Aligned And Un-Aligned Data Access On Structures

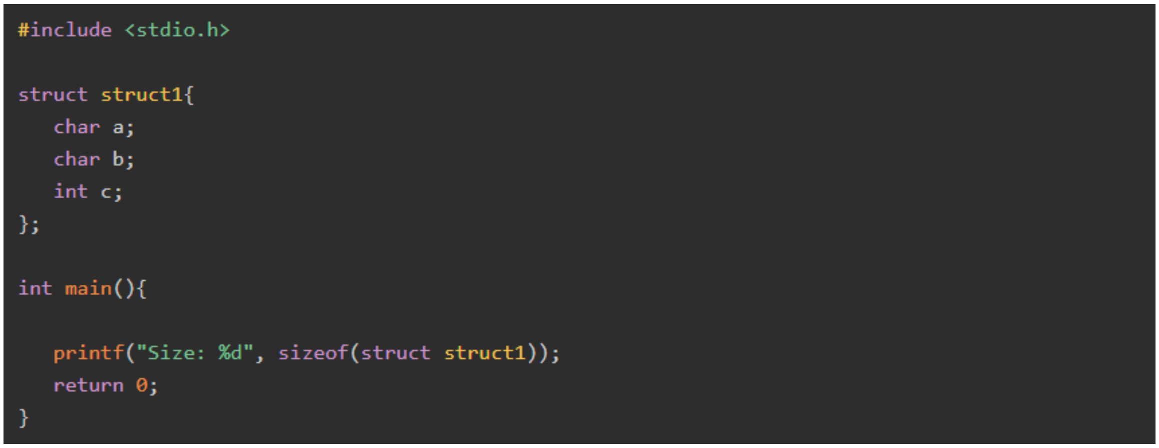
❖ Structure Padding in C

Structure padding in C:

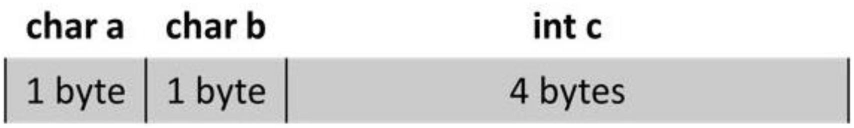
- Managed by the CPU architecture.
- Adds extra bytes within a structure for natural alignment.
- Alignment requirements depend on the processor, not the C language.
- Varies based on data bus size and architectural specifics.

Structure Padding with CPU Architecture:

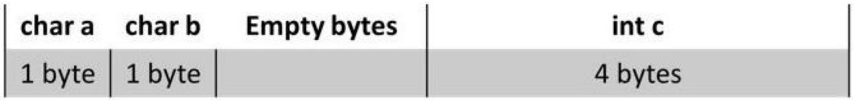
- A 32-bit CPU reads 4 bytes at a time (1 word = 4 bytes).
- Accesses are aligned to word boundaries, requiring padding for efficient reading.
- For example, to access an `int`, the CPU may need two cycles if the data isn't aligned.
- Padding adds extra bytes before data to align it with word boundaries, optimizing access.



```c
#include <stdio.h>

struct struct1{
   char a;
   char b;
   int c;
};

int main(){

   printf("Size: %d", sizeof(struct struct1));
   return 0;
}
```



char a	char b	int c
1 byte	1 byte	4 bytes

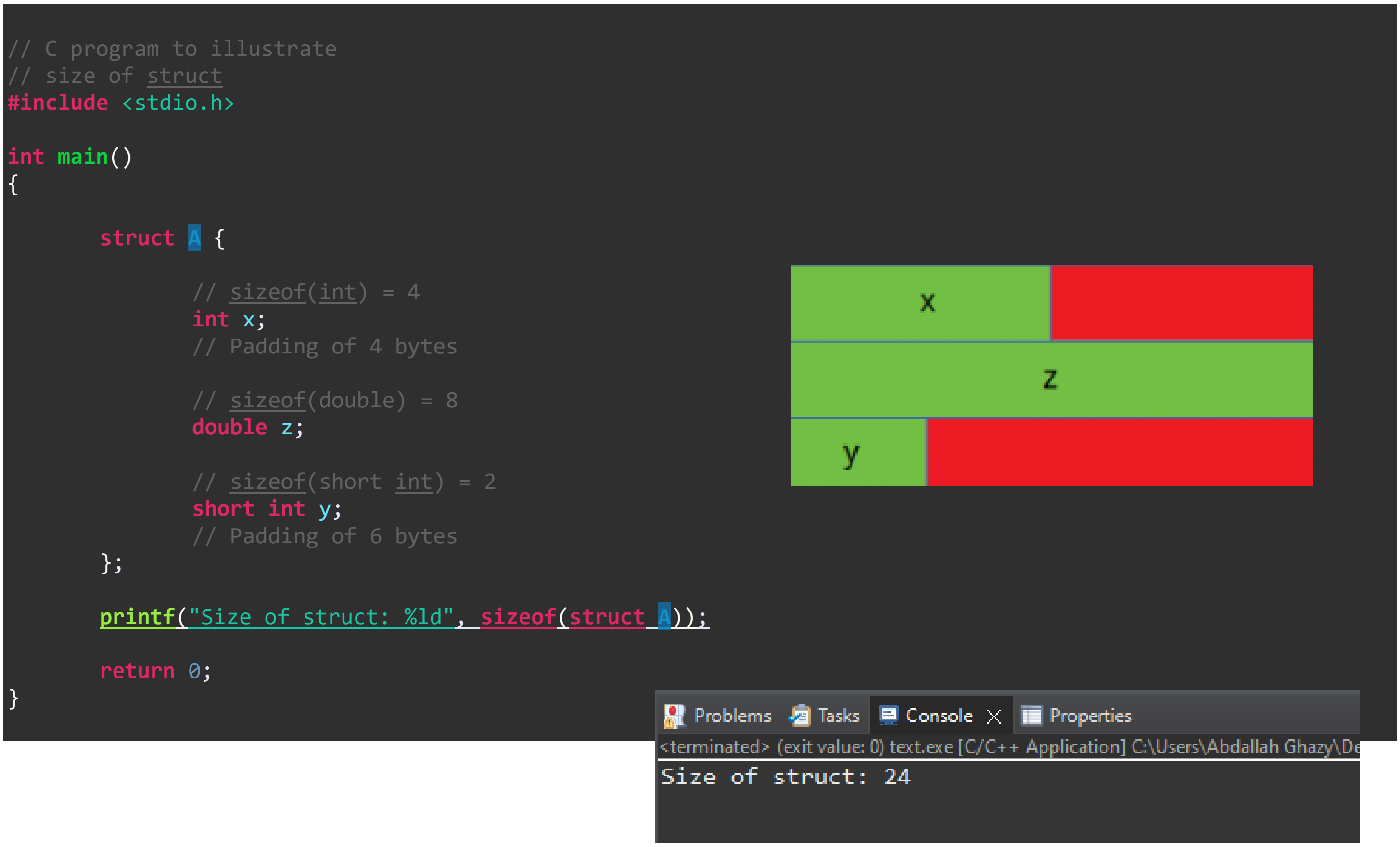


char a	char b	Empty bytes	int c
1 byte	1 byte		4 bytes

Is sizeof for a struct equal to the sum of sizeof of each member?

- The sizeof for a struct is not always equal to the sum of sizeof of each individual member.

This is because of the padding added by the compiler to avoid alignment issues. Padding is only added when a structure member is followed by a member with a larger size or at the end of the structure.

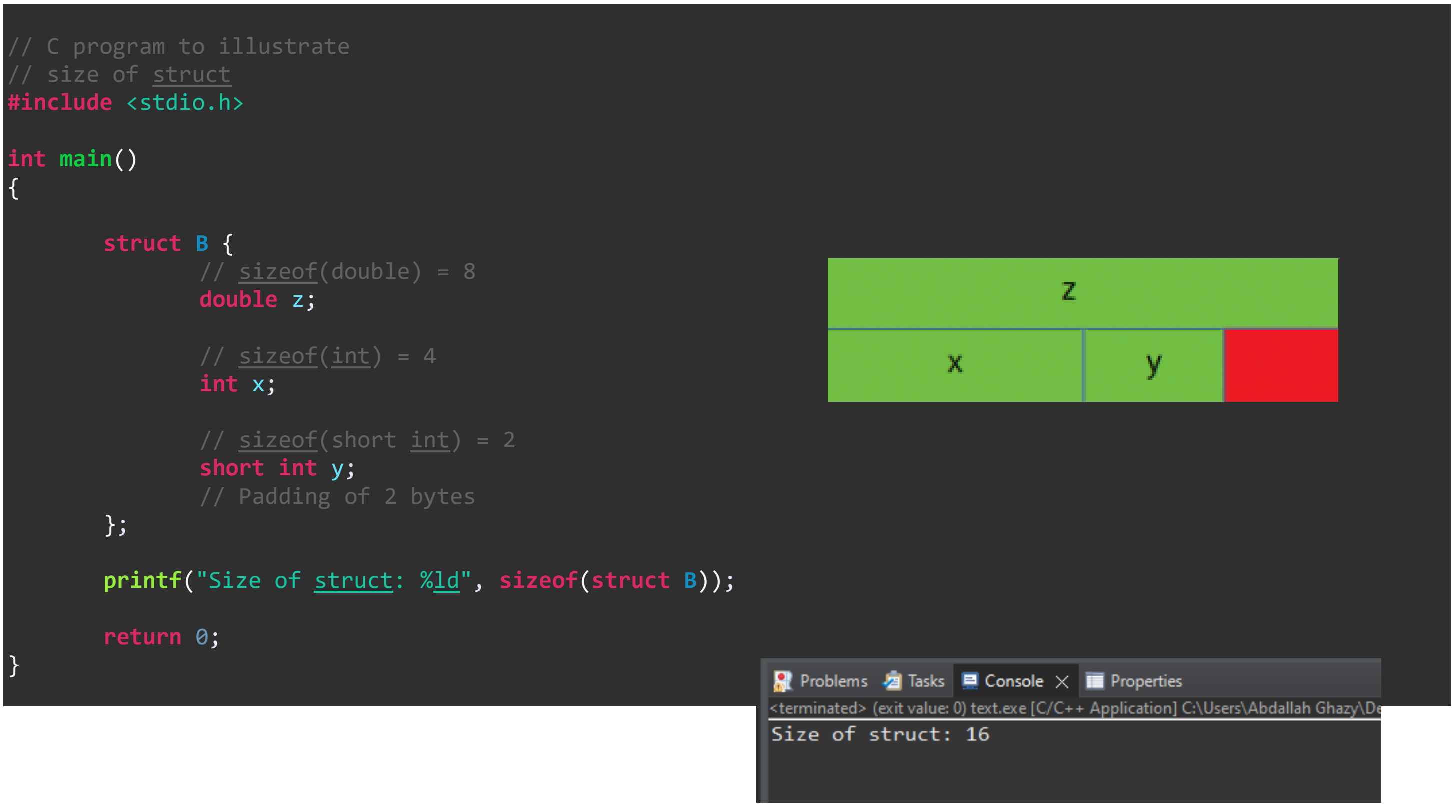


```
// C program to illustrate
// size of struct
#include <stdio.h>

int main()
{

        struct A {

                // sizeof(int) = 4
                int x;
                // Padding of 4 bytes

                // sizeof(double) = 8
                double z;

                // sizeof(short int) = 2
                short int y;
                // Padding of 6 bytes
        };

        printf("Size of struct: %ld", sizeof(struct A));

        return 0;
}
```

```
<terminated> (exit value: 0) text.exe [C/C++ Application] C:\Users\Abdallah Ghazy\De
Size of struct: 24
```

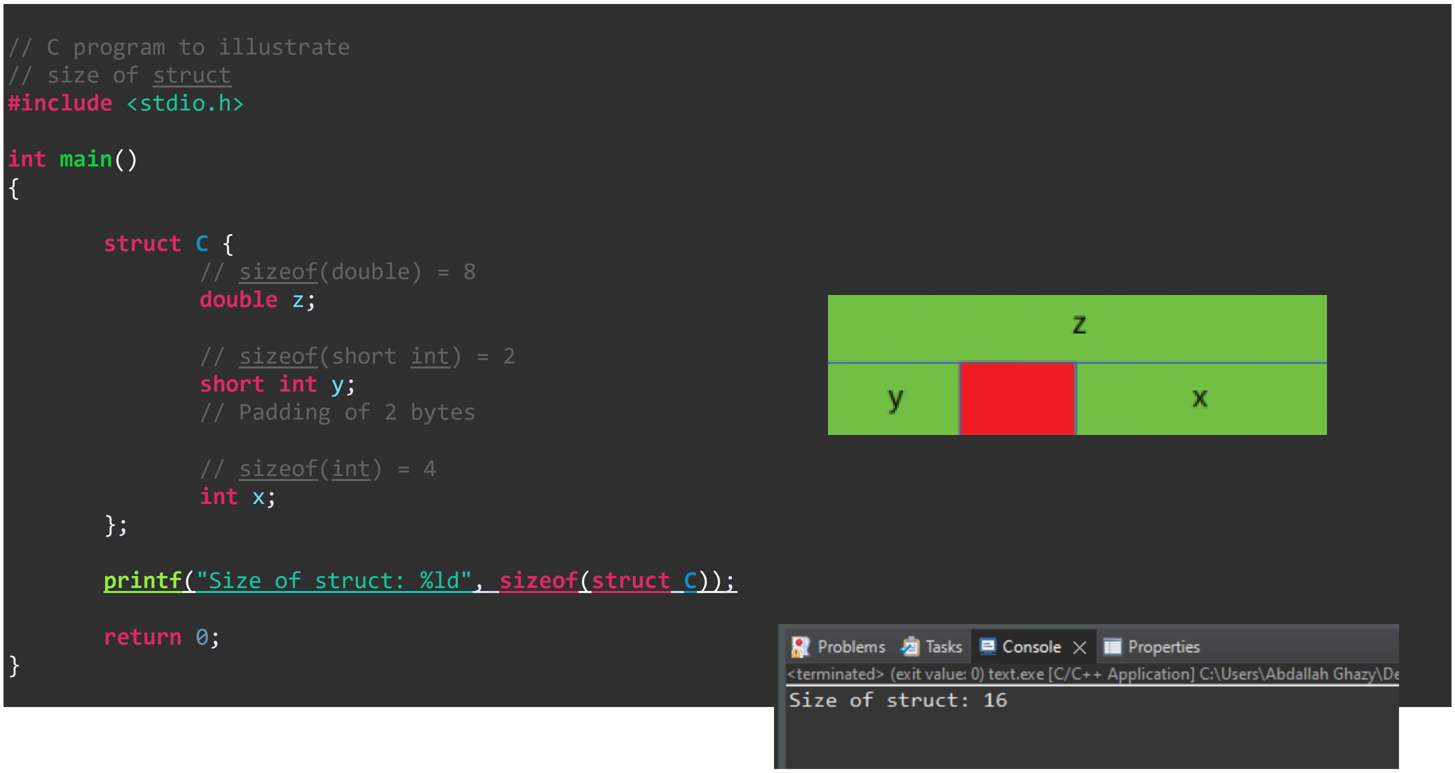
The red portion represents the padding added for data alignment and the green portion represents the struct members.

In this case, x (int) is followed by z (double), which is larger in size as compared to x. Hence padding is added after x. Also, padding is needed at the end for data alignment.



```c
// C program to illustrate
// size of struct
#include <stdio.h>

int main()
{

        struct B {
                // sizeof(double) = 8
                double z;

                // sizeof(int) = 4
                int x;

                // sizeof(short int) = 2
                short int y;
                // Padding of 2 bytes
        };

        printf("Size of struct: %ld", sizeof(struct B));

        return 0;
}
```

```
<terminated> (exit value: 0) text.exe [C/C++ Application] C:\Users\Abdallah Ghazy\De
Size of struct: 16
```



```c
// C program to illustrate
// size of struct
#include <stdio.h>

int main()
{

        struct C {
                // sizeof(double) = 8
                double z;

                // sizeof(short int) = 2
                short int y;
                // Padding of 2 bytes

                // sizeof(int) = 4
                int x;
        };

        printf("Size of struct: %ld", sizeof(struct C));

        return 0;
}
```

```
<terminated> (exit value: 0) text.exe [C/C++ Application] C:\Users\Abdallah Ghazy\De
Size of struct: 16
```

Alignment

Data Alignment in C:

Definition: Refers to how data is stored in memory, often aligned to specific addresses.

Impact: Proper alignment improves performance and prevents crashes, especially with structures.

Structures: Contain members of different types, requiring proper alignment.

Alignment Check: Use the `alignof` operator to determine the required alignment for data types.

For example:

```
struct MyStruct {
    char c;
    int i;
};

printf("Alignment of char: %zu\n", alignof(char));
printf("Alignment of int: %zu\n", alignof(int));
printf("Alignment of MyStruct: %zu\n", alignof(struct MyStruct));
```

Proper Data Alignment in C:

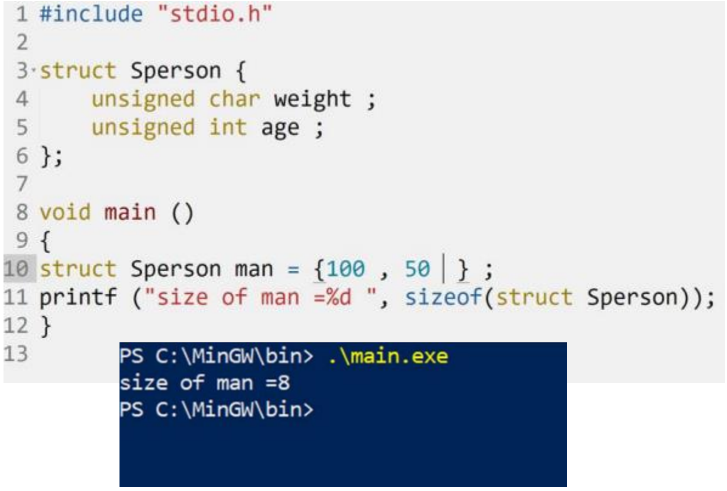
Example: Define a structure (`MyStruct`) with `char` and `int` members. Use the `alignof` operator to check alignment requirements.

Compiler Behavior: Most compilers align structures to the largest member for proper alignment.

Custom Alignment: Use compiler-specific directives/functions to control alignment, especially for hardware-specific data formats.

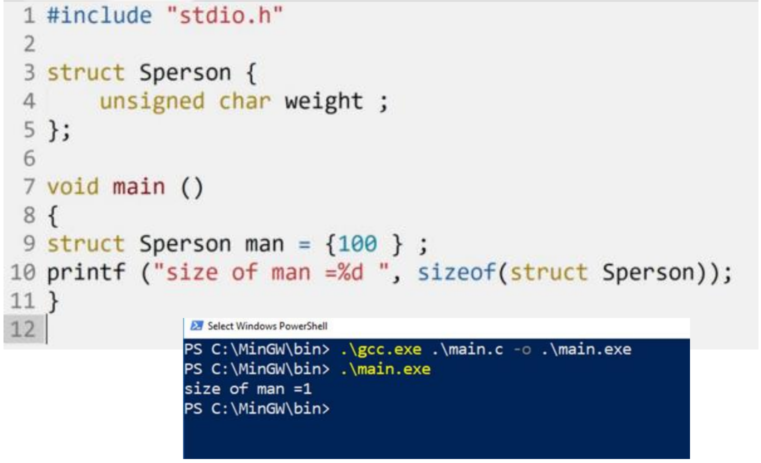
Importance: Proper alignment prevents performance issues and crashes on some architectures.

Best Practice: Ensure structures are properly aligned to optimize code performance and avoid potential issues.



```
#include "stdio.h"

struct Sperson {
    unsigned char weight ;
    unsigned int age ;
};

void main ()
{
struct Sperson man = {100 , 50 } ;
printf ("size of man =%d ", sizeof(struct Sperson));
}
```

```
PS C:\MinGW\bin> .\main.exe
size of man =8
PS C:\MinGW\bin>
```



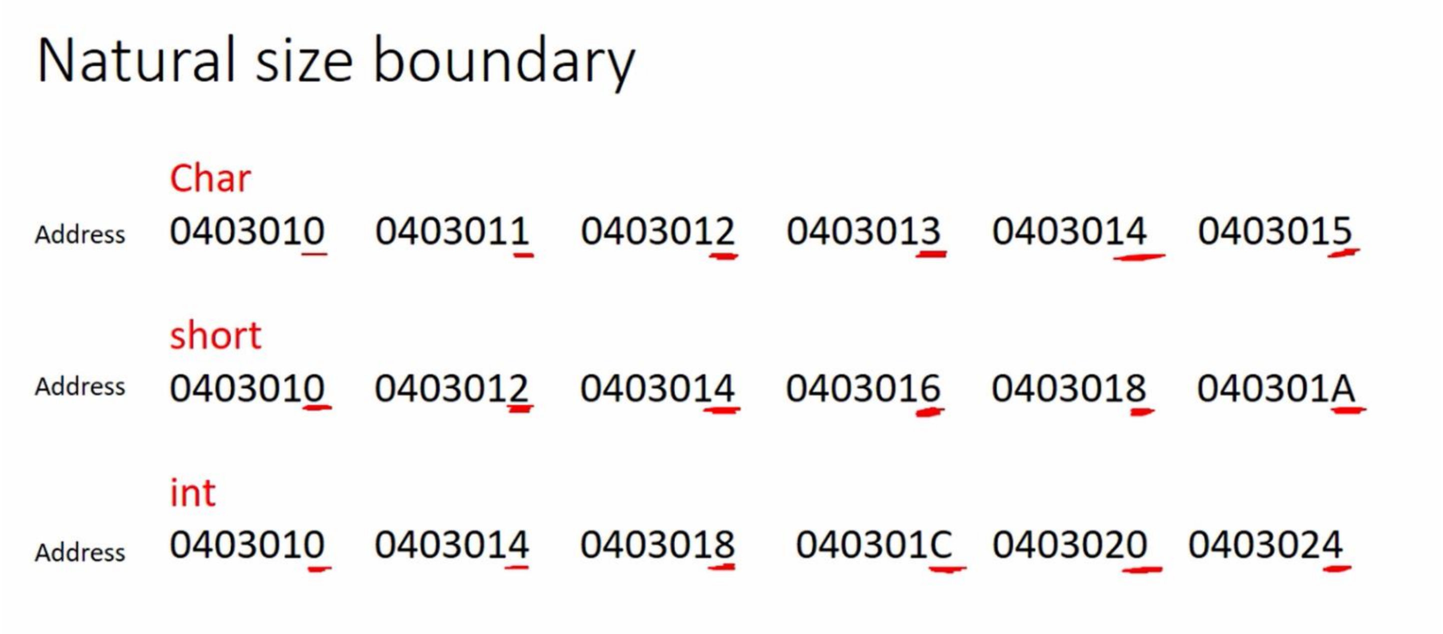
```
#include "stdio.h"

struct Sperson {
    unsigned char weight ;
};

void main ()
{
struct Sperson man = {100 } ;
printf ("size of man =%d ", sizeof(struct Sperson));
}
```

```
PS C:\MinGW\bin> .\gcc.exe .\main.c -o .\main.exe
PS C:\MinGW\bin> .\main.exe
size of man =1
PS C:\MinGW\bin>
```

Aligned Data Storage: When data is stored in aligned memory, it means that the memory address at which the data starts is a multiple of the data size.

For example, if you have a 4-byte integer, it should be stored at an address that is divisible evenly by 4.

Aligned data storage is generally more efficient because it allows the processor to fetch data in a single memory access, rather than requiring multiple accesses for unaligned data.



Natural size boundary

Char

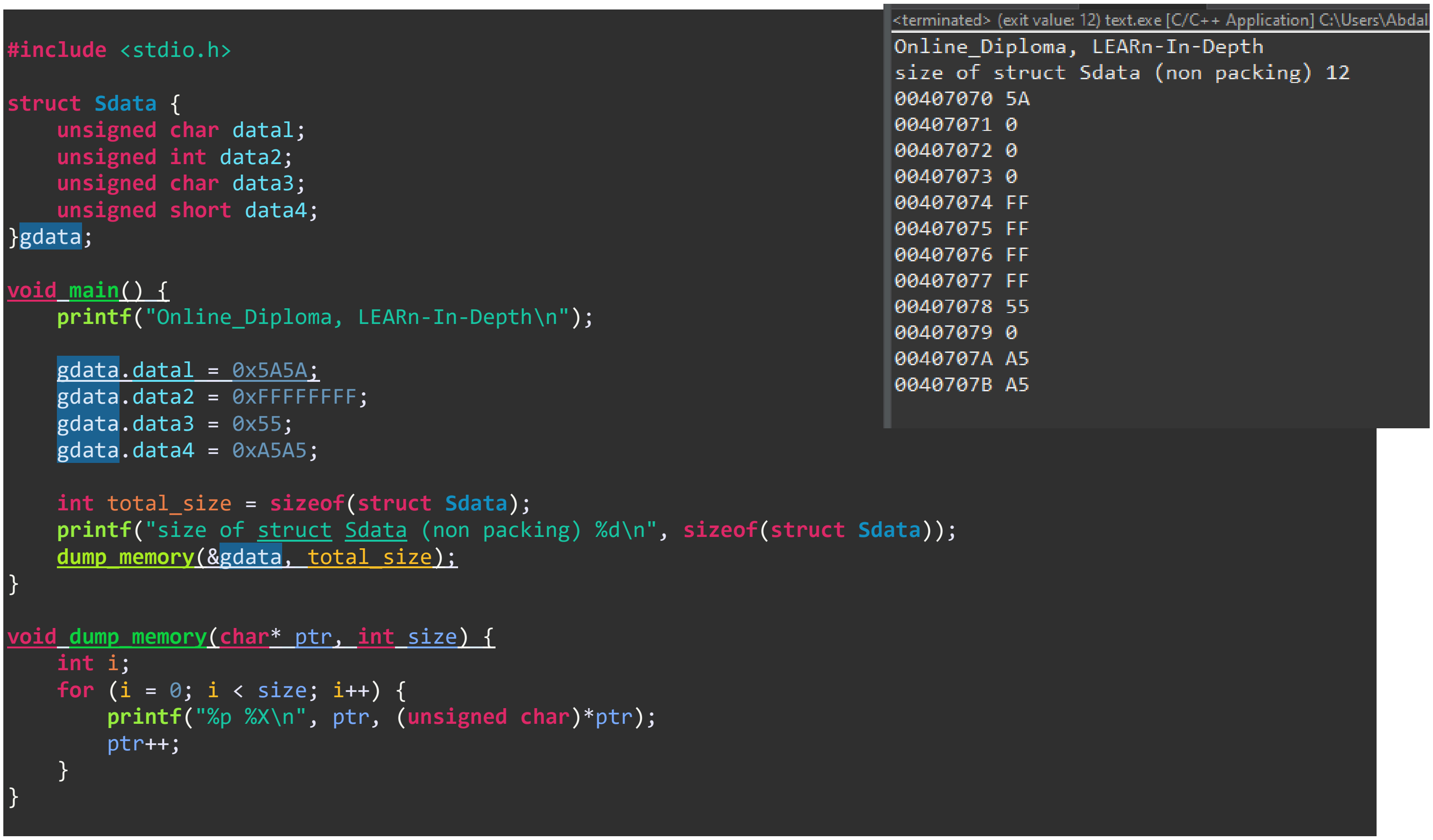
Address 0403010 0403011 0403012 0403013 0403014 0403015

short

Address 0403010 0403012 0403014 0403016 0403018 040301A

int

Address 0403010 0403014 0403018 040301C 0403020 0403024



```c
#include <stdio.h>

struct Sdata {
    unsigned char data1;
    unsigned int data2;
    unsigned char data3;
    unsigned short data4;
}gdata;

void main() {
    printf("Online_Diploma, LEARn-In-Depth\n");

    gdata.data1 = 0x5A5A;
    gdata.data2 = 0xFFFFFFFF;
    gdata.data3 = 0x55;
    gdata.data4 = 0xA5A5;

    int total_size = sizeof(struct Sdata);
    printf("size of struct Sdata (non packing) %d\n", sizeof(struct Sdata));
    dump_memory(&gdata, total_size);
}

void dump_memory(char* ptr, int size) {
    int i;
    for (i = 0; i < size; i++) {
        printf("%p %X\n", ptr, (unsigned char)*ptr);
        ptr++;
    }
}
```

```
<terminated> (exit value: 12) text.exe [C/C++ Application] C:\Users\Abdal
Online_Diploma, LEARn-In-Depth
size of struct Sdata (non packing) 12
00407070 5A
00407071 0
00407072 0
00407073 0
00407074 FF
00407075 FF
00407076 FF
00407077 FF
00407078 55
00407079 0
0040707A A5
0040707B A5
```

❖ Structure Packing in C

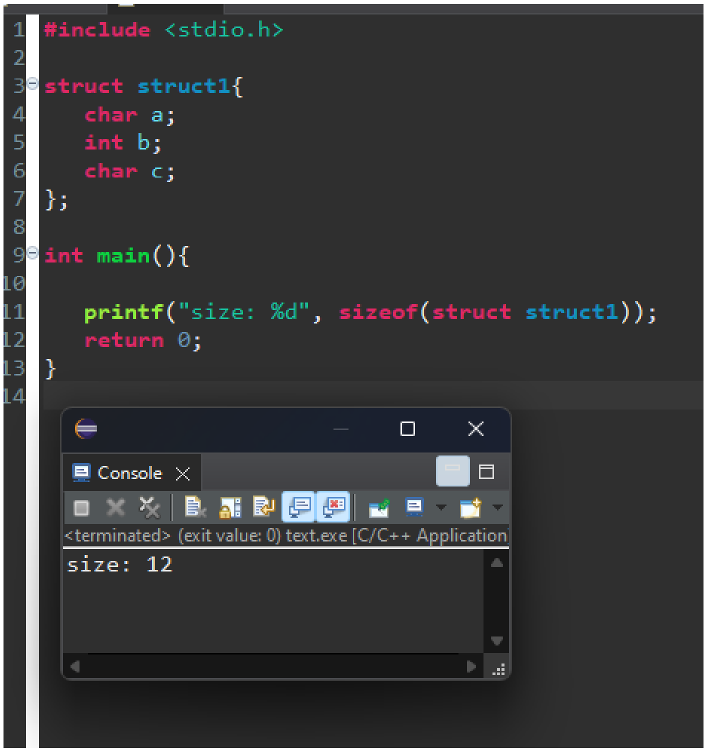
Structure packing, on the other hand, is a mechanism for minimizing the effect of padding, thereby trying and reduce wasted memory space. We can use certain pragma directives and attributes to achieve packing.

Unaligned Data Storage: Unaligned data storage means that the data is stored at memory addresses that do not match the data size.

Accessing unaligned data may require multiple memory accesses, potentially impacting performance. In some architectures, unaligned memory access can also cause alignment faults or exceptions.

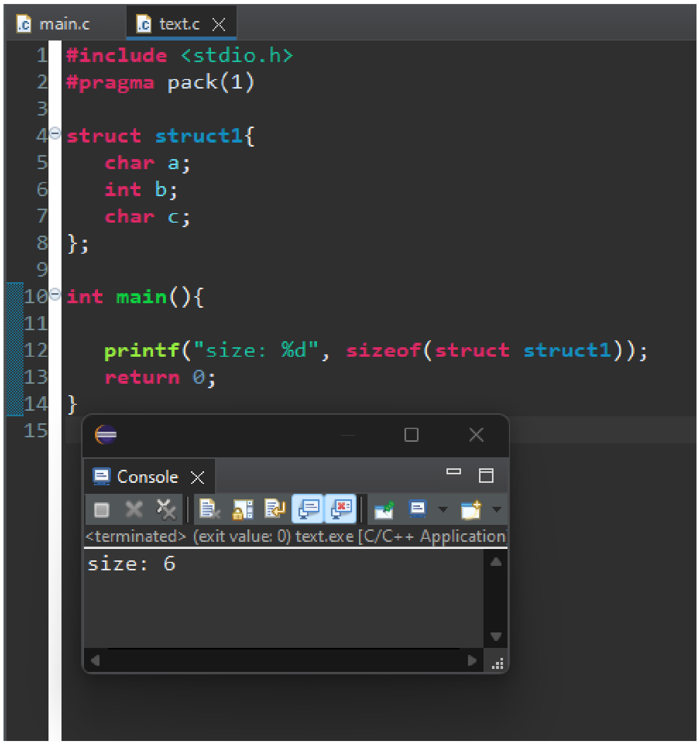
Using #pragma pack(1) Directive

The #pragma pack(1) preprocessor directive forces the compiler to disregard the padding, and align the structure members end to end during the memory allocation process.



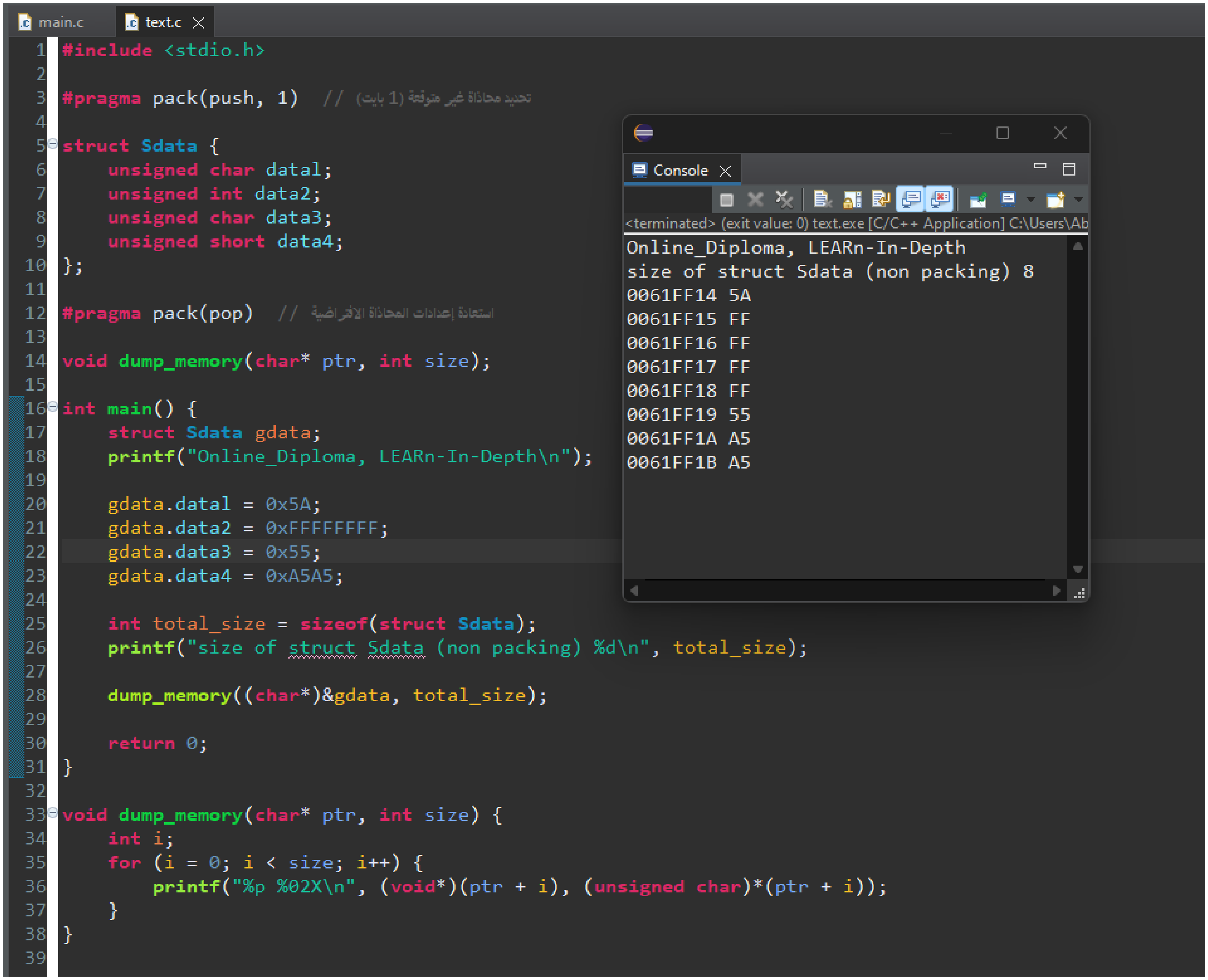
```c
#include <stdio.h>

struct struct1{
    char a;
    int b;
    char c;
};

int main(){

    printf("size: %d", sizeof(struct struct1));
    return 0;
}
```

```
<terminated> (exit value: 0) text.exe [C/C++ Application
size: 12
```



```c
#include <stdio.h>
#pragma pack(1)

struct struct1{
    char a;
    int b;
    char c;
};

int main(){

    printf("size: %d", sizeof(struct struct1));
    return 0;
}
```

```
<terminated> (exit value: 0) text.exe [C/C++ Application
size: 6
```

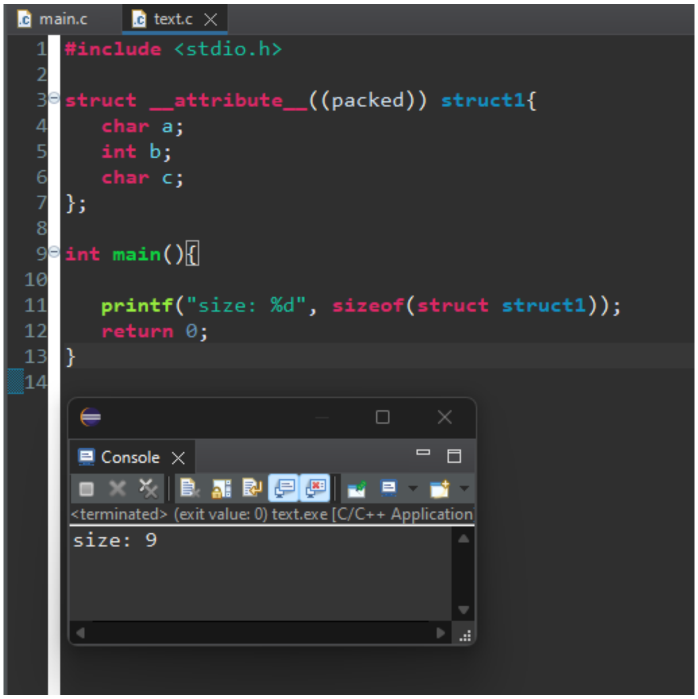


```c
#include <stdio.h>

#pragma pack(push, 1)  // تحديد محاذاة غير متوقعة (1 بايت)

struct Sdata {
    unsigned char data1;
    unsigned int data2;
    unsigned char data3;
    unsigned short data4;
};

#pragma pack(pop)  // استعادة إعدادات المحاذاة الافتراضية

void dump_memory(char* ptr, int size);

int main() {
    struct Sdata gdata;
    printf("Online_Diploma, LEARn-In-Depth\n");

    gdata.data1 = 0x5A;
    gdata.data2 = 0xFFFFFFFF;
    gdata.data3 = 0x55;
    gdata.data4 = 0xA5A5;

    int total_size = sizeof(struct Sdata);
    printf("size of struct Sdata (non packing) %d\n", total_size);

    dump_memory((char*)&gdata, total_size);

    return 0;
}

void dump_memory(char* ptr, int size) {
    int i;
    for (i = 0; i < size; i++) {
        printf("%p %02X\n", (void*)(ptr + i), (unsigned char)*(ptr + i));
    }
}
```

<terminated> (exit value: 0) text.exe [C/C++ Application] C:\Users\Ab

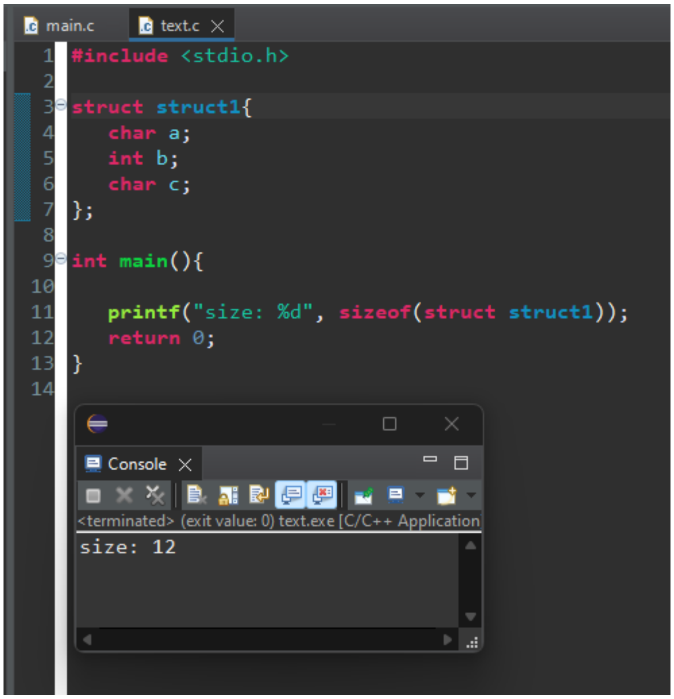
```
Online_Diploma, LEARn-In-Depth
size of struct Sdata (non packing) 8
0061FF14 5A
0061FF15 FF
0061FF16 FF
0061FF17 FF
0061FF18 FF
0061FF19 55
0061FF1A A5
0061FF1B A5
```

Using __attribute__((packed))



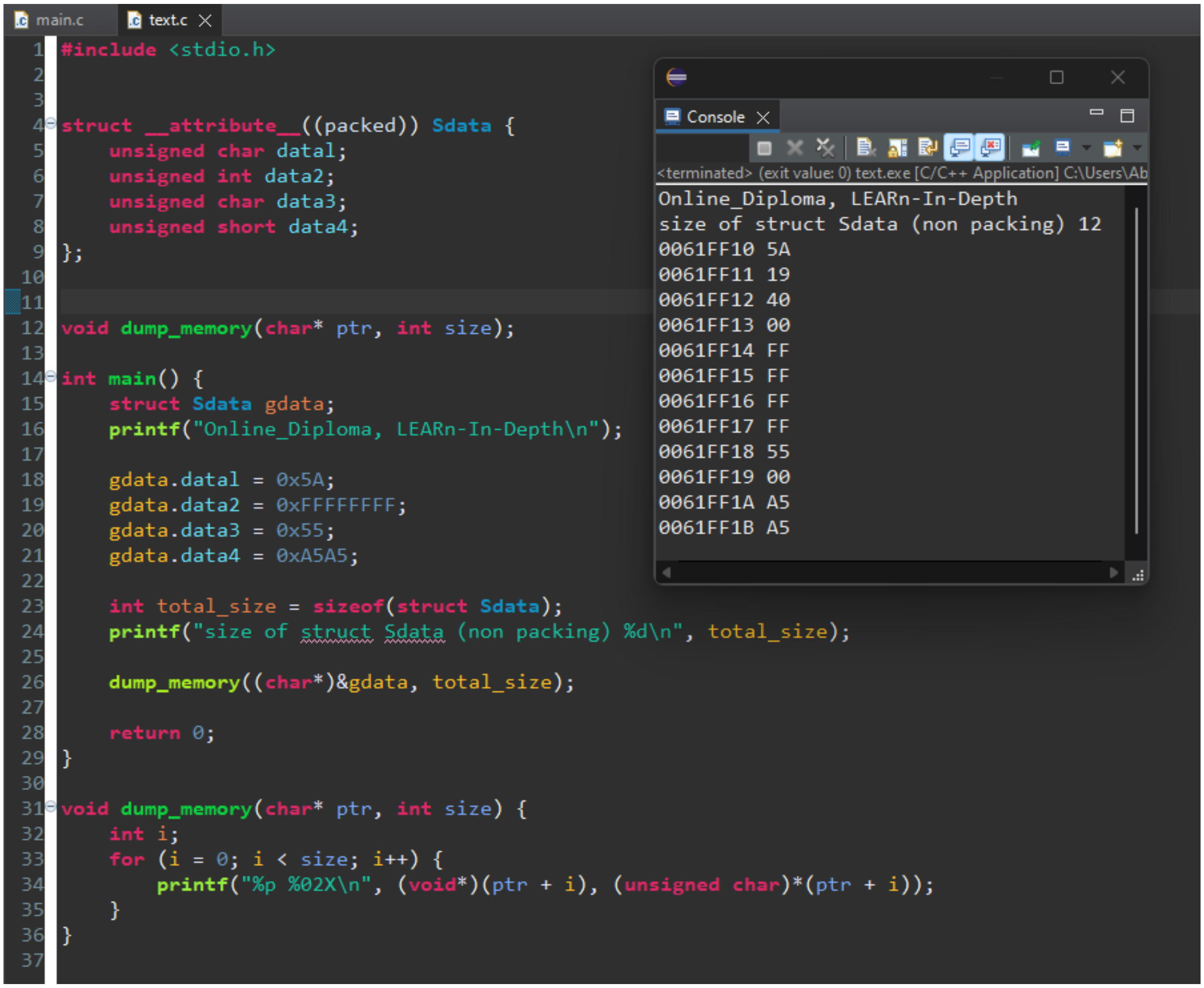
```c
#include <stdio.h>

struct __attribute__((packed)) struct1{
    char a;
    int b;
    char c;
};

int main(){
    
    printf("size: %d", sizeof(struct struct1));
    return 0;
}
```

```
<terminated> (exit value: 0) text.exe [C/C++ Application
size: 9
```



```c
#include <stdio.h>

struct struct1{
    char a;
    int b;
    char c;
};

int main(){
    
    printf("size: %d", sizeof(struct struct1));
    return 0;
}
```

```
<terminated> (exit value: 0) text.exe [C/C++ Application
size: 12
```



```c
#include <stdio.h>


struct __attribute__((packed)) Sdata {
    unsigned char datal;
    unsigned int data2;
    unsigned char data3;
    unsigned short data4;
};


void dump_memory(char* ptr, int size);

int main() {
    struct Sdata gdata;
    printf("Online_Diploma, LEARn-In-Depth\n");

    gdata.datal = 0x5A;
    gdata.data2 = 0xFFFFFFFF;
    gdata.data3 = 0x55;
    gdata.data4 = 0xA5A5;

    int total_size = sizeof(struct Sdata);
    printf("size of struct Sdata (non packing) %d\n", total_size);

    dump_memory((char*)&gdata, total_size);

    return 0;
}

void dump_memory(char* ptr, int size) {
    int i;
    for (i = 0; i < size; i++) {
        printf("%p %02X\n", (void*)(ptr + i), (unsigned char)*(ptr + i));
    }
}
```

```
<terminated> (exit value: 0) text.exe [C/C++ Application] C:\Users\Ab
Online_Diploma, LEARn-In-Depth
size of struct Sdata (non packing) 12
0061FF10 5A
0061FF11 19
0061FF12 40
0061FF13 00
0061FF14 FF
0061FF15 FF
0061FF16 FF
0061FF17 FF
0061FF18 55
0061FF19 00
0061FF1A A5
0061FF1B A5
```

Aligned and Unaligned Memory Access

Unaligned memory access is the access of data with a size of N number of bytes from an address that is not evenly divisible by the number of bytes N. We have aligned memory access if the address is evenly divisible by N.

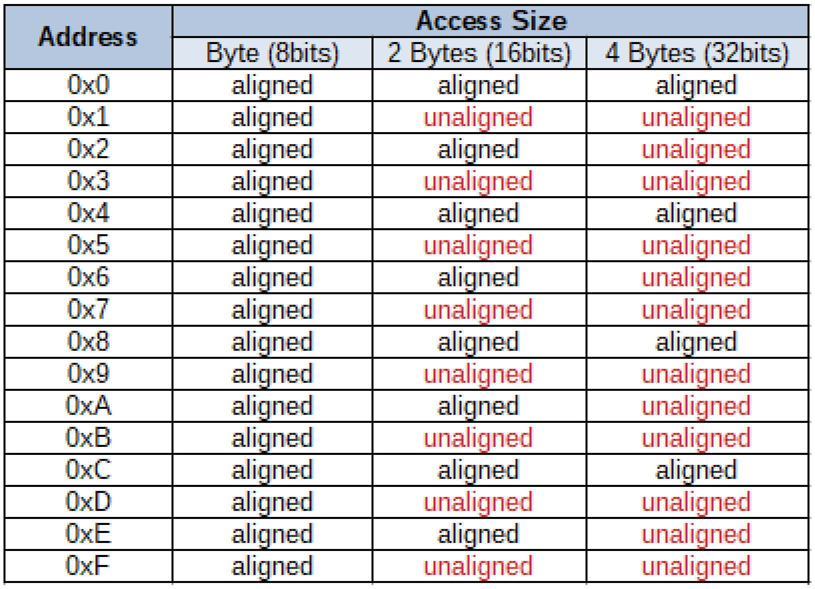
We can express this as **Address/N**, where **Address** is the memory address, and **N** is the number of bytes that are accessed. Here are some examples:

Two byte access from address 4: Address/N = 4/2 = 2 (aligned access)

Two byte access from address 3: Address/N = 3/2 = 1.5 (unaligned access)

Four byte access from address 24: Address/N = 24/4 = 6 (aligned access)

As a practical note, If the rightmost digit of the address (represented in a hexadecimal format) is divisible by the number of bytes, we have aligned memory access.



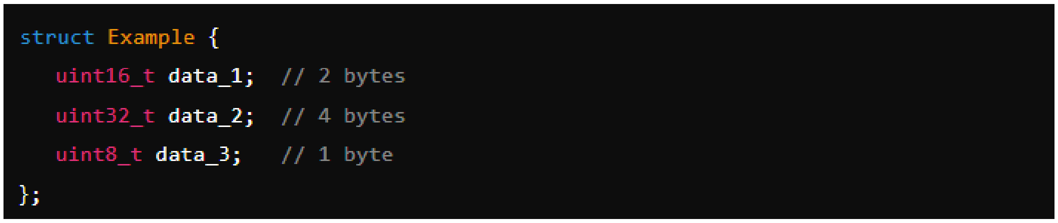
Address	Access Size		
	Byte (8bits)	2 Bytes (16bits)	4 Bytes (32bits)
0x0	aligned	aligned	aligned
0x1	aligned	unaligned	unaligned
0x2	aligned	aligned	unaligned
0x3	aligned	unaligned	unaligned
0x4	aligned	aligned	aligned
0x5	aligned	unaligned	unaligned
0x6	aligned	aligned	unaligned
0x7	aligned	unaligned	unaligned
0x8	aligned	aligned	aligned
0x9	aligned	unaligned	unaligned
0xA	aligned	aligned	unaligned
0xB	aligned	unaligned	unaligned
0xC	aligned	aligned	aligned
0xD	aligned	unaligned	unaligned
0xE	aligned	aligned	unaligned
0xF	aligned	unaligned	unaligned

There are microprocessors that allow unaligned memory access and those that don't. Unaligned access usually negatively impacts performance, as more operations (instructions) are required to perform it. If the microprocessor does not support unaligned access, an exception can be triggered (e.g., a bus error exception) when such access is attempted.

Software Point of View

From the software's point of view, memory access is just instructions for reading or writing bytes of data to or from memory.

Structure Alignment:



```
struct Example {
   uint16_t data_1;  // 2 bytes
   uint32_t data_2;  // 4 bytes
   uint8_t data_3;   // 1 byte
};
```

Memory Layout:

- Starting address: 0x00001000
- data_1 (2 bytes) occupies 0x00001000 and 0x00001001 (aligned).
- data_2 (4 bytes) occupies 0x00001002 to 0x00001005.
- data_3 (1 byte) occupies 0x00001006.

Alignment Considerations:

- data_1 is aligned at 0x00001000 (multiple of 2 bytes).
- data_2 starts at 0x00001002, which is not aligned to a 4-byte boundary (aligned would be 0x00001004).
- data_3 is aligned at 0x00001006 (single-byte variables are always aligned).

Compiler's Role:

- To align data_2 properly, the compiler can insert padding bytes after data_1. For instance, it might place 2 bytes of padding after data_1 to align data_2 at 0x00001004.

With Padding:

- data_1 (2 bytes) at 0x00001000 to 0x00001001
- Padding (2 bytes) at 0x00001002 to 0x00001003
- data_2 (4 bytes) at 0x00001004 to 0x00001007
- data_3 (1 byte) at 0x00001008

Summary:

- **Alignment in Structures:** Compilers align structure members to optimize memory access and may add padding to meet alignment requirements.
- **Unaligned Access Issues:** Casting pointers to different types and accessing unaligned memory can lead to undefined behavior and performance penalties.
- **Compiler Limitations:** The compiler does not handle runtime checks for pointer alignment, so developers must ensure proper alignment manually when dealing with unaligned memory access.

Compiler Specifics

The C programming language classifies unaligned memory access as undefined behavior.

The default behavior of the compiler when it comes to unaligned access is dependent on the target CPU architecture.

If the architecture does not allow unaligned accesses, then the compiler will place all variables, functions, etc., in an aligned manner.

If the CPU architecture allows unaligned access, then the compiler should have options where we can select whether it should take advantage of this or not. For example, **gcc** compiler has the following options for ARM processors that can be used: `-munaligned-access -mno-unaligned-access`.

Abdallah Ghazy

Abdallah-Ghazy

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