

Data types: Struct, Union, Enum, Bit Fields

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Lecture 05

PRG – Programming in C

Overview of the Lecture

- Part 1 – Data types
 - Structures – struct
 - Unions
 - Type definition – typedef
 - Enumerations – enum
 - Bit-Fields
- Part 2 – Assignment HW 05
- Part 3 – Coding Examples (optional)
 - Pointer Casting - Print Hex Values
 - Casting Pointer to Array
 - String Sorting
 - Simple Calculator
 - Casting Pointer to Array

K. N. King: chapters 16 and 20

Part I

Data types – Struct, Union, Enum and Bit Fields

Structures, Unions, and Enumerations

- Structure is a collection of values, possibly of different types.
 - It is defined with the keyword **struct**.
 - Structures represent **records** of data **fields**.
- Union is also a collection of values, but its members share the same storage.

Union can store one member at a time, but not all simultaneously.
- Enumeration represents **named integer values**.

struct

- Structure `struct` is a finite set of data field members that can be of different type.
- Structure is defined by the programmer as a new data type.
- It allows storing a collection of the related data fields.
- Each structure has a separate **name space** for its members.
- Definition of the compound type (`struct`) variable `user_account`.

```
#define USERNAME_LEN 8 Using anonymous structure declaration.
struct {
    int login_count;
    char username[USERNAME_LEN + 1];
    int last_login; // date as the number of seconds
                  // from 1.1.1970 (unix time)
} user_account; // variable of the struct defined type
```

- The declaration follows other variable declaration where `struct {...}` specifies the type and `user_account` the variable name.
- We access the members using the `.` operator, e.g.,


```
user_account.login_count = 0;
```

Structure Tag

- Declaring a **structure tag** allows to identify a particular structure and avoids repeating all the data fields in the structure variable.

```
struct user_account {
    int login_count;
    char username[USERNAME_LEN + 1];
    int last_login;
}; Notice VLA is not allowed in structure type because the size of the structure needs to be known and determined.
```

- After creating the `user_account` tag, variables can be defined as follows.


```
struct user_account user1, user2;
```
- The defined tag is not a type name, therefore it has to be used with the `struct` keyword.
- The new type can be defined using the `typedef` keyword.


```
typedef struct { ... } new_type_name;
```

Initialization of the Structure Variables and Assignment Operator

- Structure variables can be initialized in the declaration.
- In C99, we can also use the designated initializers.

```
struct {
    int login_count;
    char name[USERNAME_LEN + 1];
    int last_login;
} user1 = { 0, "admin", 1477134134 }, //get unix time 'date +%s'
          // designated initializers in C99
user2 = { .name = "root", .login_count = 128 };
```

```
printf("User1 '%s' last login on: %d\n", user1.name, user1.last_login);
printf("User2 '%s' last login on: %d\n", user2.name, user2.last_login);
```

```
user2 = user1; // assignment operator structures
```

```
printf("User2 '%s' last login on: %d\n", user2.name, user2.last_login);
```

`lec05/structure_init.c`

- The assignment operator `=` is defined for the structure variables of the same type.

No other operator like `!=` or `==` is defined for the structures!

Example of Defining Structure

- Without definition of the new type (using `typedef`) adding the keyword `struct` before the structure tag is mandatory.

```
struct record {
    int number;
    double value;
};

typedef struct {
    int n;
    double v;
} item;

record r; /* THIS IS NOT ALLOWED! */
        /* Type record is not known */
```

```
struct record r; /* Keyword struct is required */
item i; /* type item defined using typedef */
```

- Introducing new type by `typedef`, the defined `struct` type can be used without the `struct` keyword.

`lec05/struct.c`

Structure Tag and Structure Type

- We define a new structure tag `record` using `struct record`.

```
struct record {
    int number;
    double value;
};
```

- The tag identifier `record` is defined in the name space of the structure tags.

It is not mixed with other type names.

- Using the `typedef`, we introduce a new type named `record`.

Or any other name.

```
typedef struct record record;
```

- We define a new identifier `record` as the type name for the `struct record`.

- Structure tag and definition of the type can be combined.

```
typedef struct record {
    int number;
    double value;
} record;

typedef struct struct_name {
    int number;
    double value;
} type_name;
```

Example struct – Direct Copy of the Memory

- Having two structure variables of the same size, the content can be directly copied using memory copy.

E.g., using `memcpy()` from `<string.h>`.

```
struct record r = { 7, 21.4};
item i = { 1, 2.3 };
print_record(r); /* number(7), value(21.400000) */
print_item(&i); /* n(1), v(2.300000) */
if (sizeof(i) == sizeof(r)) {
    printf("i and r are of the same size\n");
    memcpy(&i, &r, sizeof(i));
    print_item(&i); /* n(7), v(21.400000) */
}
```

- Notice**, in the example, the interpretation of the stored data in both structures is identical. In general, it may not be always the case.

`lec05/struct.c`

Example struct – Assignment

- The assignment operator `=` can be used for two variables of the same struct type.

```
struct record {
    int number;
    double value;
};

typedef struct {
    int n;
    double v;
} item;
```

```
struct record rec1 = { 10, 7.12 };
struct record rec2 = { 5, 13.1 };
item i;
print_record(rec1); /* number(10), value(7.120000) */
print_record(rec2); /* number(5), value(13.100000) */
rec1 = rec2;
i = rec1; /* THIS IS NOT ALLOWED! */
print_record(rec1); /* number(5), value(13.100000) */
```

`lec05/struct.c`

Size of Structure Variables

- Data representation of the structure may be different from the sum of sizes of the particular data fields (types of the members).

```
struct record {
    int number;
    double value;
};

typedef struct {
    int n;
    double v;
} item;
```

```
printf("Size of int: %lu size of double: %lu\n", sizeof(int),
      sizeof(double));
printf("Size of record: %lu\n", sizeof(struct record));
printf("Size of item: %lu\n", sizeof(item));
```

Size of int: 4 size of double: 8

Size of record: 16

Size of item: 16

`lec05/struct.c`

Size of Structure Variables 1/2

- Compiler might align the data fields to the size of the word (address) of the particularly used architecture.
E.g., 8 bytes for 64-bits CPUs.
- A compact memory representation can be explicitly prescribed for the `clang` and `gcc` compilers by the `__attribute__((packed))`.

```
struct record_packed {
    int n;
    double v;
} __attribute__((packed));
```

- Or


```
typedef struct __attribute__((packed)) {
    int n;
    double v;
} item_packed;
```

lec05/struct.c

Accessing Members using Pointer to Structure

- The operator `->` can be used to access structure members using a pointer.

```
typedef struct {
    int number;
    double value;
} record_s;
```

```
record_s a;           // variable a of the type record_s
record_s *p = &a;    // variable p of the type pointer (to record_s)
```

```
printf("Number %d\n", p->number);
```

Size of Structure Variables 2/2

```
printf("Size of int: %lu size of double: %lu\n",
       sizeof(int), sizeof(double));
```

```
printf("record_packed: %lu\n", sizeof(struct record_packed));
```

```
printf("item_packed: %lu\n", sizeof(item_packed));
```

```
Size of int: 4 size of double: 8
```

```
Size of record_packed: 12
```

```
Size of item_packed: 12
```

lec05/struct.c

- The address alignment provides better performance for addressing the particular members at the cost of higher memory requirements.

Eric S. Raymond: The Lost Art of Structure Packing - <http://www.catb.org/esr/structure-packing>.

Structure Variables as a Function Parameter

- Structure variable can be pass to a function and also returned.
- We can pass/return the struct itself.

```
struct record print_record(struct record rec) {
    printf("record: number(%d), value(%lf)\n",
          rec.number, rec.value);
    return rec;
}
```

- Struct **value** – a new variable is allocated on the stack and data are copied.

- Or, as a pointer to a structure.

Be aware of shallow copy of pointer data fields.

```
item* print_item(item *v) {
    printf("item: n(%d), v(%lf)\n", v->n, v->v);
    return v;
}
```

- Struct **pointer** – only the address is passed to the function.

By passing a pointer, we can save copy of large structures to stack.

lec05/struct.c

Union – variables with Shared Memory

- **Union** is a set of members, possibly of different types.
- All the members share the same memory. *Members are overlapping.*
- The size of the union is according to the largest member.
- Union is similar to the **struct** and particular members can be accessed using `.` or `->` for pointers.
- The declaration, union tag, and type definition is also similar to the **struct**.

```

1 union Nums {
2     char c;
3     int i;
4 };
5 Nums nums; /* THIS IS NOT ALLOWED! Type Nums is not known! */
6 union Nums nums;
```

Example union 2/2

- The particular members of the **union**

```

1 numbers.c = 'a';
2 printf("\nSet the numbers.c to 'a'\n");
3 printf("Numbers c: %d i: %d d: %lf\n", numbers.c, numbers.i, numbers.d);
4
5 numbers.i = 5;
6 printf("\nSet the numbers.i to 5\n");
7 printf("Numbers c: %d i: %d d: %lf\n", numbers.c, numbers.i, numbers.d);
8
9 numbers.d = 3.14;
10 printf("\nSet the numbers.d to 3.14\n");
11 printf("Numbers c: %d i: %d d: %lf\n", numbers.c, numbers.i, numbers.d);
```

- Example output:

```

Set the numbers.c to 'a'
Numbers c: 97 i: 1374389601 d: 3.140000

Set the numbers.i to 5
Numbers c: 5 i: 5 d: 3.139999

Set the numbers.d to 3.14
Numbers c: 31 i: 1374389535 d: 3.140000
```

lec05/union.c

Example union 1/2

- A **union** composed of variables of the types: **char**, **int**, and **double**.

```

1 int main(int argc, char *argv[])
2 {
3     union Numbers {
4         char c;
5         int i;
6         double d;
7     };
8     printf("size of char %lu\n", sizeof(char));
9     printf("size of int %lu\n", sizeof(int));
10    printf("size of double %lu\n", sizeof(double));
11    printf("size of Numbers %lu\n", sizeof(union Numbers));
12
13    union Numbers numbers;
14
15    printf("Numbers c: %d i: %d d: %lf\n", numbers.c, numbers.i, numbers.d);
```

- Example output:

```

size of char 1
size of int 4
size of double 8
size of Numbers 8
Numbers c: 48 i: 740313136 d: 0.000000
```

lec05/union.c

Initialization of Unions

- The union variable can be initialized in the declaration.

```

1 union {
2     char c;
3     int i;
4     double d;
5 } numbers = { 'a' };
```

Only the first member can be initialized

- In C99, we can use the designated initializers.

```

1 union {
2     char c;
3     int i;
4     double d;
5 } numbers = { .d = 10.3 };
```

Type Definition – typedef

- The `typedef` can also be used to define new data types, not only structures and unions but also pointers or pointers to functions.
- Example of the data type for pointers to `double` or a new type name for `int`.

```

1 typedef double* double_p;
2 typedef int integer;
3 double_p x, y;
4 integer i, j;

```

- The usage is identical to the default data types.


```

1 double *x, *y;
2 int i, j;

```

- Definition of the new data types (using `typedef`) in header files allows a systematic use of new data types in the whole program.

See, e.g., `<inttypes.h>`

- The main advantage of defining a new type is for complex data types such as structures and pointers to functions.

Example – Enumerated Type as Subscript 1/4

- Enumeration constants are integers, and they can be used as subscripts.
- We can also use them to initialize an array of structures.

```

1 #include <stdio.h>
2 #include <stdlib.h>
3 #include <string.h>
4
5 enum weekdays { MONDAY, TUESDAY, WEDNESDAY, THURSDAY, FRIDAY };
6
7 typedef struct {
8     char *name;
9     char *abbr; // abbreviation
10 } week_day_s;
11
12 const week_day_s days_en[] = {
13     [MONDAY] = { "Monday", "mon" },
14     [TUESDAY] = { "Tuesday", "tue" },
15     [WEDNESDAY] = { "Wednesday", "wed" },
16     [THURSDAY] = { "Thursday", "thr" },
17     [FRIDAY] = { "Friday", "fri" },
18 };

```

lec05/demo-struct.c

Enumeration Tags and Type Names

- Enum allows to define a subset of integer values and named them.
- We can define enumeration tag similarly to struct and union.

```

enum suit { SPADES, CLUBS, HEARTS, DIAMONDS };
enum s1, s2;

```

- A new enumeration type can be defined using the `typedef` keyword.


```

typedef enum { SPADES, CLUBS, HEARTS, DIAMONDS } suit_t;
suit_t s1, s2;

```
- The enumeration can be considered as an `int` value.

However, we should avoid to directly set enum variable as an integer, as, e.g., value 10 does not correspond to any suit.

- Enumeration can be used in a structure to declare “tag fields”,

```

typedef struct {
    enum { SPADES, CLUBS, HEARTS, DIAMONDS } suit;
    enum { RED, BLACK } color;
} card;

```

By using `enum` we clarify meaning of the suit and color data fields.

Example – Enumerated Type as Subscript 2/4

- We can prepare an array of structures for particular language.
- The program prints the name of the week day and particular abbreviation.

```

19 const week_day_s days_cs[] = {
20     [MONDAY] = { "Pondělí", "po" },
21     [TUESDAY] = { "Úterý", "út" },
22     [WEDNESDAY] = { "Středa", "st" },
23     [THURSDAY] = { "Čtvrtek", "čt" },
24     [FRIDAY] = { "Pátek", "pá" },
25 };
26
27 enum { EXIT_OK = 0, ERROR_INPUT = 101 };
28
29 int main(int argc, char *argv[], char **envp)
30 {
31     int day_of_week = argc > 1 ? atoi(argv[1]) : 1;
32     if (day_of_week < 1 || day_of_week > 5) {
33         fprintf(stderr, "(EE) File: '%s' Line: %d -- Given day of week out of range\n",
34             __FILE__, __LINE__);
35         return ERROR_INPUT;
36     }
37     day_of_week -= 1; // start from 0

```

lec05/demo-struct.c

Example – Enumerated Type as Subscript 3/4

- Detection of the user “locale” is based on the set environment variables.

For simplicity we just detect Czech based on occurrence of 'cs' substring in LC_CTYPE environment variable.

```

35 _Bool cz = 0;
36 while (*envp != NULL) {
37     if (strstr(*envp, "LC_CTYPE") && strstr(*envp, "cs")) {
38         cz = 1;
39         break;
40     }
41     envp++;
42 }
43 const week_day_s *days = cz ? days_cs : days_en;
44
45 printf("%d %s %s\n",
46        day_of_week,
47        days[day_of_week].name,
48        days[day_of_week].abbr);
49 return EXIT_OK;
50 }

```

lec05/demo-struct.c

Example – Enumerated Type as Subscript 4/4

```

$ clang demo-struct.c -o demo-struct
$ ./demo-struct
0 Monday mon
$ ./demo-struct 3
2 Wednesday wed
$ LC_CTYPE=cs ./demo-struct 3
2 Středa st
$ lec05 LC_CTYPE=cs_CZ.UTF-8 ./demo-struct 5; echo $?
4 Pátek pá
0
$ LC_CTYPE=cs_CZ.UTF-8 ./demo-struct 9; echo $?
(EE) File: 'demo-struct.c' Line: 32 -- Given day of week out of range
101

```

lec05/demo-struct.c

Bitwise Operators

- In low-level programming, such as programs for MCU (micro controller units), we may need to store information as single bits or collection of bits.
- We can use bitwise operators to set or extract particular bit, e.g., a 16-bit unsigned integer variable `uint16_t i`.

- Set the 4 bit of `i`.

```
if ( i & 0x0010) ...
```

- Clear the 4 bit of `i`.

```
i &= ~0x0010;
```

- We can give names to particular bits.

```

35 #define RED 1
36 #define GREEN 2
37 #define BLUE 3
38
39 i |= RED; // sets the RED bit
40 i &= ~GREEN; // clears the GREEN bit
41 if (i & BLUE) ... // test BLUE bit

```

Bit-Fields in Structures

- In addition to bitwise operators, we can declare structures whose members represent bit-fields, e.g., time stored in 16 bits.

```

typedef struct {
    uint16_t seconds: 5; // use 5 bits to store seconds
    uint16_t minutes: 6; // use 6 bits to store minutes
    uint16_t hours: 5; // use 5 bits to store hours
} file_time_t;

```

```
file_time_t time;
```

- We can access the members as a regular structure variable.

```
time.seconds = 10;
```

- The only restriction is that the bit-fields do not have address in the usual sense, and therefore, using address operator `&` is not allowed.

```
scanf("%d", &time.hours); // NOT ALLOWED!
```

Bit-Fields Memory Representation

- The way how a compiler handle bit-fields depends on the notion of the **storage units**.
- Storage units are implementation defined (e.g., 8 bits, 16 bits, etc.).
- We can omit the name of the bit-field for padding, i.e., to ensure other bit fields are properly positioned.

```
typedef struct {
    unsigned int seconds: 5;
    unsigned int minutes: 6;
    unsigned int hours: 5;
} file_time_int_s;

// size 4 bytes
printf("Size %lu\n", sizeof(
    file_time_int_s));
```

```
typedef struct {
    unsigned int seconds: 5;
    unsigned int : 0;
    unsigned int minutes: 6;
    unsigned int hours: 5;
} file_time_int_skip_s;

// size 8 bytes because of padding
printf("Size %lu\n", sizeof(
    file_time_int_skip_s));
```

Part II

Part 2 – Assignment HW 05

Bit-Fields Example

```
typedef struct {
    unsigned int seconds: 5;
    unsigned int minutes: 6;
    unsigned int hours: 5;
} file_time_int_s;

void print_time(const file_time_s *t)
{
    printf("%02u:%02u:%02u\n", t->hours, t->minutes, t->seconds);
}

int main(void)
{
    file_time_s time = { // designated initializers
        .hours = 23, .minutes = 7, .seconds = 10 };
    print_time(&time);
    time.minutes += 30;
    print_time(&time);

    // size 2 bytes (for 16 bit short
    printf("Size of file_time_s %lu\n", sizeof(time));
    return 0;
}
```

HW 05 – Assignment

Topic: Matrix Operations

Mandatory: 2 points; Optional: 2 points; Bonus : 5

- **Motivation:** Variable Length Array (VLA) and 2D arrays.
- **Goal:** Familiar yourself with VLA and pointers. (optional and bonus) Dynamic allocation and structures.
- **Assignment:** <https://cw.fel.cvut.cz/wiki/courses/b3b36prg/hw/hw05>
 - Read matrix expression – matrices and operators (+, -, and *) from standard input (dimensions of the matrices are provided).
 - Compute the result of the matrix expression or report an error . Dynamic allocation is not needed! Functions for implementing +, *, and - operators are highly recommended!
 - **Optional assignment** – compute the matrix expression with respect to the priority of * operator over + and - operators. Dynamic allocation is not need, but it can be helpful.
 - **Bonus assignment** – Read declaration of matrices prior the matrix expression. Dynamic allocation can be helpful, structures are not needed but can be helpful.
- **Deadline:** 20.04.2024, 23:59 AoE (bonus 24.5.2024, 23:59 CEST).

Part III

Part 3 – Coding Examples
(optional)

Coding Example – Print Hex Values – Implementation 1/3

- Retrive address of variable `float v` by `&v`.
- We need access values at the address `&v` as bytes; therefore, we type cast it to a pointer to char value(s).

```
unsigned char *p = (unsigned char*)&v;
```

- The value at the address stored in `p` can be accessed by the indirect addressing operator `*p`.

- We can advance the next address by incrementing the value stored in `p`, e.g., `p = p + 1`;

Because it is a pointer to `char`, the increment is about `sizeof(char)`, i.e., by 1. It is the pointer arithmetic.

- However, the printed values are in the reversed order than the expected order `0x42aa4000` and `0x3dcccccd`.

```
int main(void)
{
    print_float_hex(85.125);
    print_float_hex(0.1);
    ...
    void print_float_hex(float v)
    {
        unsigned char *p = (unsigned char*)&v;
        printf("Value %13.10f is 0x", v);
        for (int i = 0; i < 4; ++i, p = p + 1) {
            printf("%02x", *p); // or use p[i]
        }
        putchar('\n');
    }
}

$ clang floats.c -o floats && ./floats
Value 85.1250000000 is 0x0040aa42
Value 0.1000000015 is 0xcdcccc3d
```

Coding Example – Print Hex Values

- Representation of the `float` values.
 - Value 85.125 is `0x42aa4000`.
 - Value 0.1 is `0x3dcccccd` but encoded `0x3dcccccd`.
- Implement a function to print a hex representation of a float value.
- Access to a float value as a sequence of bytes and print individual bytes as hex values using `"%02x"` in `printf()`.
 - Use addressing operator `&` to get variable address.
 - Type case to get a pointer to char (a single byte).
 - Use indirect addressing operator `*` to access to the variable at the address stored in the pointer variable.
- Access to a float value as a sequence of bytes and print individual bytes as hex values using `"%02x"` in `printf()`.

```
#include <stdio.h>

void print_float_hex(float v);

int main(void)
{
    print_float_hex(85.125);
    print_float_hex(0.1);
    return 0;
}

void print_float_hex(float v)
{
    ...
}
```

Coding Example – Print Hex Values – Implementation 2/3

- Expected hexadecimal representation of the values 85.125 and 0.1 is `0x42aa4000` and `0x3dcccccd` but the printed values are `0x0040aa42` and `0xcdcccc3d`, respectively.

- It is because of the way how multi-byte values are stored in the memory. For the used architecture (amd64), it is little endian.

- Thus, we need to detect the endianness.

<https://en.wikipedia.org/wiki/Endianness>

- E.g., using a function

```
_Bool is_big_endian(void);
```

- and print values in the reversed order.

```
void print_float_hex(float v)
{
    const _Bool big_endian = is_big_endian();
    // cast pointer to float to pointer to char
    unsigned char *p = (unsigned char*)&v
        + (big_endian ? 0 : 3);
    printf("Value %13.10f is 0x", v);
    for (int i = 0; i < 4; ++i) {
        printf("%02x",
            *(big_endian ? p++ : p--));
    }
    printf("\n");
}

$ clang floats.c -o floats && ./floats
Value 85.1250000000 is 0x42aa4000
Value 0.1000000015 is 0x3dcccccd
```

Coding Example – Print Hex Values – Implementation 3/3

- The detection of the endianness can be based on various techniques.
- Intuitively, we need to store a defined value with all zeros but one byte non-zero.
- We can take advantage of the `union` type that allows different views on the identical memory block.
 1. Define an integer variable with the specified size of four bytes, e.g., `uint32_t` from `stdint.h` library.
 2. Set the value of `0x01 00 00 00` to the variable.
 3. Check the first byte of the memory representation, if it is zero or one.

```
#include <stdint.h>

_Bool is_big_endian(void)
{
    union {
        uint32_t i;
        char c[4];
    } e = { 0x01000000 };
    return e.c[0];
}
```

Coding Example – Array and Pointer to Function 2/4

```
void fill_random(size_t l, int a[l])
{
    for (size_t i = 0; i < l; ++i) {
        a[i] = rand() % MAX_NUM;
    }
}

void print(const char *s, size_t l, int a[l])
{
    if (s) {
        printf("%s", s);
    }
    for (size_t i = 0; i < l; ++i) {
        printf("%s%d", i > 0 ? " " : "", a[i]);
    }
    putchar('\n');
}
```

- See `man qsort` for `qsort` synopsis.
- ```
void qsort(
 void *base, size_t nmemb, size_t size,
 int (*compar)(const void *, const void *)
);
 ■ base is the pointer to the initial member.
 ■ nmemb is the no. of members.
 ■ size is the size of each member.
 ■ compar is a pointer to the comparison function.

int compare(const void *ai, const void *bi)
{
 const int *a = (const int*)ai;
 const int *b = (const int*)bi;
 //ascending
 return *a == *b ? 0 : (*a < *b ? -1 : 1);
}
 Change the order to descending.
```

## Coding Example – Array and Pointer to Function 1/4

- Implement a program that creates an array of random integer values using `rand()` function from `stdlib.h`. *Fill random function.*
- The integer values are limited to `MAX_NUM` set to, e.g., 20, by `#define MAX_NUM 20`.
- The default number can be adjusted at the compile time – `clang -DLEN=10 program.c`.
- The array is printed to `stdout`. *Print function.*
- The array is sorted using `qsort()` from `stdlib.h`. *Become familiar with `man qsort`.*
- The sorted array is printed to `stdout`.
- The program is then enhanced by processing program arguments to define the no. of values as the first program argument using `atoi()`.

```
#ifndef LEN
#define LEN 5
#endif

#define MAX_NUM 20

void fill_random(size_t l, int a[l]);
void print(const char *s, size_t l, int a[l]);

int main(void)
{
 int a[LEN]; // allocate the array
 fill_random(LEN, a); // fill the array
 print("Array random: ", LEN, a);
 // TODO call qsort
 print("Array sorted: ", LEN, a);
 return 0;
}
```

## Coding Example – Array and Pointer to Function 3/4

- Use the function name as the pointer to the function.
- ```
int compare(const void *, const void *);

int main(void)
{
    int a[LEN]; // do not initialize
    fill_random(LEN, a);
    print("Array random: ", LEN, a);
    qsort(a, LEN, sizeof(int), compare);
    print("Array sorted: ", LEN, a);
    return 0;
}
```

- Compile and run if the compilation is successful using `shell logical and` operator `&&`.


```
$ clang sort.c -o sort && ./sort
Array random: 13 17 18 15 12
Array sorted: 12 13 15 17 18
```
- Use compiler flag `-DLEN=10` to define the array length 10.


```
$ clang -DLEN=10 sort.c -o sort && ./sort
Array random: 13 17 18 15 12 3 7 8 18 10
Array sorted: 3 7 8 10 12 13 15 17 18 18
```

Coding Example – Array and Pointer to Function 4/4

- Extend `main()` to pass program arguments.
- Define an error value.

```
enum { ERROR = 100 };

int main(int argc, char *argv[])
{
    const size_t len = argc > 1 ?
        atoi(argv[1]) : LEN;
    if (len > 0) {
        int a[len];
        fill_random(len, a);
        print("Array random: ", len, a);
        qsort(a, len, sizeof(int), compare);
        print("Array sorted: ", len, a);
    }
    return len > 0 ? EXIT_SUCCESS : ERROR;
}
```

- We use the **Variable Length Array (VLA)**, which length is determined during the runtime.

```
$ clang sort-vla.c -o sort && ./sort
Array random: 13 17 18 15 12 3
Array sorted: 3 12 13 15 17 18

$ clang sort-vla.c -DLEN=7 -o sort && ./sort
Array random: 13 17 18 15 12 3 7
Array sorted: 3 7 12 13 15 17 18

$ clang sort-vla.c -o sort && ./sort 11
Array random: 13 17 18 15 12 3 7 8 18 10 19
Array sorted: 3 7 8 10 12 13 15 17 18 18 19
```

- Be aware the size of the array `a` is limited by the size of the **stack**, see `ulimit -s`.

Coding Example – String Sorting 1/5

- Implement a program that sorts program arguments lexicographically using `strcmp` (from `string.h`) and `qsort` (from `stdlib.h`).

- Print the arguments. *Print function.*
- Copy the passed `argv` to newly allocated memory on the heap to avoid changes in `argv`.

- Exit with `-1` if allocation fails. *My malloc function.*
- Copy strings using `strncpy`. *Copy and copy strings functions.*

- Sort the copied array of strings with the help of `strcmp`. *String compare function.*
- Release the allocated memory. *Release function.*

```
#include <stdio.h>
#include <string.h>
#include <stdlib.h>

void print(int n, char *strings[n]);

char* copy(const char *str);
char** copy_strings(int n, char *strings[n]);

void* my_malloc(size_t size);
void release(int n, char **strings);

int string_compare(
    const void *p1, const void *p2);

enum { EXIT_OK = 0, EXIT_MEM = -1 };

int main(int argc, char *argv[]);
```

Coding Example – String Sorting 2/5

- Print function directly iterates over strings.

```
void print(int n, char *strings[n])
{
    for (int i = 0; i < n; ++i) {
        printf("%3d. \"%s\"\n", i, strings[i]);
    }
}
```

- Allocate array of pointers to char.

```
char** copy_strings(int n, char *strings[n])
{
    char** ret = my_malloc(n * sizeof(char*));
    for (int i = 0; i < n; ++i) {
        ret[i] = copy(strings[i]);
    }
    return ret;
}
```

We take advantage that the allocation succeeds, or the program terminates with an error.

- Copy call `my_malloc` and use `strncpy`.

```
char* copy(const char *str)
{
    char *ret = NULL;
    if (str) {
        size_t len = strlen(str);
        ret = my_malloc(len + 1); // +1 for '\0'
        strncpy(ret, str, len + 1); // +1 for '\0'
    }
    return ret;
}
```

- The length of the string (by `strlen`) is without the null terminating `'\0'`.
- The copy of the string content needs to include the null terminating character as well.

Coding Example – String Sorting 3/5

- Dynamic allocation calls `malloc` and terminates the program on error.

```
void* my_malloc(size_t size)
{
    void *ret = malloc(size);
    if (!ret) {
        fprintf(stderr,
            "ERROR: Mem allocation error!\n");
        exit(EXIT_MEM);
    }
    return ret;
}
```

- The dynamically allocated array of pointers to (dynamically allocated) strings needs releasing the strings and then the array itself.

```
void release(int n, char **strings)
{
    if (strings && *strings)
        return;

    for (int i = 0; i < n; ++i) {
        if (strings[i]) {
            free(strings[i]); // free string
        }
    }
    free(strings); // free array of pointers
}
```

Coding Example – String Sorting 4/5

- Synopsis of the `qsort` function, see [man qsort](#).


```
void qsort(void *base, size_t nmemb, size_t size,
           int (*compar)(const void *, const void *)
           );
```

It passes pointers to the array elements as pointers to constant values.
- We call `qsort` on an array of pointers to strings, which are pointers to char.


```
char **strings = copy_strings(n, argv);
qsort(strings, n, sizeof(char*), string_compare);
```
- We cast the pointer to void as a pointer to pointer to char for accessing the string.


```
int string_compare(const void *p1, const void *p2)
{
    char * const *s1 = p1; // qsort passes a pointer to the array item (string)
    char * const *s2 = p2;
    return strcmp(*s1, *s2);
}
```

Coding Example – Simple Calculator 1/6

- Implement a calculator that processes an input string containing expression with interger values and operators '+', '-', '*'.

Sum, sub, and mult functions.
 - It reports error and return error values 100 if value is not an interger and 101 in the case of unsupported operator.
 - Use pointer to operation functions.
 - Process the input step-by-step, avoid reading the whole input, print partial results.
 - Handle all possible errors.
 - There must by at least single interger value.
 - If an operator is given, it must be valid and there must be the second operand.
 - If end-of-file (input), and the operator is not given, print the result.
- ```
enum status { EXIT_OK = 0, ERROR_INPUT = 100,
 ERROR_OPERATOR = 101 };
enum status printe(enum status error);
int main(int argc, char *argv[])
{
 enum status ret = EXIT_OK;
 ...
 return printe(ret);
}
enum status printe(enum status error)
{
 if (error == ERROR_INPUT) {
 fprintf(stderr, "ERROR: Input value\n");
 } else if (error == ERROR_OPERATOR) {
 fprintf(stderr, "ERROR: Operator\n");
 }
 return error;
}
```

### Coding Example – String Sorting 5/5

- Call `qsort` on array of pointers.
 

```
int main(int argc, char *argv[])
{
 int ret = EXIT_OK;
 const int n = argc;
 printf("Arguments:\n");
 print(argc, argv);

 char **strings = copy_strings(n, argv);
 qsort(
 strings, n,
 sizeof(char*), string_compare
);

 printf("\n Sorted arguments:\n");
 print(n, strings);
 release(n, strings);
 return ret;
}
```
- `clang str_sort.c && ./a.out 4 2 a z c`

| Arguments:               | Sorted arguments:        |
|--------------------------|--------------------------|
| 0. <code>"/a.out"</code> | 0. <code>"/a.out"</code> |
| 1. <code>"4"</code>      | 1. <code>"2"</code>      |
| 2. <code>"2"</code>      | 2. <code>"4"</code>      |
| 3. <code>"a"</code>      | 3. <code>"a"</code>      |
| 4. <code>"z"</code>      | 4. <code>"c"</code>      |
| 5. <code>"c"</code>      | 5. <code>"z"</code>      |
- Further tasks.
  - Implement `strings` as an array of pointers without explicit number of items, but with terminating `NULL` pointer.
  - Implement allocation for strings as a single continuous block of memory storing all the strings separated by `'\0'`.

### Coding Example – Simple Calculator 2/6

- Implement a calculator that processes an input string containing expression with interger values and operators '+', '-', '\*'.
 

*Sum, sub, and mult functions.*
  - It reports error and return error values 100 if value is not an interger and 101 in the case of unsupported operator.
  - Use pointer to operation functions.
  - Process the input step-by-step, avoid reading the whole input, print partial results.
  - Handle all possible errors.
    - There must by at least single interger value.
    - If an operator is given, it must be valid and there must be the second operand.
    - If end-of-file (input), and the operator is not given, print the result.
- ```
int sum(int a, int b); // return a + b
int sub(int a, int b); // return a - b
int mult(int a, int b); // return a * b
//define a pointer to a function
typedef int (*ptr)(int, int);
//typedef ptr is needed for the return value
ptr getop(const char *op)
{
    int (*operation)(int, int) = NULL;
    if (op[0] == '+') {
        operation = sum;
    } else if (op[0] == '-') {
        operation = sub;
    } else if (op[0] == '*') {
        operation = mult;
    }
    return operation;
}
```

Coding Example – Simple Calculator 3/6

- Implement a calculator that processes an input string containing expression with interger values and operators '+', '-', '*'.
 - Sum, sub, and mult functions.*
- It reports error and return error values 100 if value is not an interger and 101 in the case of unsupported operator.
- Use pointer to operation functions.
- Process the input step-by-step, avoid reading the whole input, print partial results.
- Handle all possible errors.
 - There must by at least single interger value.
 - If an operator is given, it must be valid and there must be the second operand.
 - If end-of-file (input), and the operator is not given, print the result.

```
int r = 1; //the first v1
char opstr[2] = {}; //store the operator
ptr op = NULL; // function pointer
int v2; //store the second operand
while (r == 1 && ret == EXIT_OK) {
    r = (op = readop(opstr, &ret)) ? 1 : 0;
    // operator is valid and second operand read
    int v3 = op(v1, v2);
    printf("%3d %s %3d = %3d\n",
        v1, opstr, v2, v3);
    v1 = v3; //shift the results
} else if (!op) { // no operator
    printf("Result: %3d\n", v1);
    r = 0;
} else if (r != 1) { //no operand
    ret = ERROR_INPUT;
}
} //end of while
```

Coding Example – Simple Calculator 5/6

- Example of program execution.

```
enum status process(enum status ret, int v1)
{
    int r = 1; //the first operand is given in v1
    char opstr[2] = {}; //store the operator
    ptr op = NULL; // function pointer to operator
    int v2; //store the second operand
    while (r == 1 && ret == EXIT_OK) {
        r = (op = readop(opstr, &ret)) ? 1 : 0; // operand read succesfully
        if (r == 1 && (r = scanf("%d", &v2)) == 1) { // while ends for r == 0 or r == -1
            int v3 = op(v1, v2);
            printf("%3d %s %3d = %3d\n", v1, opstr, v2, v3);
            v1 = v3; //shift the results
        } else if (!op) { // no operator in the input
            printf("Result: %3d\n", v1); //print the final results
            r = 0;
        } else if (r != 1) { //no operand on the input
            ret = ERROR_INPUT;
        }
    } //end of while
    return ret;
}
```

Coding Example – Simple Calculator 4/6

- Implement a calculator that processes an input string containing expression with interger values and operators '+', '-', '*'.
 - Sum, sub, and mult functions.*
- It reports error and return error values 100 if value is not an interger and 101 in the case of unsupported operator.
- Use pointer to operation functions.
- Process the input step-by-step, avoid reading the whole input, print partial results.
- Handle all possible errors.
 - There must by at least single interger value.
 - If an operator is given, it must be valid and there must be the second operand.

```
enum status ret = EXIT_OK;
int v1;
int r = scanf("%d", &v1) == 1;
ret = r == 0 ? ERROR_INPUT : ret;
if (ret == EXIT_OK) {
    ret = process(ret, v1);
}
...
ptr readop(char *opstr, enum status *error)
{
    ptr op = NULL; // pointer to a function
    int r = scanf("%1s", opstr);
    if (r == 1) {
        *error = (op = getop(opstr)) ? *error :
            ERROR_OPERATOR;
    } // else end-of-file
    return op;
}
```

Coding Example – Simple Calculator 6/6

```
1 enum status { EXIT_OK = 0, ERROR_INPUT = 100,
2   ERROR_OPERATOR = 101 };
3 ...
4 typedef int (*ptr)(int, int);
5 ptr getop(const char *op);
6 enum status printe(enum status error);
7 enum status process(enum status ret, int v1);
8
9 int main(int argc, char *argv[])
10 {
11     enum status ret = EXIT_OK;
12     int v1;
13
14     int r = scanf("%d", &v1) == 1;
15     ret = r == 1 ? ret : ERROR_INPUT;
16     if (ret == EXIT_OK) {
17         ret = process(ret, v1);
18     }
19     return printe(ret);
20 }
```

```
$ clang calc.c -o calc
$ echo "1 + 2 * 6 - 2 * 3 + 19" | ./calc
1 + 2 = 3
3 * 6 = 18
18 - 2 = 16
16 * 3 = 48
48 + 19 = 67
Result: 67
$ echo "1 + 2 *" | ./calc; echo $?
1 + 2 = 3
ERROR: Input value
100
$echo "1 + 2 a" | ./calc; echo $?
1 + 2 = 3
Result: 3
ERROR: Operator
```

Coding Example – Casting Pointer to Array 1/4

- Allocate array of the size `ROWS × COLS` and fill it with random integer values with up to two digits, and print the values are an array.
- Implement fill and print functions.
- Implement print function to print matrix of the size `rows × cols`.
- Cast the array of `int` values into `m` - a pointer of arrays of the size `cols`.
- Pass `m` to the function that prints the 2D array (matrix) with `cols` columns.

```
#define MAX_VALUE 100
#define ROWS 3
#define COLS 4
void fill(int n, int *v);
void print_values(int n, int *a);
int main(int argc, char *argv[])
{
    const int n = ROWS * COLS;
    int array[n];
    int *p = array;
    fill(n, p);
    print_values(n, p);
    return 0;
}
```

Coding Example – Casting Pointer to Array 3/4

- Allocate array of the size `ROWS × COLS` and fill it with random integer values with up to two digits, and print the values are an array.
- Implement fill and print functions.
- Implement print function to print matrix of the size `rows × cols`.
- Cast the array of `int` values into `m` - a pointer of arrays of the size `cols`.
- Pass `m` to the function that prints the 2D array (matrix) with `cols` columns.

```
void print(int rows, int cols, int m[][cols])
{
    for (int r = 0; r < rows; ++r) {
        for (int c = 0; c < cols; ++c) {
            printf("%3i", m[r][c]);
        }
        putchar('\n');
    }
}
```

- The number of columns is mandatory to determine the address of the cell `m[r][c]` in the 2D array (matrix) `m`.
- The pointer `m` can refer to arbitrary number of rows.

Coding Example – Casting Pointer to Array 2/4

- Allocate array of the size `ROWS × COLS` and fill it with random integer values with up to two digits, and print the values are an array.
- Implement fill and print functions.
- Implement print function to print matrix of the size `rows × cols`.
- Cast the array of `int` values into `m` - a pointer of arrays of the size `cols`.
- Pass `m` to the function that prints the 2D array (matrix) with `cols` columns.

```
void fill(int n, int *v)
{
    for (int i = 0; i < n; ++i) {
        v[i] = rand() % MAX_VALUE;
    }
}
void print_values(int n, int *a)
{
    for (int i = 0; i < n; ++i) {
        printf("%s%i",
            (i > 0 ? " " : ""),
            a[i]
        );
    }
    putchar('\n');
}
```

Coding Example – Casting Pointer to Array 4/4

- Allocate array of the size `ROWS × COLS` and fill it with random integer values with up to two digits, and print the values are an array.
- Implement fill and print functions.
- Implement print function to print matrix of the size `rows × cols`.
- Cast the array of `int` values into `m` - a pointer of arrays of the size `cols`.
- Pass `m` to the function that prints the 2D array (matrix) with `cols` columns.

Try to print the array as matrix with `cols` columns and `rows` columns that is as matrix with `rows×cols` and `cols×rows`, respectively.

```
#define MAX_VALUE 100
#define ROWS 3
#define COLS 4
...
void print(int rows, int cols, int m[][cols]);
int main(int argc, char *argv[])
{
    const int n = ROWS * COLS;
    int array[n];
    int *p = array;
    int (*m)[COLS] = (int(*)[COLS])p;
    printf("\nPrint as matrix %d x %d\n",
        ROWS, COLS);
    print(ROWS, COLS, m);
    return 0;
}
```

Summary of the Lecture

Topics Discussed

- Data types
 - Structure variables
 - Unions
 - Enumeration
 - Type definition
 - Bit-Fields
- Next: Input/output operations and standard library