represented in hex as `eax = 0xffffffffeb`. `edx` is zero so `idiv` will try to define the positive number (leading 0) in `edx:eax` = `00000000:ffffffeb` = 4294967275 . As a result, 4294967275 will be divided by 2 , writing $4294967275 \div 2 = 2147483637$ to `eax` and $4294967275 \bmod 2 = 1$ to `edx`.

To get the value right, we need to ensure the whole dividend (`edx:eax`) is negative. This is done by sign extending `edx` into `eax`, i.e. set `edx = 0xffffffff` is `eax < 0`. Example 2 correctly performs the division, writing `0xffffffff` (-1) to `edx` and `0xffffffff6` (-10) to `eax`.

The next section describes an instruction that can generalise this zero/sign extension before `idiv`.

A.2.3 The `cdq` instruction

`cdq` converts the doubleword (32 bits) in `EAX` into a quadword in `EDX:EAX` by sign-extending `EAX` into `EDX` (i.e. each bit of `EDX` is filled with the most significant bit of `EAX`).

For example, if `EAX` contained `0x7FFFFFFF` we'd get `0` in `EDX`, since the most significant bit of `EAX` is clear. But if we had `EAX = 0x80000000` we'd get `EDX = 0xFFFFFFFF` since the most significant bit of `EAX` is set. The point of `cdq` is to set up `EDX` prior to a division by a 32-bit operand, since the dividend is `EDX:EAX`.

The program below demonstrates the instruction.

Listing 28: Chaining `cdq` with `idiv` to avoid potential arithmetic errors due to sign. (`src/idiv_correct.asm`).

```

1 ; idiv_correct.asm
2 ;
3 ; assemble: nasm -f elf -g -F stabs idiv_correct.asm
4 ; link:      ld -o idiv_correct idiv_correct.o -melf_i386
5
6 SECTION .data      ; data section
7
8 SECTION .text      ; code section
9 global _start      ; make label available to linker
10 _start:            ; standard nasm entry point
11
12     ;;; Example 1 - zero extend eax
13     mov     eax, 22
14     mov     ebx, 4
15     cdq
16     idiv    ebx
17
18     ;;; Example 2 - sign extend eax
19     mov     eax, -22
20     mov     ebx, 4
21     cdq
22     idiv    ebx
23     nop

```

After line 16, `edx = 0x2` and `eax = 0x5`. After line 21, `edx = 0xffffffff` and `eax = 0xffffffffea`. After line 22, `edx = 0xffffffe` = -2 and `eax = 0xfffffbf` = -5 .

A.3 Increment and decrement operators

A.3.1 Pre vs post increment operator

In C, pre-increment ($++i$) and post-increment ($i++$) work slightly differently. Pre-decrement ($--i$) and post-decrement ($i--$) also work in a similar manner. Pre-increment means that the variable is incremented and the incremented value is returned. Post-increment means that the variable is returned as its original value and then incremented. The way to remember them is:

- *pre* → first increment, then evaluate,
- *post* → increment *after* evaluating.

The following table summarises the differences. In the equivalent assembly code, we can see that

- in the first case ($j=i++$), `eax` register stores the initial value of local variable $i=0x42$. Next, $edx=eax+1=0x43$. Finally, `edx` is copied to `i` and `eax` is copied to `j` so $i=0x43$, $j=0x42$.
- In the second case ($j=++i$), `eax` stores again $i=0x42$. `eax` gets incremented. Then, it gets copied to both local variables `i` and `j` so $i=0x42$, $j=0x42$.

Table 1: Post vs pre-increment differences and generated code.

Operation	How it appears	Pseudocode	Assembly code ⁸ (initially $i=0x42$, $j=0x41$)	Final ⁹ values (initially $i=0x42$)
Post-increment	$j=i++$	$j=i$ $i++$	<pre> mov DWORD PTR [ebp-0x10], 0x42 mov DWORD PTR [ebp-0xc], 0x41 mov eax, DWORD PTR [ebp-0x10] lea edx, [eax+0x1] mov DWORD PTR [ebp-0x10], edx mov DWORD PTR [ebp-0xc], eax </pre>	$i=0x43$, $j=0x42$
Pre-increment	$j=++i$	$i++$ $j=i$	<pre> mov DWORD PTR [ebp-0x10], 0x42 mov DWORD PTR [ebp-0xc], 0x41 mov eax, DWORD PTR [ebp-0x10] add eax, 0x1 mov DWORD PTR [ebp-0x10], eax mov DWORD PTR [ebp-0xc], eax </pre>	$i=0x43$, $j=0x43$

EXAMPLE A.1. In the following snippet, pre (post) increment evaluate before (after) the array indexing. Notice how the increment operator writes to its “lvalue” (either index `i` or array `arr`) each time.

```

1 #include <stdio.h>
2
3 #define SIZE 5
4
5 int main(int argc, char *argv[])
6 {
7     int arr[SIZE] = {0, 1, 2, 4, 5};
8     int i = 0;
9
10    printf("%d, ", arr[i++]);
11    printf("%d, ", arr[i]);
12    printf("%d, ", arr[++i]);
13    printf("%d, ", arr[i]++);
14    printf("%d\n", ++arr[i]);
15    for (i = 0; i < SIZE; ++i)
16        printf("arr[%i] = %d, ", i, arr[i]);
17    printf("\n");
18
19    return 0;

```

⁸Instruction `lea edx, [eax+0x1]` achieves the same as incrementing `eax` and moving it to `edx`.

⁹`j` of course doesn't need to be initialised but it was added just for clarity in the disassembly.

20 }

The output is:

0, 1, 2, 2, 4
arr[0] = 0, arr[1] = 1, arr[2] = 4, arr[3] = 4, arr[4] = 5,

A.3.2 How much does the ++ increase the value?

When we have an integers, increment operator increases the value by one. For floats/ doubles it also works the same. What if we have a pointer that points to some address and increment its value?

Assume we have an array of int called arr and a pointer p_arr pointing to its first element. Assume an int takes 4 bytes. Then it would be natural to want to move from arr[0] to arr[1], which are 4 bytes away. So incrementing the pointer would make sense only if it was incremented by 4 (bytes). In general, here's what happens when we increment a pointer of type T.

TAKEAWAY A.1. When we increment a T*, it moves sizeof(T) bytes. It doesn't make sense to move any other value as then the pointer would point to incomplete data.

figure for
explana-
tion

The following example confirms it.

EXAMPLE A.2. #include <stdio.h>

```
2
3 #define SIZE 5
4
5 int main(int argc, char *argv[])
6 {
7     int arr[SIZE] = {0, 1, 2, 3, 4};
8     short int sarr[SIZE] = {0, 1, 2, 3, 4};
9     int* p_arr = &arr[0]; // point to beginning - same as p_arr = arr
10    short int* p_sarr = &sarr[0];
11
12    printf("p_arr points to: 0x%x\n", p_arr);
13    printf("next, p_arr points to: 0x%x\n", ++p_arr);
14    printf("p_arr contains: %d\n", *p_arr);
15
16    printf("p_sarr points to: 0x%x\n", p_sarr);
17    printf("next, p_sarr points to: 0x%x\n", ++p_sarr);
18    printf("p_sarr contains: %d\n", *p_sarr);
19
20    return 0;
21 }
```

The output is:

p_arr points to: 0xbfc8ce78
next, p_arr points to: 0xbfc8ce7c
p_arr contains: 1
p_sarr points to: 0xbfc8ce6e
next, p_sarr points to: 0xbfc8ce70
p_sarr contains: 1

In this system, int takes 4 bytes and short int 2. Hence we move from 0xbfc8ce78 to 0xbfc8ce78+4 in the first case and from 0xbfc8ce6e to 0xbfc8ce6e+2 in the second.

A.4 Find the number of elements in array

<https://stackoverflow.com/questions/27518251/how-does-sizeof-know-the-size-of-array>
<https://stackoverflow.com/questions/671790/how-does-sizeofarray-work>