Exercises in System Level Programming (SLP) – Summer Term 2025

Exercise 9

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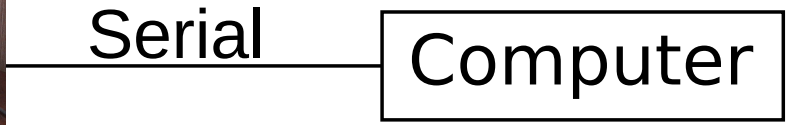
Linux

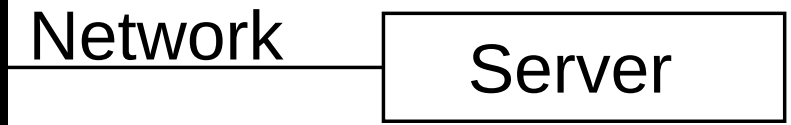
Terminal - History (simplified)

- When computers were bigger than today:



Televideo 925 (Public Domain: Wtshymanski @Wikipedia)

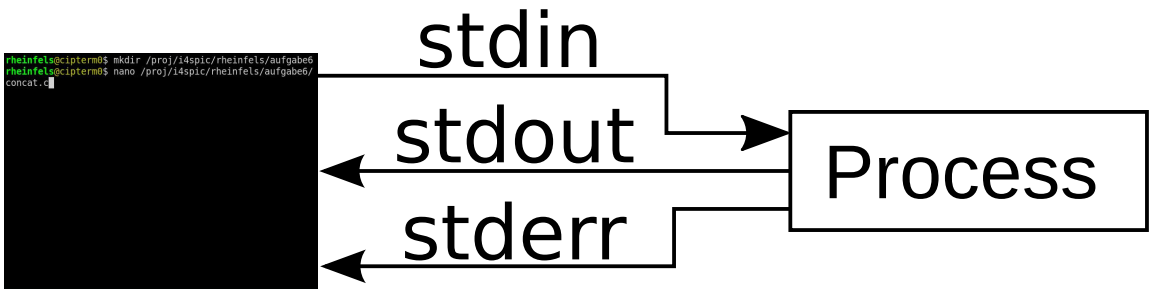
- When the internet was really slow:



- Colors, position jumps, etc. are indicated by special character sequences

Terminal - Functionality

- Three standard streams for in- and output



`stdin` Input

`stdout` Output

`stderr` Error message

- Standard behaviour
  - Inputs are received from the keyboard
  - Outputs & error messages appear on the screen

Terminal - Redirect Standard Streams

- Write `stdout` into a file

```
01 find . > directories.txt
```

- Use `stdout` as `stdin` for other programs

```
01 cat directories.txt | grep tmp | wc -l
```

- Advantage of `stderr`
  - ⇒ Error messages are still displayed in the terminal
- Overview
  - `>` Write standard output `stdout` into file
  - `>>` Append standard output `stdout` to an existing file
  - `2>` Write error messages `stderr` into a file
  - `<` Read `stdin` from a file
  - `|` Use output of one command as input for another command

Shell - Important Commands

- Change directory with `cd`

```
01 # absolute path to the directory
02 cd /proj/i4spic/<login>/aufgabeX/
03
04 # relative path to the directory
05 cd aufgabe5/
06
07 cd ~          # user directory ($HOME)
08 cd ..         # parent directory
```

- List directory contents with `ls`

```
01 ls           # show files in current directory
02 ls -A        # also show hidden files
03 ls -lh       # show more meta data
```

Shell - Important Commands

- Copy file or directory with `cp`

```
01 # Copy file ampel.c from $HOME to the project directory
02 cp ~/ampel.c /proj/i4spic/xy42abcd/aufgabe5/ampel.c
03
04 # Copy directory aufgabe5/ from $HOME to the project directory
05 cp -r ~/aufgabe5/ /proj/i4spic/xy42abcd/
```

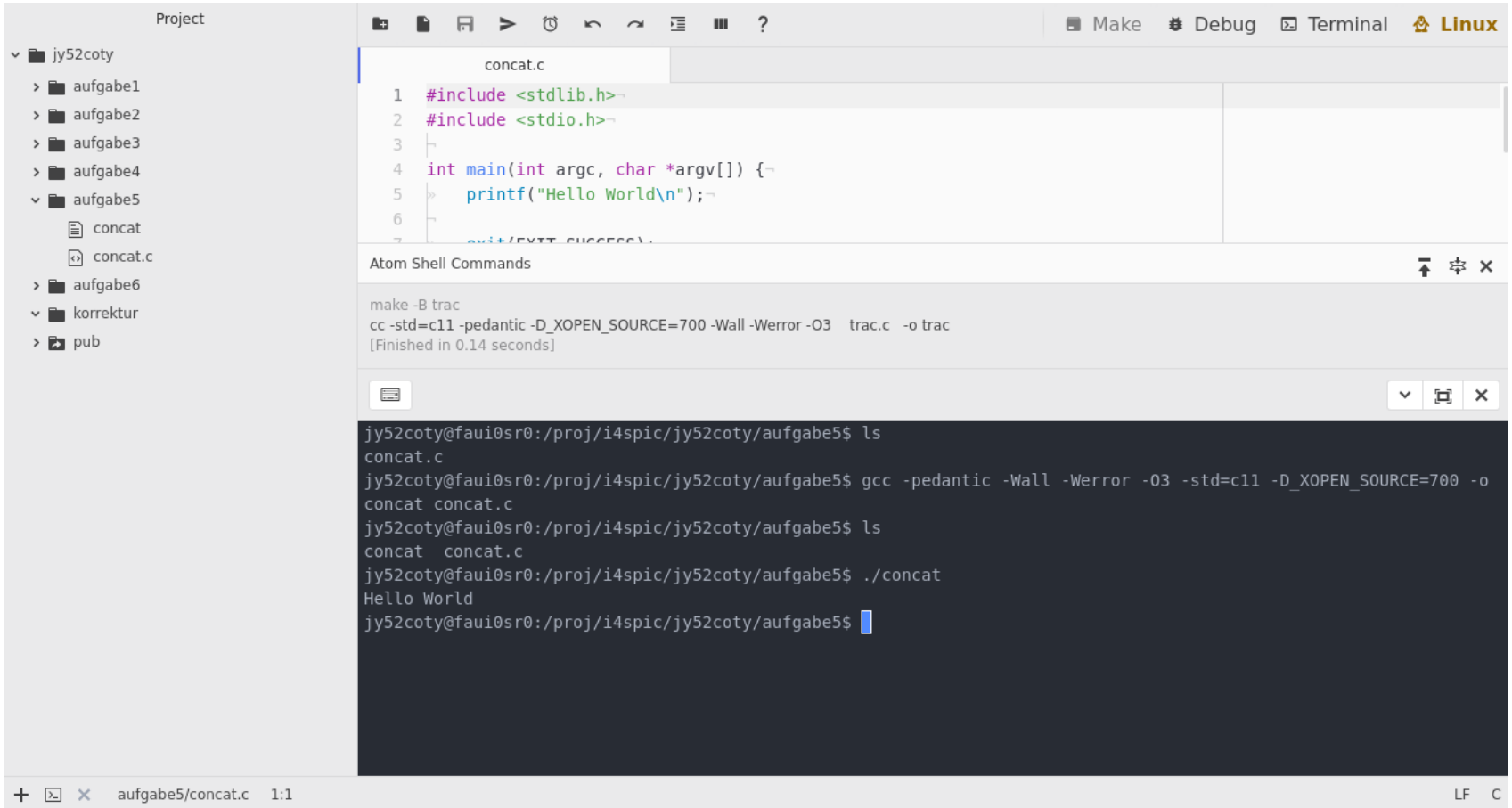
- (Permanently) Delete file or directory with `rm` (remove)

```
01 # Remove file test1.c inside the current directory
02 rm test1.c
03
04 # Remove subdirectory aufgabe1/ and all contained files
05 rm -r aufgabe1
```

Shell - Terminate Programs

- With a signal: `CTRL-C` (can be ignored by the program)
- Using another console: `killall concat` terminates all programs with the name “concat”
- Using the same console:
  - `CTRL-Z` stops the currently running process
  - `killall concat` then terminates all programs with the name `concat`
    - ⇒ Programs of other users shall never be terminated
  - `fg` continues the stopped process
- If nothing else works: `killall -9 concat`

SPiC IDE (Linux)



- **Terminal**: opens a terminal and starts a shell
  - efficient interaction with the system
  - optionally full screen
- **Debug**: starts the debug mode
- **Make**: see next week

Compiling & Executing

- Compile program with GCC

```
01 gcc -pedantic -Wall -Werror -O3 -std=c11 -D_XOPEN_SOURCE=700 -o
     ↪ concat concat.c
```

`gcc`	calls the compiler (GNU Compiler Collection)
`-pedantic`	activates warnings (different to the C standard)
`-Wall`	activates warnings (typical errors, e. g.: `if(x = 7)`)
`-Werror`	makes warnings into errors
`-O3`	activates optimizations (level 3)
`-std=c11`	sets the used standard to C11
`-D_XOPEN_SOURCE=700`	adds certain POSIX extensions
`-o concat`	specifies the name of the output file (standard: `a.out`)
`concat.c …`	file(s) that have to be compiled

- Execute the program with `./concat`
- All submitted assignments will be tested with these flags

Compilation & Execution

- Compile the program with GCC
  (including debug symbols and without optimizations)

```
01 gcc -pedantic -Wall -Werror -O0 -std=c11 -D_XOPEN_SOURCE=700 -g -
     ↪ o concat concat.c
```

-O0 prevents the compiler from optimizing the program
-g produces debug symbols in the executable file

⇒ enables the debugger to create references to the source file

- Hint: Arrow key ⇑ iterates over previous commands

⇒ GCC command only has to be typed once

Valgrind

- Information about:
  - Memory leaks (malloc(3)/free(3))
  - Invalid memory accesses
- Ideal for debugging segmentation faults (SIGSEGV)
- Calls:
  - `valgrind ./concat`
  - `valgrind --leak-check=full --show-reachable=yes --track-origins=yes ./concat`
- The output is way more useful, if the analyzed binary was built with debug symbols

Manual Pages

- Interface to the system reference manuals
- Divided into multiple sections
  1. Executable programs or shell commands
  2. System calls
  3. Library calls
  5. File formats and conventions (special data structures, etc.)
  7. Miscellaneous (e. g. terminal drivers, IP, …)
- man pages are usually cited with the appropriate section: `printf(3)`

```
01 # man [section] term
02 man 3 printf
```

- Search for sections: `man -f term`
- Search man pages for a keyword: `man -k keyword`

Linux `libc`-API

- Trimmed (nicer) version of the man pages
- Only provide an overview and not a full specification
- Can be called from inside the SPiC-IDE (`Hilfe`-button when inside the Linux mode)
- Can be found on the website

  `https://sys.cs.fau.de/lehre/ss25/slp/exercises/linux-libc-doc`

- Our overview does not replace the man pages
- In the exam: Printed man pages!

Error Handling

Error Causes

- Errors can happen due to different reasons
  - System resources are completely exhausted
    ⇒ `malloc(3)` fails
  - Invalid user inputs (e. g. non existent files)
    ⇒ `fopen(3)` fails
  - Temporary errors (e. g. unavailable server)
    ⇒ `connect(2)` fails

Error Handling

- Good software:
  - Detects the error
  - Handles error appropriately
  - Prints out a meaningful error message afterwards

- Can a program continue after an error occurred?

  Example 1: Determining the hostname of an IP address to add both values to a log file

  ⇒ Add IP address to the log, program can continue

  Example 2: Opening a file, that has to be copied, fails

  ⇒ Error handling: Copying impossible, terminate program
  ⇒ Or continue the copying process with the next file
  ⇒ Decision has to be made by the software developer

Errors in Library Functions

- Errors often occur in `libc` functions
  - Can (usually) be detected by the return value (man page)
  - Checking for errors is essential

- Error causes are usually written to `errno` (global variable)
  - Can be included with `errno.h`
  - Error codes are `> 0`
  - Error codes for all possible errors (refer to `errno(3)`)

- Only evaluate `errno` if an error was signaled
  - Functions are allowed to modify `errno` arbitrarily
    - ⇒ `errno` can also be modified if no error occurred

Errors in Library Functions

- Print error codes:
  - `perror(3)`: Output on `stderr`
  - `strerror(3)`: Convert into error message (string)

Example:

```
01 char *mem = malloc(...);
02
03 // Error case
04 if(NULL == mem) {
05   fprintf(stderr, "%s:%d: malloc failed with reason: %s\n",
06       __FILE__, __LINE__-5, strerror(errno));
07   //alternativ: perror("malloc");
08
09   exit(EXIT_FAILURE);
10 }
```

Extended Error Handling

- Indicating an error via the return value is not always possible
- Return value EOF: Error case **or** `End-Of-File`

```
01 int c;
02 while ((c=getchar()) != EOF) { ... }
03 /* EOF or error? */
```

- Detection for I/O streams: `ferror(3)` bzw. `feof(3)`

```
01 int c;
02 while ((c=getchar()) != EOF) { ... }
03 /* EOF or error? */
04 if(ferror(stdin)) {
05   /* Error */
06   ...
07 }
```

The Function main()

The main() Function

- Function `main()`: Entry point of a C program
- Signature depends on its usage:
  - AVR: Only one program
    - ⇒ `void main(void)`
  - Linux: Multiple programs
    - ⇒ `int main(void)`
    - ⇒ `int main(int argc, char *argv[])`
- Parameters and return value used for communication

Command Line Parameters

- Command line arguments: Parameters for the program
- `main()` receives them as function parameters:
  - `argc`: Number of arguments
  - `argv`: Array of pointers to the arguments

  $\Rightarrow$ Array of strings
- First argument: program name

Command Line Parameters – Example

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

int main(int argc, char *argv[]) {
  for(int i = 0; i < argc; ++i) {
    printf("argv[%d]: %s\n", i, argv[i]);
  }

  return EXIT_SUCCESS;
}
```

```
$ ./commandline
argv[0]: ./commandline
$ ./commandline Hello world
argv[0]: ./commandline
argv[1]: Hello
argv[2]: world
```

Return Status

- Return status: Information for the caller
- Usual codes:
  - `EXIT_SUCCESS`: Execution succeeded
  - `EXIT_FAILURE`: Error occurred

Return Status – Example

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

int main(int argc, char *argv[]) {
  if(argc == 1) {
    fprintf(stderr, "No parameters given!\n");
    return EXIT_FAILURE;
  }

  // [...]

  return EXIT_SUCCESS;
}
```

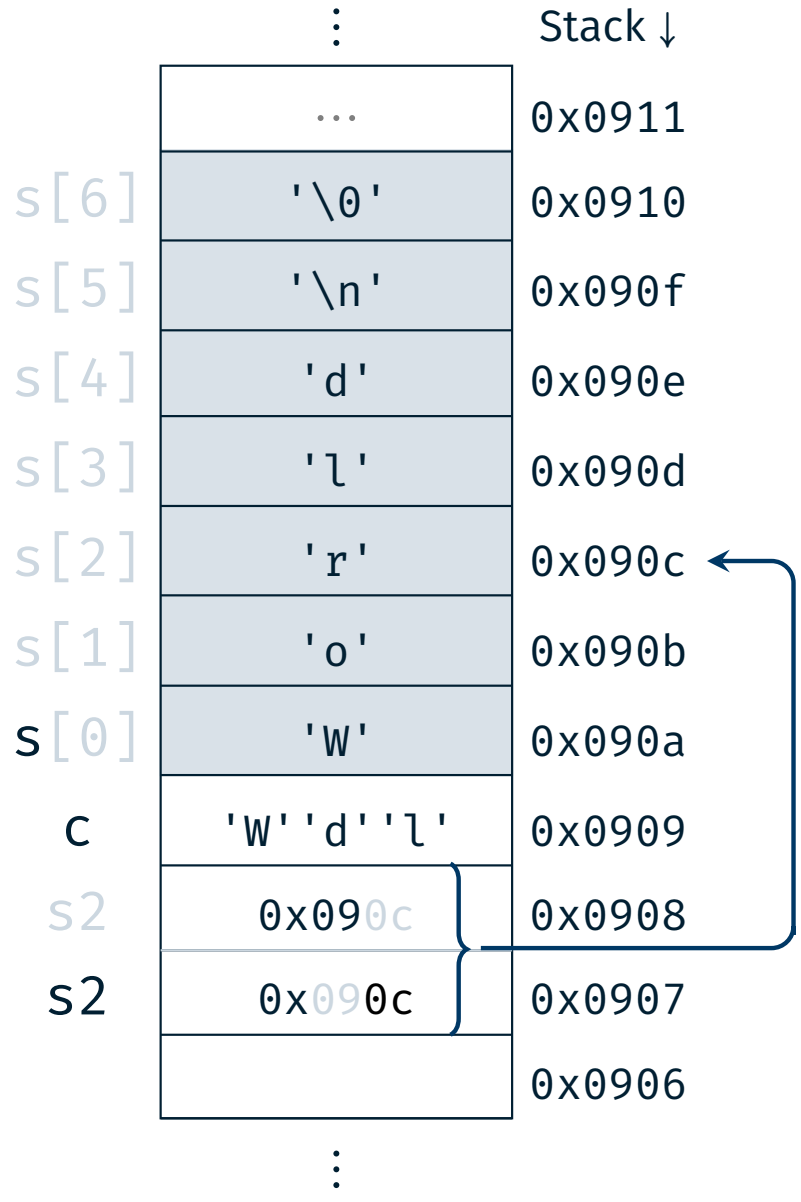
```
$ ./exitcode
No parameters given!
$ echo $?
1
$ ./exitcode Hello world
$ echo $?
0
```

C Strings in Detail

In Depth: Strings

- `char`: Single character (e. g. `'a'`)
- String: Array of `char`s (e. g. `"Hello"`)
- C: Last char of a string: `'\0'`
  - ⇒ Memory requirement: strlen(s) + 1

```
01 char s[] = "World\n";
02 char c = s[0];
03 c = s[4];
04 char *s2 = s + 2;
05 c = s2[1];
```



String Functions

- `size_t strlen(const char *s)`
  - Determine the length of a string `s` (without trailing NULL character)
- `char *strcpy(char *dest, const char *src)`
  - Copy a string `src` into a buffer `dest` (including NULL character)
  - Caution: Buffer overflow (⇒ `strncpy(3)`)
- `char *strcat(char *dest, const char *src)`
  - Concatenate a string `src` after an existing string inside the buffer `dest` (including NULL character)
  - Caution: Buffer overflow (⇒ `strncat(3)`)
- Documentation: `strlen(3)`, `strcpy(3)`, `strcat(3)`

String Functions – Exmaple

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

int main(void) {
  const char *hello = "Hello";
  const char *spic = "SPiC";

  char altered_string[11];  // Space for "Hello SPiC"

  strcpy(altered_string, hello);  // "Hello"
  strcat(altered_string, " ");    // "Hello "
  strcat(altered_string, spic);   // "Hello SPiC"
  strlen(altered_string);         // -> 10

  return EXIT_SUCCESS;
}
```

Assignment: concat

Assignment: concat

- Concatenate the passed command line arguments into a single string and output of this string
- Procedure:
  - determine the required length
  - allocate the buffer dynamically
  - fill the buffer step by step
  - output the string on stdout
  - free the dynamically allocated buffer

- Re-implement the string library functions (from `string.h`):
- Important: identical behaviour (even in case of an error)

```
01  size_t str_len(const char *s)
02  char  *str_cpy(char *dest, const char *src)
03  char  *str_cat(char *dest, const char *src)
```

Dynamic Management of Memory

- `malloc(3)` allocates memory on the heap
  - reserves a minimum of `size` bytes of memory
  - returns a pointer to the start of the allocated memory
  - can potentially return an error
- `free(3)` frees the allocated memory again

```
01 char* s = (char *) malloc(...);
02 if(s == NULL) {
03   perror("malloc");
04   exit(EXIT_FAILURE);
05 }
06
07 // [...]
08
09 free(s);
```

Hands-on: Buffer Overflow

Hands-on: Buffer Overflow

- Program secured with a password

```
01 # Usage: ./print_exam <password>
02 ./print_exam spic
03 Correct Password
04 Printing exam...
```

- Unchecked user inputs ⇒ buffer overflow

```
01 long check_password(const char *password) {
02   char buff[8];
03   long pass = 0;
04
05   strcpy(buff, password);
06   if(strcmp(buff, "spic") == 0) {
07     pass = 1;
08   }
09   return pass;
10 }
```

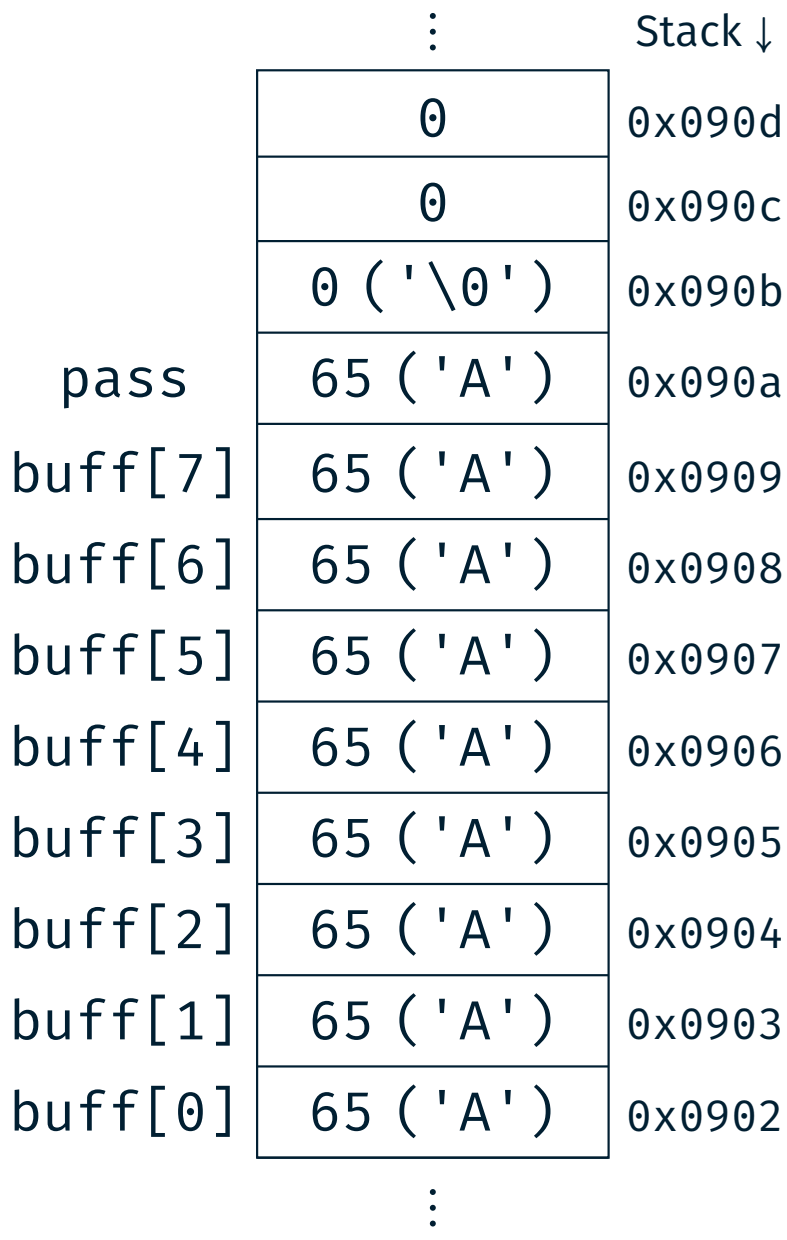
Hands-on: Buffer Overflow

```
01 long check_password(const char *password) {
02   char buff[8];
03   long pass = 0;
04
05   strcpy(buff, password);
06   if(strcmp(buff, "spic") == 0) {
07     pass = 1;
08   }
09   return pass;
10 }
```

- Possible solutions
  - Check the user input
  - Allocate the buffer dynamically
  - Use of secure library functions ⇒ z.B. `strncpy(3)`

Buffer Overflow

```
01 long pass = 0;
02 char buff[8];
03 strcpy(buff, password);
04
05 if(strcmp(buff, "spic")) {
06   printf("Wrong Pass.\n");
07 } else {
08   printf("Correct Pass.\n");
09   pass = 1;
10 }
11
12 return pass;
13
```



Hands-on: Linux, GCC & Valgrind

Screencast: `https://www.video.uni-erlangen.de/clip/id/18667`

Hands-on: Linux, GCC & Valgrind

- *Only online!*
- Goals:
  - Use SPiC IDE for Linux
  - Compile program from the command line
  - Practice th use of valgrind