Alignment, Padding, and Packing

CSE 220: Systems Programming

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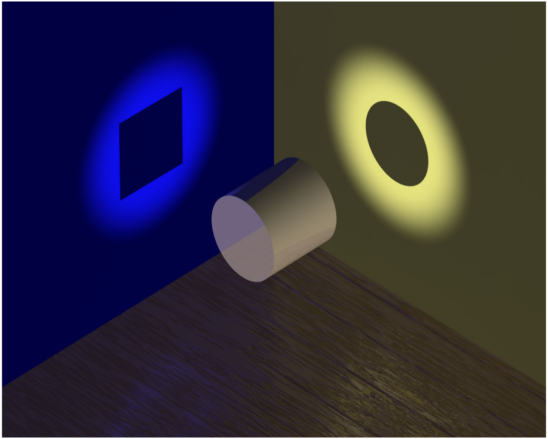
Planning and Development I



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Planning and Development II

When writing code, arrange different views of the problem:

- Documentation (your handout!)
- Diagrams
- Pseudocode
- Code

Each view will give you different insight.

Compare them against each other!

Simple vs. Compound

C has two basic kinds of types: simple and compound.

A simple type is a type that contains a single value.

In C, the simple types are:

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

Compound types are collections of other values.

In C, the compound types are:

- arrays of simple or compound values of the same type
- structs containing values 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.
(In many languages, it is impossible to tell!)

Compound types, and pointers to compound 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

The C Struct

A struct is a compound 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
} varname; // semicolon required!
```

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

```
struct StructureTypeName varname;
```

Accessing Structure Members

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

```
struct IntList node = { 7, NULL };
node.value = 3;
```

Any member of a structure can be accessed with .:

```
struct Complex {
    double real, im;
};
struct ComplexList {
    struct Complex 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)

Simple Type Layout

Simple types must typically be aligned to their size.

Alignment rules vary between architectures.

Some platforms can still access unaligned simple types.

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 simple types is typically aligned to the size of an array element.

This automatically aligns all items in the array.

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

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

Structure Layout

The members of a structure are adjacent in memory.

This is similar to simple types 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.

Uncomplicated Layout

In the least complicated case, members are adjacent.
Every member is laid out in order.

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

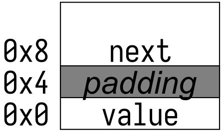
0x4	imaginary
0x0	real

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.



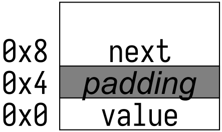
Struct Alignment

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 largest requirement of any 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 requirement on the system.

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 compound types, this can get more complicated.

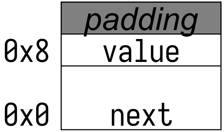
`void *` is a special case, and its stride is 1.

Stride in Compound 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 — Compound Types

Stride for compound 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

```c
#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);
    }
    putchar('\n');
}
```

dump_mem Details

What is this for?

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const char *buffer = mem;
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Finally:

```
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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 = "Imogen Temult";

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];
}
```

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```

```
03 00 00 00 00 00 00 00
2a 00 00 00 69 7a 00 00
1d 70 01 00 49 6d 6f 67
65 6e 20 54 65 6d 75 6c
74 00
```

Summary

- Integers, pointers, and floating point numbers are simple types.
- Arrays and structures are compound types.
- Structures can contain members of mixed type.
- Simple types must be aligned.
- Compound types must align for simple types.
- Allocation normally aligns to the largest requirement.
- 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.

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