

# Alignment, Padding, and Packing

CSE 220: Systems Programming

Ethan Blanton

Department of Computer Science and Engineering

University at Buffalo



# Scalars vs. Aggregates

C has two basic kinds of types: **scalars** and **aggregates**.

A **scalar type** is a type that contains a **single value**.

In C, the scalar types are:

- **arithmetic types** (integers and floating point numbers)
- **pointers** (which we have learned are special integers)

**Aggregate types** are **collections of scalar values**.

In C, the aggregate types are:

- **arrays** of scalar values of the same type
- **structs** containing scalars of the same or different types

# Memory Layout

Many data types must be located in memory according to certain rules.

In most cases, this is not obvious to the programmer.

Aggregate types, and pointers to aggregate types, expose this.

We will explore alignment and stride.

## More on `void` Pointers

Void pointers are powerful for `raw memory manipulation`.

You can use them to put `arbitrary values` into memory.

You will use this in PA3 and PA4!

We will look at using `void *` to:

- Pass a pointer of an arbitrary type
- Read and write arbitrary types in memory
- Manipulate memory without respect to alignment and stride

# Effective Questions

Asking follow-up questions **is also a skill**.

When you get an answer, **set a timer**.

(Maybe 5 or 10 minutes, this time!)

**Think about the answer** during that time.

When the timer goes off:

- Can you make progress now?
- If not, **why not?**
- Do you need to ask a clarifying question?

# The C Struct

A **struct** is an **aggregate data type** consisting of **one or more other types**.

```
struct IntList {  
    int          value;  
    struct IntList *next;  
};
```

This struct contains an **integer** and a **pointer**.

`value` and `next` are called **members** of the structure.

Any **variable of type** `struct IntList` contains both of these members.

# Declaring and Using Structures

The syntax for structure declaration is

```
struct StructureTypeName {  
    // Members in structure  
    // Each member has a type and a name  
} instance; // semicolon required!
```

An **instance of the structure** may be created where the structure is declared, or using the type name later:

```
struct StructureTypeName instance;
```

# Accessing Structure Members

The `.` operator is used to access the members of a structure.

```
struct IntList node;  
node.value = 3;  
node.next = NULL;
```

Any member of a structure can be accessed with `.`:

```
struct ComplexList {  
    struct Complex {  
        double real, im;  
    } complex;  
    struct ComplexList *next;  
} complexlist;  
complexlist.complex.real = 0.0;
```



# Structure Pointers

The `.` operator is **cumbersome for structure pointers**:

```
struct IntList *list = malloc(sizeof(struct IntList));  
(*list).next = NULL;
```

The `->` operator is **syntactic sugar** for `(*)` `.`:

```
list->next = NULL;
```

The `->` operator can be used to access any member of a structure **via a pointer to the structure type**.

# Operations on Structures

A structure **value**:

- Can have its address taken with `&`
- Can be copied with `=`
- Can be used to access a member with `.`

A structure **pointer**:

- Can do all the things any pointer can do
- Can be used to access a member with `->`

**No other operations** on structures are legal!

# Alignment

We have previously discussed [words](#).

Recall that:

- The [memory bus](#) has a certain width
- Memory transfers data in [words](#)

Most systems can only access [words in memory](#) on [addresses divisible by the word size](#).

Often the [address](#) of a value must be [evenly divisible](#) by the [size of its type](#).

Thus, if an [int](#) is 32 bits, its address is divisible by 4.  
(32 bits / 8 bits per byte = 4 bytes, addressed in bytes)

# Scalar Layout

Scalar values must typically be **aligned to their size**.

Alignment rules **vary between architectures**.

Some platforms can **still access** unaligned scalars.

Some platforms **will raise a hardware error** for unaligned access.

**Most platforms suffer a performance penalty** for unaligned access.

# Array Layout

The first element of an array of scalars is typically aligned to the size of an array element.

This aligns all items in the array.

For other types of arrays, things can get more complicated.

To understand alignment of aggregate types, we must understand structure layout.

# Structure Layout

The members of a structure are **adjacent** in memory.

This is similar to scalars in an array.

However, there are **additional considerations** regarding layout.

The **alignment of array members** must be preserved!

**Padding** is inserted between values to bring them into alignment.

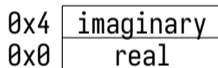
Padding is **unused memory** and you **cannot assume its value**.

# Simple Layout

In the simple case, **members are adjacent**.

Every member is laid out **in order**.

```
struct ComplexFloat {  
    float real;  
    float imaginary;  
};
```

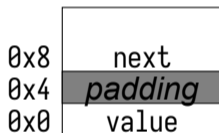


# Struct Padding

In a structure, padding is applied **between values**.

```
struct IntList {  
    int          value;  
    struct IntList *next;  
};
```

This struct is **16 bytes** and contains **4 bytes of padding**.





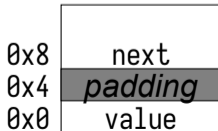
# Struct Alignment

For [padding in structures](#) to work, [the struct must be aligned](#).

Consider the previous example:

- If the address of the struct is divisible by 4, value is aligned, but next **might not be**
- If the address of the struct is divisible by 8, **both are aligned**

The [struct itself](#) is ordinarily aligned to the requirements of its [largest member](#).



# Alignment and Allocation

Recall that the standard allocator doesn't know what you're allocating.

For this reason, `malloc()` et al. normally align to the largest system requirement.

This ensures that any properly aligned structure will be aligned.

This leads to overhead which can cause significant waste.

We'll see much more about this later.

# Stride

Stride is closely related to [alignment](#), yet different.

Stride is the [difference between two pointers](#) to [adjacent values](#) of a particular type.

For simple types, [stride is the same as size](#).

For example:

- `int` is 32 b, `sizeof(int)` is 4, stride of `int *` is 4.
- `double` 64 b, `sizeof(double)` is 8, stride of `double *` is 8.

For [aggregate types](#), this can get more complicated.

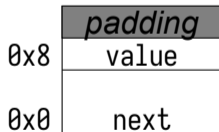
`void *` is a [special case](#), and its stride is 1.

# Stride in Aggregate Types

Consider this struct:

```
struct IntList {  
    struct IntList *next;  
    int             value;  
};
```

It lays out in memory like this:



Padding here is to **adjust stride** to **preserve alignment**.

# Pointer Arithmetic

Pointers are **integer types**, and **can be computed**.

**Pointer arithmetic** operates in **stride-sized** chunks.  
(This is why pointers can dereference like arrays!)

```
double *dptr = &somedouble;
```

If the value of `dptr` were `0`, `dptr + 1` would be **eight**, not one!  
This is because a double is **8 bytes wide**.

# Pointer Arithmetic — Aggregate Types

Stride for **aggregate types** can be quite large.

Consider:

```
struct Big {  
    char array[256];  
};  
struct Big *b = NULL;
```

In this case,  $b + 1$  is **the address 256!**

# Dumping Memory

```
#include <stdio.h>

void dump_mem(const void *mem, size_t len) {
    const char *buffer = mem;    // Cast to char *
    size_t i;

    for (i = 0; i < len; i++) {
        if (i > 0 && i % 8 == 0) { putchar('\n'); }

        printf("%02x ", buffer[i] & 0xff);
    }
    if (i > 1 && i % 8 != 1) { puts(""); }
}
```

# dump\_mem Details

What is this for?

```
const char *buffer = mem;
```



# dump\_mem Details

What is this for?

```
const char *buffer = mem;
```

It tells the compiler “we’re going to use `mem` as an array of bytes”.

# dump\_mem Details

What is this for?

```
const char *buffer = mem;
```

It tells the compiler “we’re going to use `mem` as an array of bytes”.

What about this:

```
if (i > 0 && i % 8 == 0){ putchar('\n'); }
```

## dump\_mem Details

What is this for?

```
const char *buffer = mem;
```

It tells the compiler “we’re going to use `mem` as an array of bytes”.

What about this:

```
if (i > 0 && i % 8 == 0){ putchar('\n'); }
```

It prints a newline after every 8th byte excepting the first.

# dump\_mem Details

What is this for?

```
const char *buffer = mem;
```

It tells the compiler “we’re going to use `mem` as an array of bytes”.

What about this:

```
if (i > 0 && i % 8 == 0){ putchar('\n'); }
```

It prints a newline after every 8th byte excepting the first.

Finally:

```
buffer[i] & 0xff
```

## dump\_mem Details

What is this for?

```
const char *buffer = mem;
```

It tells the compiler “we’re going to use `mem` as an array of bytes”.

What about this:

```
if (i > 0 && i % 8 == 0){ putchar('\n'); }
```

It prints a newline after every 8th byte excepting the first.

Finally:

```
buffer[i] & 0xff
```

This is necessary to avoid [sign extension](#).

# Inconvenient Representation

Pointers to `void *` can be used to store and interpret representations that are inconveniently represented in C.

Consider the following structure:

```
struct Inconvenient {  
    int fourbytes;  
    long eightbytes;  
} inconvenient;
```

This structure contains 12 bytes of data, but occupies 16 bytes.  
(Because of padding...)

To communicate this structure we wish to send only 12 bytes.

# Serialization

Communicating such data is often done via **serialization**.

**Serialization** is the storage of data into a **byte sequence**.

In C, we do this with **pointers**, and often **void pointers**.

Consider:

```
void *p = malloc(12);
*(int *)p = inconvenient.fourbytes;
*(long *)(p + sizeof(int)) = inconvenient.eightbytes;
```

This builds a 12-byte structure **without padding**.

(In the process, it **violates alignment restrictions**.)

# Flexible Sizes

Another use for `void` pointer representation is **flexible sizes**.

Consider a structure (**not legal C**):

```
struct Variable {  
    size_t nentries;  
    int entries[nentries];  
    char name[]; /* name is NUL-terminated */  
} variable;
```

This structure **does not have a well-defined size**.

Its size depends on `nentries` and the length of `name`!



# Packing the Data

We can **serialize** this data as follows:

```
size_t nentries = 3;
int entries[] = { 42, 31337, 0x1701D };
const char *name = "Caleb Widogast";

void *buf = malloc(sizeof(size_t)
                  + nentries * sizeof(int)
                  + strlen(name) + 1);
void *cur = buf;
```

# Packing the Data

We can **serialize** this data as follows:

```
*(size_t *)cur = nentries;
cur += sizeof(size_t);
for (int i = 0; i < nentries; i++) {
    *(int *)cur = entries[i];
    cur += sizeof(int);
}

for (int i = 0; i <= strlen(name); i++) {
    *(char *)cur++ = name[i];
}
```

# Packing the Data

We can **serialize** this data as follows:

```
size_t nentries = 3;
int entries[] = { 42, 31337, 0x1701D };
const char *name = "Caleb Widogast";
```

```
03 00 00 00 00 00 00 00
2a 00 00 00 69 7a 00 00
1d 70 01 00 43 61 6c 65
62 20 57 69 64 6f 67 61
73 74 00
```

# Summary

- Integers, pointers, and floating point numbers are **scalar types**.
- Arrays and structures are **aggregate types**.
- Structures can contain members of **mixed type**.
- Scalar types must be **aligned**.
- Aggregate types must **align for scalars**.
- Allocation normally aligns to the **largest type**.
- Pointer arithmetic **uses stride** in computations.
- `void *` has a **stride of 1**.
- The `void *` type can be used for **raw memory manipulation**
- **Casting** `void *` to another type is convenient
- Math on `void *` is **by byte**

# References I

## Required Readings

- [1] Randal E. Bryant and David R. O'Hallaron. *Computer Science: A Programmer's Perspective*. Third Edition. Chapter 3: 3.8.1–3.8.3, 3.9.1, 3.9.3. Pearson, 2016.
- [2] Brian W. Kernighan and Dennis M. Ritchie. *The C Programming Language*. Second Edition. Chapter 5: Intro, 5.1-5.7; Chapter 6: Intro, 6.1-6.7. Prentice Hall, 1988.

# License

Copyright 2019, 2020, 2021 Ethan Blanton, All Rights Reserved.  
Copyright 2019 Karthik Dantu, All Rights Reserved.

Reproduction of this material without written consent of the author is prohibited.

To retrieve a copy of this material, or related materials, see <https://www.cse.buffalo.edu/~eblanton/>.