Arrays, Strings, and Pointers

Jan Faigl

Department of Computer Science
Faculty of Electrical Engineering
Czech Technical University in Prague

Lecture 04

PRG(A) – C Programming Language

Overview of the Lecture

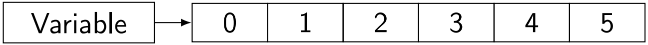
Part I

Arrays

Outline

Array

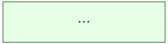
- Data structure to store **several values of the same type**



- 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 Array** (**VLA**)
- Array represents a continuous block of memory
- Array declaration as a local variable allocates the memory from the stack (if not defined as `static`)
- Array variable is passed to a function as a pointer (the address of the allocated memory)

Array – Visualization of the Allocation and Assignment of Values

- Variable of the array type refers to the beginning of the memory where individual array elements are allocated. An array type variable refers to the beginning of memory where individual array elements are allocated.
- Access to the array elements is realized by the index operator `[]` that computes the address of the particular element (i.e., `index * sizeof(type)`).



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int i;
int a[2];

i = 1;

a[1] = 5;
a[0] = 7;
```

In this example, the variable allocation starts from the address 0×100 *just for visualization and better understandability. Automatic variables on the stack are usually allocated from the upper address to the lower ones.*

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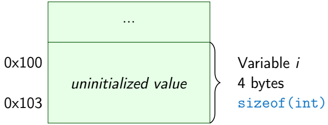

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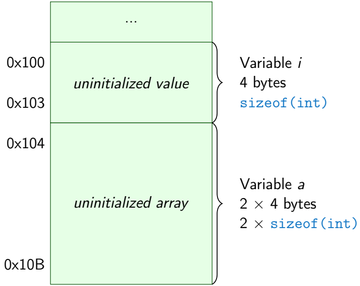

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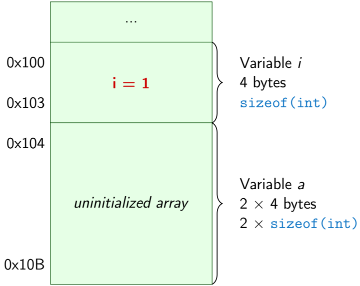

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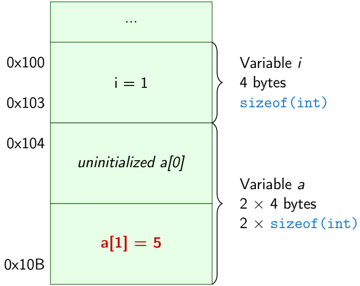

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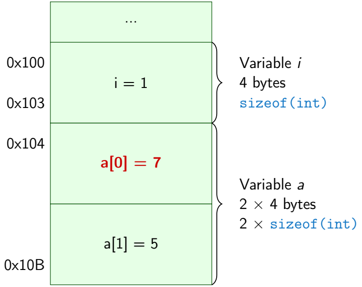

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Arrays – Example 1/2

- Example of definition of the array variable

```
#include <stdio.h>

int main(void)
{
   int array[10];

   for (int i = 0; i < 10; i++) {
      array[i] = i;
   }

   int n = 5;
   int array2[n * 2];

   for (int i = 0; i < 10; i++) {
      array2[i] = 3 * i - 2 * i * i;
   }

   printf("Size of array: %lu\n", sizeof(array));
   for (int i = 0; i < 10; ++i) {
      printf("array[%i]=%+2i \t array2[%i]=%6i\n", i, array[i], i,
     array2[i]);
   }
   return 0;
}
```

```
Size of array: 40
array[0]=+0     array2[0]=    0
array[1]=+1     array2[1]=    1
array[2]=+2     array2[2]=   -2
array[3]=+3     array2[3]=   -9
array[4]=+4     array2[4]=  -20
array[5]=+5     array2[5]=  -35
array[6]=+6     array2[6]=  -54
array[7]=+7     array2[7]=  -77
array[8]=+8     array2[8]= -104
array[9]=+9     array2[9]= -135
```

lec04/demo-array.c

Arrays – Example 2/2

- Example of definition of the array variable with initialization

```
#include <stdio.h>

int main(void)
{
   int array[5] = {0, 1, 2, 3, 4};

   printf("Size of array: %lu\n", sizeof(array));
   for (int i = 0; i < 5; ++i) {
      printf("Item[%i] = %i\n", i, array[i]);
   }
   return 0;
}
```

```
Size of array: 20
Item[0] = 0
Item[1] = 1
Item[2] = 2
Item[3] = 3
Item[4] = 4
```

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" };
```

Arrays – Example 2/2

- Example of definition of the array variable with initialization

```c
#include <stdio.h>

int main(void)
{
   int array[5] = {0, 1, 2, 3, 4};

   printf("Size of array: %lu\n", sizeof(array));
   for (int i = 0; i < 5; ++i) {
      printf("Item[%i] = %i\n", i, array[i]);
   }
   return 0;
}
```

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Size of array: 20
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lec04/array-init.c

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Outline

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

Variable-Length Array (C99) – Example

```c
#include <stdio.h>

int main(void)
{
   int i, n;
   printf("Enter number of integers to be read: ");
   if (scanf("%d", &n) != 1 && n > 0) {
      return 100;
   }

   int a[n]; /* variable length array */
   for (i = 0; i < n; ++i) {
      if (scanf("%d", &a[i]) != 1) {
         return 101;
      }
   }
   printf("Entered numbers in reverse order: ");
   for (i = n - 1; i >= 0; --i) {
      printf(" %d", a[i]);
   }
   printf("\n");
   return 0;
}
```

lec04/vla.c

Outline

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 }
};

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");
}
```

```
Size of m: 36 == 36
1  2  3
4  5  6
7  8  9
```

lec04/matrix.c

Multidimensional Array and Memory Representation

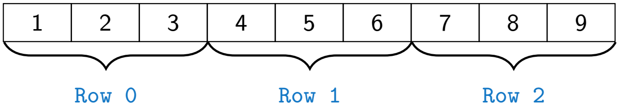
- Multidimensional array is **always** a continuous block of memory

E.g., `int a[3][3];` *represents allocated memory of the size* `9*sizeof(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
```

lec04/matrix.c



- Two-dimensional array can be declared as pointer to a pointer, e.g.,
  - `int **a;` – pointer to pointer of the int value(s)
  - Such 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

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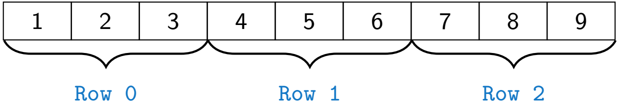
printf("m[0][0]=%i m[1][0]=%i\n", m[0][0], m[1][0]); // 1 4
printf("pm[0]=%i pm[3]=%i\n", m[0][0], m[1][0]); // 1 4
```

lec04/matrix.c



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`int *b = (int *)a;`

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Outline

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 also be 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);
```

```
m0 - not initialized
-584032767743694227
   0   1   0
740314624   0   0

m1 - init by rows
   1   2   3
   4   5   6
   7   8   9

m2 - partial init
   1   2   3
   0   0   0
   0   0   0

m3 - indexed init
   1   0   0
   0   2   0
   0   0   3
```

lec04/array_inits.c

Outline

Array vs Pointer 1/2

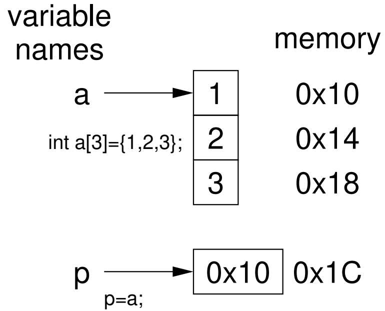
- Variable of the type array of `int` values `int a[3] = {1,2,3};`

  `a` refers to the address of the 1st element of `a`

- Pointer variable `int *p = a;`

  Pointer `p` contains the address of the 1st element

- Value `a[0]` directly represents the value at the address `0x10`.



- Value of `p` is the address `0x10`, where the value of the 1st 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 2nd 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 (name) to a continuous block of memory space

```
int *p; //pointer (address) where a value of int type is stored
int a[10]; //a continuous block of memory for 10 int values

sizeof(p); //no.of bytes for storing the address (8 for 64-bit)
sizeof(a); //size of the allocated array is 10*sizeof(int)
```

- Both variables refer to memory space, but 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**)

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

- Passing array to a function, it is passed as a pointer!

  Viz compilation of the `lec01/main_env.c` *file by* `clang`

Example – Passing Array to Function 1/2

- Array is an argument of the function `fce()`

```c
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);
```

lec04/fce_array.c

- 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 (3×4 bytes– `int`)
- **Array is passed to a function as a pointer to the first element!**

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

- 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!

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

```c
#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;
}
```

lec04/fce_pointer.c

- Using `array` in `fce()` we can access to the array declared in `main()`

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

printf("Size of p: %lu\n", sizeof(p));
printf("Size of *p: %lu\n", sizeof(*p)); // 3 * sizeof(int) = 12
```

```
Size of p: 8
Size of *p: 12
```

- Function argument cannot be declared as the type `[][]`, 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)*sizeof(int))`

- 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]);`
  - or in C99 as `int fce(int n, int m, int a[n][m]);` or
  - `int fce(int n, int m, int a[][m]);`

Part II

Strings

Outline

String Literals

String Variable

Reading Strings

C String Library

String Literals

- It is a sequence of characters (and control characters – escape sequences) enclosed within double quotes:

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

  - 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

'w'	'o'	'r'	'd'	'\0'

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!

Outline

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[9] = { 'B', '3', 'B', '3', '6', 'P', 'R', 'G', '\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 behavior 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 represents 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.

Outline

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 case erratic behaviour, characters may be stored out of the dedicated size

```c
char str0[4] = "PRG"; // +1 \0
char str1[5]; // +1 for \0
printf("String str0 = '%s'\n", str0);
printf("Enter 4 chars: ");
if (scanf("%s", str1) == 1) {
   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];
...
if (scanf("%4s", str1) == 1) {
   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 `readl_line`, you have to care about it by yourself.

Outline

String Literals

String Variable

Reading Strings

C String Library

Getting the Length of the String

- In C, string is an array (`char[]`) or pointer (`char*`) refering 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;
}
```

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

```
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

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`

Part III

Pointers

Outline

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**

    &variable

    - Returns address of the variable
  - *** – Indirection operator**

    ***pointer_variable**

    - 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

Definition of Pointer Variables

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

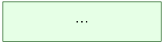
```
int *p;  // points only to integers
double *q; // points only to doubles
char *r; // points only to characters

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
```

Pointers – Visualization of the Allocation and Value Assignment

- Pointers are variables that stores addresses of other variables




```
char c;

c = 10;

char *pc;

pc = &c;

int i = 17;
int *pi = &i;

*pi = 15;
*pc = 2;

int **ppi = &pi;
```

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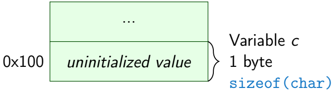

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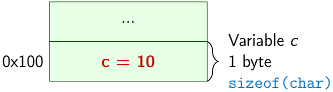

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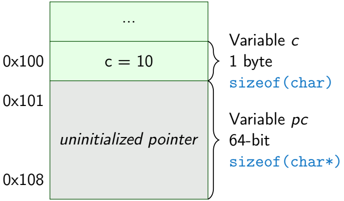

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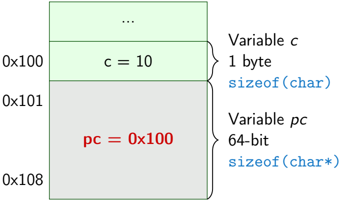

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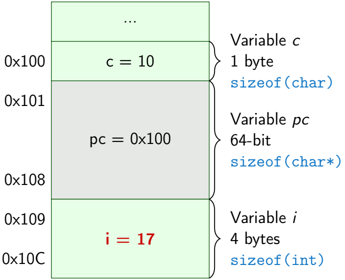

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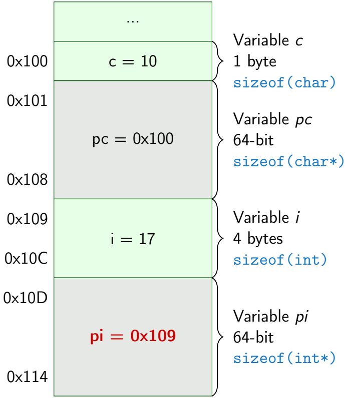

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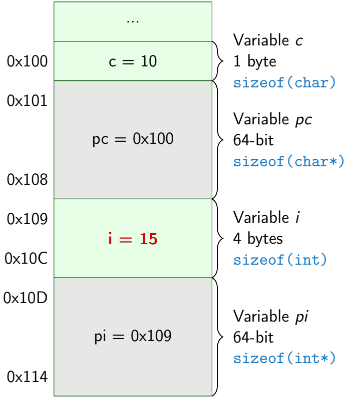

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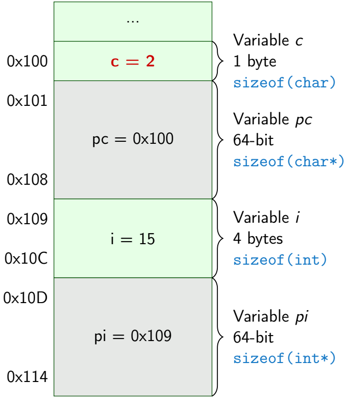

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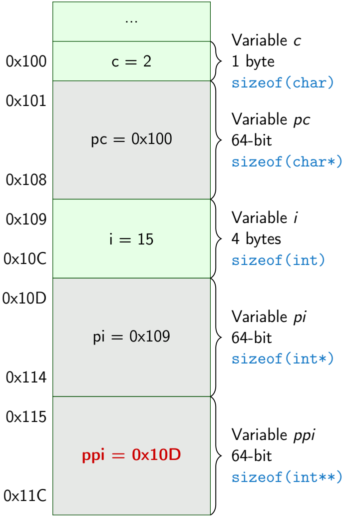

Pointer Arithmetic

- 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, 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

The compiler uses `p[i]` as `*(p+i)`

```c
#define N 10

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, pa[i]);
   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!

Example – Pointer Arithmetic

```c
int a[] = {1, 2, 3, 4};
int b[] = {[3] = 10, [1] = 1, [2] = 5, [0] = 0}; //initialization

// b = a; It is not possible to assign arrays
for (int i = 0; i < 4; ++i) {
   printf("a[%i] =%3i   b[%i] =%3i\n", i, a[i], i, b[i]);
}

int *p = a; //you can use *p = &a[0], but not *p = &a
a[2] = 99;

printf("\nPrint content of the array 'a' with pointer arithmetic\n");
for (int i = 0; i < 4; ++i) {
   printf("a[%i] =%3i   p+%i =%3i\n", i, a[i], i, *(p+i));
}
```

```
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

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

```c
void swap(int x, int y)
{
    int z;
    z = x;
    x = y;
    y = z;
}
int a, b;
swap(a, b);
```

```c
void swap(int *x, int *y)
{
    int z;
    z = *x;
    *x = *y;
    *y = z;
}
int a, b;
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

```
int* fnc(void)
{
   int i;      // i is a local (automatic) variable
               // allocated on the stack
   ...         // it is valid only within the function
   return &i; // passsing pointer to the i is legal,
               // but the address will not be valid
               // address of the automatically
               // destroyed local variable a
               // after ending the function
}
```

- Returning pointer to dynamically allocated memory is OK

Outline

Pointers

`const` Specifier

Pointers to Functions

Dynamic Allocation

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 have type, and thus compiler can perform type check

Reminder

Pointers to Constant Variables and Constant Pointers

- The keyword **const** can be writable before the type name or before the variable name
- There are 3 options how to define a pointer with `const`
  (a) `const int *ptr;` – pointer to a const variable
    - Pointer cannot be used to change value of the variable
  (b) `int *const ptr;` – constant pointer
    - The pointer can be set during initialization, but it cannot be set to another address after that
  (c) `const int *const ptr;` – constant pointer to a constant variable
    - Combines two cases above

lec04/const_pointers.c

- 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

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- Further complex declarations can be, e.g., `int ** const ptr;`

  A constant pointer to point to the int

Example – Pointer to Constant Variable

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

```
int v = 10;
int v2 = 20;

const int *ptr = &v;
printf("*ptr: %d\n", *ptr);

*ptr = 11; /* THIS IS NOT ALLOWED! */

v = 11;  /* We can modify the original variable */
printf("*ptr: %d\n", *ptr);

ptr = &v2; /* We can assign new address to ptr */
printf("*ptr: %d\n", *ptr);
```

lec04/const_pointers.c

Example – Const Pointer

- Constant pointer cannot be changed once it is initialized
- Definition `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

```c
int v = 10;
int v2 = 20;
int *const ptr = &v;
printf("v: %d *ptr: %d\n", v, *ptr);

*ptr = 11; /* We can modify addressed value */
printf("v: %d\n", v);

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 changed, and the pointer cannot be used to change value of the addressed variable
- Definition `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

```c
int v = 10;
int v2 = 20;
const int *const ptr = &v;

printf("v: %d *ptr: %d\n", v, *ptr);

ptr = &v2; /* THIS IS NOT ALLOWED! */
*ptr = 11; /* THIS IS NOT ALLOWED! */
```

lec04/const_pointers.c

Outline

Pointers

const Specifier

Pointers to Functions

Dynamic Allocation

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.

Outline

Dynamic Storage Allocation

- A dynamic allocation of the memory block with the `size` can be performed by calling

  `void* malloc(size);` from the <stdlib.h>

  - The **memory manager** handle the allocated memory (from the **heap** memory class)
  - **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

```
int *int_array;
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 release the memory at the addressed stored in the pointer value

  The pointer value is not changed! It has the previous address that is no longer valid!

Example – Dynamic Allocation 1/3

- If allocation may fail, `malloc()` returns `NULL` and we should test the return value

  Unless, we intentionally take the risk of erratic behaviour of the program

- The most straightforward handle of the allocation failure is to report the error and terminate the program execution *We can implement our custom function for dynamic allocation*

```c
void* mem_alloc(size_t size)
{
    void *ptr = malloc(size);  //call malloc to allocate memory

    if (ptr == NULL) {
        fprintf(stderr, "Error: allocation fail"); // report error
        exit(-1); // and exit program on allocation failure
    }
    return ptr;
}
```

lec04/malloc_demo.c

Example – Dynamic Allocation 2/3

- Filling the dynamically allocated array, just the memory address is sufficient

```c
void fill_array(int* array, int size)
{
    for (int i = 0; i < size; ++i) {
        *(array++) = random() % 10; // pointer arithmetic
        //array[i] = random() % 10; // array notation using subscript operator
    }
}
```

- After memory is released by `free()`, the pointer stil contains the same address.
- We can explicitly set the pointer to the guaranteed invalid address (`NULL` or `0`) in our custom function *Passing pointer to a pointer is required, otherwise we cannot null the original pointer.*

```c
void mem_release(void **ptr)
{
    // 1st test ptr is valid pointer, and also *ptr is a valid
    if (ptr != NULL && *ptr != NULL) {
        free(*ptr);
        *ptr = NULL;
    }
}
```

lec04/malloc_demo.c

Example – Dynamic Allocation 3/3

- Example of usage

```c
int main(int argc, char *argv[])
{
   int *int_array;
   const int size = 4;

   int_array = mem_alloc(sizeof(int) * size);
   fill_array(int_array, size);
   int *cur = int_array;
   for (int i = 0; i < size; ++i, cur++) {
      printf("Array[%d] = %d\n", i, *cur);
   }
   mem_release((void**)&int_array); // we do not need type cast to void**, it is just to highlight we are passing pointer-to-pointer
   return 0;
}
```

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 it 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`

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

```
int size = 10;
int *array = mem_alloc(size * sizeof(int)); // allocate 10 integers
... // do some code such as reading integers from a file

int *t = realloc(array, (size + 10)* sizeof(int)); // try to enlarge
if (t) {
   array = t; //realloc handle possible allocation of new memory block, and thus
              //it is safe to overwrite array by t
   size += 10; //now, we are sure array can hold 10 more int values
} else { // realloc fail, report and exit
   fprintf(stderr, "ERROR: realloc fail\n");
}
```

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)

Part IV

Part 4 – Assignment HW 03

HW 03 / HW 3 – Assignment

Topic: **Caesar Cipher**

(B3B36PRG) Mandatory: **2 points**; Optional: none; Bonus : **2 points**

(BAB36PRGA) Mandatory: **3 points**; Optional: none; Bonus : **5 points**

- **Motivation**: Experience a solution of the optimization task
- **Goal**: Familiarize with the dynamic allocation
- **Assignment**: https://cw.fel.cvut.cz/wiki/courses/b3b36prg/hw/hw03
  https://cw.fel.cvut.cz/wiki/courses/bab36prga/hw/hw3
  - Read two text messages and print decode message to the output
  - Both messages (the encoded and the poorly received) have the same length
  - Determine the best match of the decoded and received messages based on the shift value of the Caesar cipher https://en.wikipedia.org/wiki/Caesar_cipher
  - Optimization of the Hamming distance https://en.wikipedia.org/wiki/Hamming_distance
  - Bonus assignment – an extension for missing characters in the received message
    https://en.wikipedia.org/wiki/Levenshtein_distance
- (B3B36PRG) Deadline: 19.03.2022, 23:59 AoE (bonus 20.5.2022, 23:59 CEST)
- (BAB36PRGA) Deadline: 02.04.2022, 23:59 AoE (bonus 20.5.2022, 23:59 CEST)

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

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