

# Arrays, Strings, and Pointers

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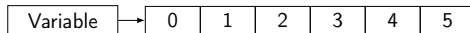
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Lecture 04

B3B36PRG – C Programming Language

## Array

- Data structure to store **several values of the same type**



- The variable name represents the address of the memory where the first element of the array is stored
- The array is declared as `type array_name[No. of elements]`
  - No. of elements is an **constant expression**
- In C99, the size of the array can be computed during run time (as a non constant expression)
  - It is called **Variable-Length Arrays**
- Array represents a continuous block of memory
- Array declaration as a local variable allocates the memory from the stack (if not defined as `static`) gcc
- **Array variable is passed to a function as a pointer**

## Variable-Length Array

- C99 allows to determined the size of the array during program runtime

*Previous versions of C requires compile-time size of the array.*

- Array size can be a function argument

```
void fce(int n)
{
    // int local_array[n] = { 1, 2 }; initialization is not allowed
    int local_array[n]; // variable length array

    printf("sizeof(local_array) = %lu\n", sizeof(local_array));
    printf("length of array = %lu\n", sizeof(local_array) / sizeof(int));
    for (int i = 0; i < n; ++i) {
        local_array[i] = i * i;
    }
}

int main(int argc, char *argv[])
{
    fce(argc);
    return 0;
}
lec04/fce_var_array.c
```

- Variable-length array cannot be initialized in the declaration

## Overview of the Lecture

- Part 1 – Arrays
  - Arrays
  - Variable-Length Array
  - Multidimensional Arrays
  - Initialization
  - Arrays and Pointers
- Part 2 – Strings
  - String Literals
  - String Variable
  - Reading Strings
  - C String Library
- Part 3 – Pointers
  - Pointers
  - const Specifier
  - Pointers to Functions
  - Dynamic Allocation

*K. N. King: chapters 8 and 12*

*K. N. King: chapters 13*

*K. N. King: chapters 11, 12, 17*

## Arrays – Example 1/2

- Example of the array declaration

```
1 #include <stdio.h>
2 int main(void)
3 {
4     int array[10];
5     for (int i = 0; i < 10; i++) {
6         array[i] = i;
7     }
8     int n = 5;
9     int array2[n * 2];
10
11     for (int i = 0; i < 10; i++) {
12         array2[i] = 3 * i - 2 * i * i;
13     }
14     printf("Size of array: %lu\n", sizeof(array));
15     for (int i = 0; i < 10; ++i) {
16         printf("array[%i]=%+2i \t array2[%i]=%6i\n", i,
17             array[i], i, array2[i]);
18     }
19     return 0;
20 }
lec04/demo-array.c
```

## Variable-Length Array (C99) – Example

```
1 #include <stdio.h>
2 int main(void)
3 {
4     int i, n;
5     printf("Enter number of integers to be read: ");
6     scanf("%d", &n);
7     int a[n]; /* variable length array */
8     for (i = 0; i < n; ++i) {
9         scanf("%d", &a[i]);
10    }
11    printf("Entered numbers in reverse order: ");
12    for (i = n - 1; i >= 0; --i) {
13        printf(" %d", a[i]);
14    }
15    printf("\n");
16    return 0;
17 }
lec04/vla.c
```

## Part I

## Arrays

## Arrays – Example 2/2

- Example of the array declaration with initialization

```
1 #include <stdio.h>
2 int main(void)
3 {
4     int array[5] = {0, 1, 2, 3, 4};
5     printf("Size of array: %lu\n", sizeof(array));
6     for (int i = 0; i < 5; ++i) {
7         printf("Item[%i] = %i\n", i, array[i]);
8     }
9     return 0;
10 }
lec04/array-init.c
```

■ Array initialization

```
double d[] = {0.1, 0.4, 0.5}; // initialization of the array
char str[] = "hallo"; // initialization with the text literal
char s[] = {'h', 'a', 'l', 'l', 'o', '\0'}; //elements
int m[3][3] = { { 1, 2, 3 }, { 4, 5, 6 }, { 7, 8, 9 } }; // 2D array
char cmd[] [10] = { "start", "stop", "pause" };
```

## Multidimensional Arrays

- Array can be declared as multidimensional, e.g., two-dimensional array for storing a matrix

```
int m[3][3] = {
    { 1, 2, 3 },
    { 4, 5, 6 },
    { 7, 8, 9 }
};
Size of m: 36 == 36
1 2 3
4 5 6
7 8 9
```

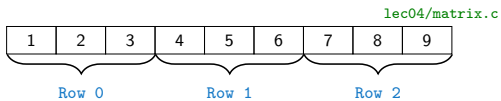
```
printf("Size of m: %lu == %lu\n",
    sizeof(m), 3*3*sizeof(int));
for (int r = 0; r < 3; ++r) {
    for (int c = 0; c < 3; ++c) {
        printf("%3i", m[r][c]);
    }
    printf("\n");
}
lec04/matrix.c
```

## Multidimensional Array and Memory Representation

- Multidimensional array is **always** a continuous block of memory  
 E.g., `int a[3][3];` represents allocated memory of the size  $9 \times \text{sizeof}(\text{int})$ , i.e., usually 36 bytes.

```
int m[3][3] = { { 1, 2, 3 }, { 4, 5, 6 }, { 7, 8, 9 } };
```

```
int *pm = (int *)m; // pointer to an allocated continuous memory block
printf("m[0][0]=%i m[1][0]=%i\n", m[0][0], m[1][0]); // 1 4
printf("pm[0]=%i pm[3]=%i\n", m[0][0], m[1][0]); // 1 4
```



- Two-dimensional array can be declared as point to a pointer, e.g.,
  - `int **a;` – pointer to pointer of the int value(s)
  - A pointer does not necessarily refer to a continuous memory
  - Therefore, when accessing to `a` as to one-dimensional array
    - `int *b = (int *)a;`
 the access to the second (and further) row cannot be guaranteed as in the above example

## Array Initialization

- An array (as any other variable) is not initialized by default
- The array can be explicitly initialized by listing the particular values in `{ }` and `}`

```
int a[5]; // elements of the array a are not initialized
/* elements of the array b are initialized
to the particular values in the given order */
int b[5] = { 1, 2, 3, 4, 5 };
```

- In C99, **designated initializers** can be used to explicitly initialize specific elements only
- Using designated initializers it is not no longer needed to preserve the order

```
int a[5] = { [3] = 1, [4] = 2 };
int b[5] = { [4] = 6, [1] = 0 };
```

## Initialization of Multidimensional Array

- Multidimensional array can be also initialized during the declaration  
 Two-dimensional array is initialized row by row.
- Using designated initializers, the other elements are set to 0

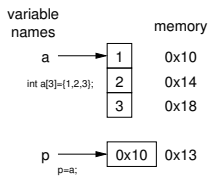
```
void print(int m[3][3])
{
    for (int r = 0; r < 3; ++r) {
        for (int c = 0; c < 3; ++c) {
            printf("%4i", m[r][c]);
        }
        printf("\n");
    }
}

int m0[3][3];
int m1[3][3] = { 1, 2, 3, 4, 5, 6, 7, 8, 9 };
int m2[3][3] = { 1, 2, 3 };
int m3[3][3] =
{ [0][0] = 1, [1][1] = 2, [2][2] = 3 };

print(m0);
print(m1);
print(m2);
print(m3);
```

## Array vs Pointer 1/2

- Variable of the type array of `int` values  
`int a[3] = {1,2,3};`  
`a` refers to the address of the 1<sup>st</sup> element of `a`
- Pointer variable `int *p = a;`  
 Pointer `p` contains the address of the 1<sup>st</sup> element
- Value `a[0]` directly represents the value at the address `0x10`.
- Value of `p` is the address `0x10`, where the value of the 1<sup>st</sup> element of the array is stored
- Assignment statement `p = a` is legal  
 A compiler sets the address of the first element to the pointer.
- Access to the 2<sup>nd</sup> element can be made by `a[1]` or `p[1]`
- Both ways provide the requested elements; however, pointer access is based on the **Pointer Arithmetic**



Further details about pointer arithmetic later in this lecture

## Array vs Pointer 2/2

- Pointer refers to the dedicated memory of some variable  
 We consider a proper usage of the pointers (without dynamic allocation for now).
- Array is a mark to a continuous block of memory space
- Both variables refer to a memory space; however, the compiler works differently with them
  - Array variable is a symbolic name of the memory space, where values of the array's elements are stored  
 Compiler (linker) substitute the name with a particular direct memory address
  - Pointer contains an address, at which the particular value is stored (indirect addressing)
- Passing array to a function, it is passed as a pointer!  
 Viz compilation of the `lec01/main_env.c` file by `clang`

<http://eli.thegreenplace.net/2009/10/21/are-pointers-and-arrays-equivalent-in-c>

## Example – Passing Array to Function 1/2

- Array is an argument of the function `fce()`
- Compiled program (by `gcc -std=c99` at `amd64`) provides
  - `sizeof(array)` returns the seize of 8 bytes (64-bit address)
  - `sizeof(local_array)` returns 12 bytes (3x4 bytes – `int`)
- Array is passed to a function as a pointer to the first element!

```
void fce(int array[])
{
    int local_array[] = {2, 4, 6};
    printf("sizeof(array) = %lu -- sizeof(local_array) = %lu\n",
        sizeof(array), sizeof(local_array));
    for (int i = 0; i < 3; ++i) {
        printf("array[%i]=%i local_array[%i]=%i\n", i,
            array[i], i, local_array[i]);
    }
}

int array[] = { 1, 2, 3 };
fce(array);
```

## Example – Passing Array to Function 2/2

- The `clang` compiler (with default settings) warns the user about using `int*` instead of `int[]`  
`fce_array.c:7:16: warning: sizeof on array function parameter will return size of 'int *' instead of 'int []' [-Wsizeof-array-argument]`  
`sizeof(array), sizeof(local_array));`
- The program can be compiled anyway; however, we cannot rely on the value of `sizeof`
- Pointer does not carry information about the size of the allocated memory!  
 For the array, the compiler may provide such a feature to warn user about wrong usage!

```
fce_array.c:3:14: note: declared here
void fce(int array[])
1 warning generated.
```

## Example – Passing Pointer to Array

- Using only a pointer to an array, the array length is not known
- Therefore, it is desirable to also pass number of elements `n` explicitly
- Using `array` in `fce()` we can access to the array declared in `main()`

```
#include <stdio.h>
void fce(int *array, int n) //array is local variable (pointer)
{ // we can modify the memory defined main()
    int local_array[] = {2, 4, 6};
    printf("sizeof(array) = %lu, n = %i -- sizeof(local_array) = %lu\n",
        sizeof(array), n, sizeof(local_array));
    for (int i = 0; i < 3 && i < n; ++i) { // ! Do the test for n
        printf("array[%i]=%i local_array[%i]=%i\n", i, array[i], i, local_array[i]);
    }
}

int main(void)
{
    int array[] = {1, 2, 3};
    fce(array, sizeof(array)/sizeof(int)); // number of elements
    return 0;
}
```

## Array as a Function Argument

- A pointer to an array, e.g., array of the `int` type  
`int (*p)[3] = m;` // pointer to array of `int`  
 Size of `p`: 8  
 Size of `*p`: 12  
`printf("Size of p: %lu\n", sizeof(p));`  
`printf("Size of *p: %lu\n", sizeof(*p)); // 3 * sizeof(int) = 12`
- Function argument cannot be declared as the type `int [] []`, e.g.,  
`int fce(int a[] [])` × not allowed  
 a compiler cannot determine the index for accessing the array elements, for `a[i][j]` the address arithmetic is used differently  
 For `int m[row][col]` the element `m[i][j]` is at the address `*m + col * i + j`
- It is possible to declare a function as follows:
  - `int g(int a[]);` which corresponds to `int g(int *a)`
  - `int fce(int a[][13]);` – the number of columns is known
  - or `int fce(int a[3][3]);`

## Part II Strings

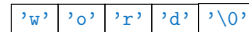
### String Literals

- It is a sequence of characters (and control characters – escape sequences) enclosed within double quotes:
  - String literals separated by white spaces are joined together, e.g.,
 

```
"String literal" "with the end of line \n"
```

 is concatenated to
 

```
"String literal with the end of line \n"
```
  - String literal is stored in array of `char` values terminated by the character `'\0'`, e.g., string literal `"word"` is stored as



The length of the array must be longer than the text itself!

### Referencing String Literal

- String literal can be used wherever `char*` pointer can be used
- The pointer `char* p = "abc";` points to the first character of the literal given literal `"abc"`
- String literal can be referenced by pointer to char; the type `char*`

```
char *sp = "ABC";
printf("Size of ps %lu\n", sizeof(sp));
printf(" ps '%s'\n", sp);
```

Size of ps 8  
ps 'ABC'

- Size of the pointer is 8 bytes (64-bit architecture)
- String has to be terminated by `'\0'`

### String Literals, Character Literals

- Pointers can be subscripted, and thus also string literals can be subscripted, e.g.,
 

```
char c = "abc"[2];
```

- A function to convert integer digit to hexadecimal character can be defined as follows

```
char digit_to_hex_char(int digit)
{
    return "0123456789ABCDEF"[digit];
}
```

- Having a pointer to a string literal, we can attempt to modify it
 

```
char *p = "123";
```

`*p = '0';` // This may cause undefined behaviour!

Notice, the program may crash or behave erratically!

### String Variables

- Any one-dimensional array of characters can be used to store a `string`
- Initialization of a string variable
 

```
char str[9] = "B3B36PRG"; // declaration with the size
```

- Compiler automatically adds the `'\0'` *There must be space for it*
- Initialization can be also by particular elements

```
char str[10] = { 'B', 'E', '5', 'B', '9', '9', 'C', 'P', 'L', '\0' };
// Do not forget null character!
```

- If the size of the array is declared larger than the actual initializing string, the rest of elements is set to `'\0'` *Consistent behaviour of the array initialization.*

- Specification of the length of the array can be omitted – it will be computed by the compiler

```
char str[] = "B3B36PRG";
```

### Example – Initialization of String Variables

- String variables can be initialized as an array of characters

```
char str[] = "123";
char s[] = { '5', '6', '7' };

printf("Size of str %lu\n", sizeof(str));
printf("Size of s %lu\n", sizeof(s));
printf("str '%s'\n", str);
printf(" s '%s'\n", s);
```

Size of str 4  
Size of s 3  
str '123'  
s '567123'

lec04/array\_str.c

- If the string is not terminated by `'\0'`, as for the `char s[]` variable, the listing continues to the first occurrence of `'\0'`

### Character Arrays vs. Character Pointers

- The string variable is a character array, while pointer can refer to string literal

```
char str1[] = "B3B36PRG"; // initialized string variable
char *str2 = "B3B36PRG"; // pointer to string literal
```

```
printf("str1 \"%s\"\n", str1);
printf("str2 \"%s\"\n", str2);
```

```
printf("size of str1 %u\n", sizeof(str1));
printf("size of str2 %u\n", sizeof(str2));
```

lec04/string\_var\_vs\_ptr.c

- The pointer just refers to the string literal you cannot modify it, it does not represent a writable memory

However, using dynamically allocated memory we can allocate desired amount of space, later in this lecture.

- Pointer to the first element of the array (string) can be used instead

```
#define STR_LEN 10 // best practice for string lengths
char str[STR_LEN + 1] // to avoid forgetting '\0'
char *p = str;
```

Notice the practice for defining size of string.

### Reading Strings 1/2

- Program arguments are passed to the program as arguments of the `main()` function

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

*Appropriate memory allocation is handled by compiler and loader*

- Reading strings during the program can be performed by `scanf()`

- Notice, using a simple control character `%s` may cause erratic behaviour, characters may be stored out of the dedicated size

```
char str0[4] = "PRG"; // +1 \0
char str1[5]; // +1 for \0
printf("String str0 = '%s'\n", str0);
printf("Enter 4 chars: ");
scanf("%s", str1);
printf("You entered string '%s'\n", str1);
printf("String str0 = '%s'\n", str0);
```

Example of the program output:

String str0 = 'PRG'  
Enter 4 chars: 1234567  
You entered string '1234567'  
String str0 = '67'

lec04/str\_scanf-bad.c

- Reading more characters than the size of the array `str1` causes overwriting the elements of `str0`

### Reading Strings 2/2

- The maximal number of characters read by the `scanf()` can be set to 4 by the control string `"%4s"`

```
char str0[4] = "PRG";
char str1[5];
scanf("%4s", str1);
printf("You entered string '%s'\n", str1);
printf("String str0 = '%s'\n", str0);
```

Example of the program output:

String str0 = 'PRG'  
Enter 4 chars: 1234567  
You entered string '1234'  
String str0 = 'PRG'

lec04/str\_scanf-limit.c

- `scanf()` skips white space before starting to read the string

- Alternative function to read strings from the `stdin` can be `gets()` or character by character using `getchar()`

- `gets()` reads all characters until it finds a new-line character E.g., `'\n'`
- `getchar()` – read characters in a loop

- `scanf()` and `gets()` automatically add `'\0'` at the end of the string

For your custom `read_line`, you have to care about it by yourself.

## Getting the Length of the String

- In C, string is an array (`char[]`) or pointer (`char*`) referring to a part of the memory where sequence of characters is stored
- String is terminated by the `'\0'` character
- Length of the string can be determined by sequential counting of the characters until the `'\0'` character

```
int getLength(char *str)
{
    int ret = 0;
    while (str && (*str++) != '\0') {
        ret++;
    }
    return ret;
}

for (int i = 0; i < argc; ++i) {
    printf("argv[%i]: getLength = %i -- strlen = %lu\n",
        i, getLength(argv[i]), strlen(argv[i]));
}

// lec04/string_length.c
```

- String functions are in standard string library `<string.h>`
- String length – `strlen()`
- The string length query has linear complexity  $O(n)$ .

## Pointers – Overview

- Pointer is a variable to store a memory address
  - Pointer is declared as an ordinary variable, where the name must be preceded by an asterisk, e.g., `int *p;`
  - Two operators are directly related to pointers
    - `&` – Address operator
      - Returns address of the variable
    - `*` – Indirection operator
      - Returns l-value corresponding to the value at the address stored in the pointer variable
  - The address can be printed using `"%p"` in `printf()`
  - Guaranteed invalid memory is defined as `NULL` or just as `0` (in C99)
  - Pointer to a value of the empty type is `void *ptr;`
- Variables are not automatically initialized in C.  
Pointers can reference to an arbitrary address

## Pointer Arithmetic, Arrays, and Subscripting

- Arrays passed as arguments to functions are pointers to the first element of the array
  - Using pointer arithmetic, we can address particular elements
  - We can use subscripting operator `[]` to access particular element
- ```
#define N 10 // The compiler uses p[i] as *(p+i)
int a[N];
int *pa = a;
int sum = 0;
for (int i = 0; i < N; ++i) {
    *(pa+i) = i; // initialization of the array a
}
int *p = &a[0]; // address of the 1st element
for (int i = 0; i < N; ++i, ++p) {
    printf("array[%i] = %i\n", i, *p);
    sum += *p; // add the value at the address of p
}

// Even though the internal representation is different – we can use pointers as one-dimensional arrays almost transparently.
```
- Special attention must be taken for memory allocation and multidimensional arrays!

## Selected Function of the Standard C Library

- The `<string.h>` library contains function for copying and comparing strings
  - `char* strcpy(char *dst, char *src);`
  - `int strcmp(const char *s1, const char *s2);`
  - Functions assume sufficient size of the allocated memory for the strings
  - There are functions with explicit maximal length of the strings
    - `char* strncpy(char *dst, char *src, size_t len);`
    - `int strncmp(const char *s1, const char *s2, size_t len);`
- Parsing a string to a number – `<stdlib.h>`
  - `atoi()`, `atof()` – parsing integers and floats
  - `long strtol(const char *nptr, char **endptr, int base);`
  - `double strtod(const char *nptr, char **restrict endptr);`
  - Functions `atoi()` and `atof()` are „obsolete“, but can be faster
  - Alternatively also `sscanf()` can be used
  - See `man strcpy, strncmp, strtol, strtod, sscanf`

## Declaring Pointer Variables

- Declaration of ordinary variables provide the way to “mark” a memory with the value to use the mark in the program
- Pointers work in similar way, but the value can be any memory address, e.g., where the value of some other variable is actually stored
 

```
int *p; // points only to integers
double *q; // points only to doubles
char *r; // points only to characters

int i; // int variable i
int *pi = &i; // pointer to the int value
// the value of pi is the address
// where the value of i is stored
*pi = 10; // will set the value of i to 10
```
- Without the allocated memory, we cannot set the value using pointer and indirection operator
 

```
int *p;
*p = 10; // Wrong, p points to somewhere in the memory
// The program can behave erratically
```

## Example – Pointer Arithmetic

```
1 int a[] = {1, 2, 3, 4};
2 int b[] = {[3] = 10, [1] = 1, [2] = 5, [0] = 0}; // initialization
3
4 // b = a; It is not possible to assign arrays
5 for (int i = 0; i < 4; ++i) {
6     printf("a[%i] = %3i b[%i] = %3i\n", i, a[i], i, b[i]);
7 }
8
9 int *p = a; // you can use *p = &a[0], but not *p = &a
10 a[2] = 99;
11
12 printf("\nPrint content of the array 'a' with pointer arithmetic\n");
13 for (int i = 0; i < 4; ++i) {
14     printf("a[%i] = %3i p+%i = %3i\n", i, a[i], i, *(p+i));
15 }

a[0] = 1 b[0] = 0
a[1] = 2 b[1] = 1
a[2] = 3 b[2] = 5
a[3] = 4 b[3] = 10

Print content of the array 'a' using pointer arithmetic
a[0] = 1 p+0 = 1
a[1] = 2 p+1 = 2
a[2] = 99 p+2 = 99
a[3] = 4 p+3 = 4

// lec04/array_pointer.c
```

## Part III

## Pointers

## Pointer Arithmetic

- Arithmetic operations `+` and `-` are defined for pointers and integers
  - `pointer = pointer of the same type +/- and integer number (int)`
  - Alternatively shorter syntax can be used, e.g., `pointer += 1` and unary operators, e.g., `pointer++`
- Arithmetic operations are useful if the pointer refers to memory block where several values of the same type are stored, e.g.,
  - array (i.e., passed to a function)
  - dynamically allocated memory
- Adding an int value and the pointer, the results is the address to the next element, e.g.,
 

```
int a[10];
int *p = a;

int i = *(p+2); // refers to address of the 3rd element

// According to the type of the pointer, the address is appropriately increased (or decreased)
// (p+2) is equivalent to the address computed as
// address of p + 2*sizeof(int)
```

## Pointer Arithmetic – Subtracting

- Subtracting an integer from a pointer
 

```
int a[10] = { 0, 1, 2, 3, 4, 5, 6, 7, 8, 9 };
int *p = &a[8]; // p points to the 8th element (starting from 0)
int *q = p - 3; // q points to the 5th element (starting from 0)
p -= 6; // p points to the 2nd element (starting from 0)
```
  - Subtracting one pointer from another, e.g.,
 

```
int i
int *q = &a[5];
int *p = &a[1];

i = p - q; // i is 4
i = q - p; // i is -4
```
  - The result is a the distance between the pointers (no. of elements)
  - Subtracting one pointer from another is **undefined** unless both point to elements of the **same array**
- Performing arithmetic on a pointer that does not point to an array element causes undefined behaviour.

## Pointers as Arguments

- Pointers can be used to pass the memory addressed of same variable to a function
- Then, using the pointer, the memory can be filled by a new value, e.g., like in the `scanf()` function
- Consider an example of swapping values of two variables
 

```

1 void swap(int x, int y)    1 void swap(int *x, int *y)
2 {                          2 {
3     int z;                3     int z;
4     z = x;                4     z = *x;
5     x = y;                5     *x = *y;
6     y = z;                6     *y = z;
7 }                          7 }
8 int a, b;                8 int a, b;
9 swap(a, b);              9 swap(&a, &b);
            
```
- The left variant does not propagate the local changes to the calling function

## Pointers as Return Values

- A function may also return a pointer value
  - Such a return value can be a pointer to an external variable
  - It can also be a local variable declared `static`
  - Never return a pointer to an automatic local variable
- ```

1 int* fnc(void)
2 {
3     int i; // i is a local (automatic) variable
4           // allocated on the stack
5     ... // it is valid only within the function
6     return &i; // passing pointer to the i is legal,
7              // but the address will not be valid
8              // address of the automatically
9              // destroyed local variable a
10             // after ending the function
11 }
            
```
- Returning pointer to dynamically allocated memory is OK

## Specifier const

- Using the keyword `const` a variable is declared as constant
 

*Compiler check assignment to such a variable*
- The constant variable can be declared, e.g.,
 

```
const float pi = 3.14159265;
```
- In contrast to the symbolic constant
 

```
#define PI 3.14159265
```
- Constant variables has type, and thus compiler can perform type check

*Reminder*

## Pointers to Constant Variables and Constant Pointers

- The keyword `const` can be written before the type name or before the variable name
- There are 3 options how to define a pointer with `const`
  - `const int *ptr;` – pointer to a const variable
    - Pointer cannot be used to change value of the variable
  - `int *const ptr;` – constant pointer
    - The pointer can be set during initialization, but it cannot be set to another address after that
  - `const int *const ptr;` – constant pointer to a constant variable
    - Combines two cases above
- Further variants of (a) and (c) are
  - `const int *` can be written as `int const *`
  - `const int * const` can also be written as `int const * const`
  - `const` can on the left or on the right side from the type name
- Further complex declarations can be, e.g., `int ** const ptr;`

*A constant pointer to point to the int*

`lec04/const_pointers.c`

## Example – Pointer to Constant Variable

- It is not allowed to change variable using pointer to constant variable
- ```

1 int v = 10;
2 int v2 = 20;
3
4 const int *ptr = &v;
5 printf("ptr: %d\n", *ptr);
6
7 *ptr = 11; /* THIS IS NOT ALLOWED! */
8
9 v = 11; /* We can modify the original variable */
10 printf("ptr: %d\n", *ptr);
11
12 ptr = &v2; /* We can assign new address to ptr */
13 printf("ptr: %d\n", *ptr);
            
```
- `lec04/const_pointers.c`

## Example – Const Pointer

- Constant pointer cannot be changed once it is initialized
  - Declaration `int *const ptr;` can be read from the right to the left
    - `ptr` – variable (name) that is
    - `*const` – constant pointer
    - `int` – to a variable/value of the `int` type
- ```

1 int v = 10;
2 int v2 = 20;
3 int *const ptr = &v;
4 printf("v: %d ptr: %d\n", v, *ptr);
5
6 *ptr = 11; /* We can modify addressed value */
7 printf("v: %d\n", v);
8
9 ptr = &v2; /* THIS IS NOT ALLOWED! */
            
```
- `lec04/const_pointers.c`

## Example – Constant Pointer to Constant Variable

- Value of the constant pointer to a constant variable cannot be change and the pointer cannot be used to change value of the addressed variable
  - Declaration `const int *const ptr;` can be read from the right to the left
    - `ptr` – variable (name) that is
    - `*const` – const pointer
    - `const int` – to a variable of the `const int` type
- ```

1 int v = 10;
2 int v2 = 20;
3 const int *const ptr = &v;
4
5 printf("v: %d ptr: %d\n", v, *ptr);
6
7 ptr = &v2; /* THIS IS NOT ALLOWED! */
8 *ptr = 11; /* THIS IS NOT ALLOWED! */
            
```
- `lec04/const_pointers.c`

## Pointers to Functions

- Implementation of a function is stored in a memory and similarly as for a variable, we can refer a memory location with the function implementation
- Pointer to function allows to dynamically call a particular function according to the value of the pointer
- Function is identified (except the name) by its arguments and return value. Therefore, these are also a part of the declaration of the pointer to the function
- Function (a function call) is the function name and `()`, i.e.,
 

```
return_type function_name(function arguments);
```
- Pointer to a function is declared as
 

```
return_type (*pointer)(function arguments);
```
- It can be used to specify a particular implementation, e.g., for sorting custom data using the `qsort()` algorithm provided by the standard library `<stdlib.h>`

## Example – Pointer to Function 1/2

- Indirection operator `*` is used similarly as for variables
 

```
double do_nothing(int v); /* function prototype */
```

```
double (*function_p)(int v); /* pointer to function */
```

```
function_p = do_nothing; /* assign the pointer */
```

```
(*function_p)(10); /* call the function */
```
- Brackets `(*function_p)` “help us” to read the pointer definition
 

*We can imagine that the name of the function is enclosed by the brackets. Definition of the pointer to the function is similar to the function prototype.*
- Calling a function using pointer to the function is similar to an ordinary function call. Instead of the function name, we use the variable of the pointer to the function type.

## Example – Pointer to Function 2/2

- In the case of a function that returns a pointer, we use it similarly

```
double* compute(int v);
```

```
double* (*function_p)(int v);
          ^^^^^^^^^^^^^^^^^ substitute a function name
```

```
function_p = compute;
```

- Example of the pointer to function usage – `lec04/pointer_fnc.c`
- Pointers to functions allows to implement a dynamic link of the function call determined during the program run time

*In object oriented programming, the dynamic link is a crucial feature to implement polymorphism.*

## Dynamic Storage Allocation

- A dynamic memory allocation of the memory block with the `size` can be performed by calling `void* malloc(size);`

from the `<stdlib.h>`

- The size of the allocated memory (from the `heap` memory class) is stored in the memory manager
- The size is not a part of the pointer
- Return value is of the `void*` type – cast is required
- The programmer is fully responsible for the allocated memory

- Example of the memory allocation for 10 values of the `int` type

```
1 int *int_array;
2 int_array = (int*)malloc(10 * sizeof(int));
```

- The usage is similar to array (pointer arithmetic and subscripting)

- The allocated memory must be explicitly released

```
void* free(pointer);
```

- By calling `free()` the memory manager released the memory associated to the pointer. The value of the pointer is not changed!

The pointer has the previous address, which is no longer valid!

## Example – Dynamic Allocation 1/3

- Allocation may fail – we can test the return value of the `malloc()`
- E.g., our custom function for memory allocation check the return value and terminate the program in a case of allocation fail

- Since we want to fill the value of the pointer to the newly allocated memory, we pass pointer to the pointer

```
1 void* allocate_memory(int size, void **ptr)
2 {
3     // use **ptr to store value of newly allocated
4     // memory in the pointer ptr (i.e., the address the
5     // pointer ptr is pointed).
6
7
8     // call library function malloc to allocate memory
9     *ptr = malloc(size);
10
11    if (*ptr == NULL) {
12        fprintf(stderr, "Error: allocation fail");
13        exit(-1); /* exit program if allocation fail */
14    }
15    return *ptr;
16 }
```

lec04/malloc\_demo.c

## Example – Dynamic Allocation 2/3

- For filling the memory (dynamically allocated array), just the address of this array is sufficient

```
1 void fill_array(int* array, int size)
2 {
3     for (int i = 0; i < size; ++i) {
4         *(array++) = random();
5     }
6 }
```

- After memory is released by calling `free()`, the pointer still points to the previous address. Therefore, we can explicitly set it to guaranteed invalid address (`NULL` or `0`) in our custom function.

Passing pointer to a pointer is required, otherwise we cannot null the original pointer.

```
1 void deallocate_memory(void **ptr)
2 {
3     if (ptr != NULL && *ptr != NULL) {
4         free(*ptr);
5         *ptr = NULL;
6     }
7 }
```

lec04/malloc\_demo.c

`realloc()`

- The behaviour of the `realloc()` function is further specified
  - It does not initialize the bytes added to the block
  - If it cannot enlarge the memory, it returns null pointer and the old memory block is untouched
  - If it is called with null pointer as the argument, it behaves as `malloc()`
  - If it is called with `0` as the second argument, it frees the memory block

## Example – Dynamic Allocation 3/3

- Example of usage

```
1 int main(int argc, char *argv[])
2 {
3     int *int_array;
4     const int size = 4;
5
6     allocate_memory(sizeof(int) * size, (void**)&int_array);
7     fill_array(int_array, size);
8     int *cur = int_array;
9     for (int i = 0; i < size; ++i, cur++) {
10        printf("Array[%d] = %d\n", i, *cur);
11    }
12    deallocate_memory((void**)&int_array);
13    return 0;
14 }
```

lec04/malloc\_demo.c

## Standard Function for Dynamic Allocation

- `malloc()` – allocates a block of memory, but does not initialize it
- `calloc()` – allocates a block of memory and clears it
- `realloc()` – resizes a previously allocated block of memory
  - It tries to enlarge the previous block
  - If it is not possible, a new (larger) block is allocated.
  - The previous block is copied into the new one
  - The previous block is deleted
  - The return values points to the enlarged block

See [man malloc](#), [man calloc](#), [man realloc](#)

## Restricted Pointers

- In C99, the keyword `restrict` can be used in the pointer declaration

```
int * restrict p;
```

- The pointer declared using `restrict` is called `restricted pointer`
- The main intent of the restricted pointers is that
  - If `p` points to an object that is later modified
  - Then that object is not accessed in any way other than through `p`
- It is used in several standard functions, e.g., such as `memcpy()` and `memmove()` from `<string.h>`

```
void *memcpy(void * restrict dst, const void * restrict src, size_t len);
```

```
void *memmove(void *dst, const void *src, size_t len);
```

- In `memcpy()`, it indicates `src` and `dst` should not overlap, but it does not guarantee that
- It provides useful documentation, but its main intention is to provide information to the compiler to produce more efficient code (e.g., similarly to `register` keyword)

## Summary of the Lecture

## Topics Discussed

- Arrays
  - Variable-Length Arrays
  - Arrays and Pointers
- Strings
- Pointers
  - Pointer Arithmetic
  - Dynamic Storage Allocation
  
- Next: Data types: struct, union, enum, and bit fields