

Exercises in System Level Programming (SLP) – Summer Term 2026

Exercise 11

Arne Vogel

Maxim Ritter von Onciul

Eva Dengler

Lehrstuhl für Informatik 4
Friedrich-Alexander-Universität Erlangen-Nürnberg



Lehrstuhl für Informatik 4
Systemsoftware



Friedrich-Alexander-Universität
Faculty of Engineering

Presentation Assignment 6

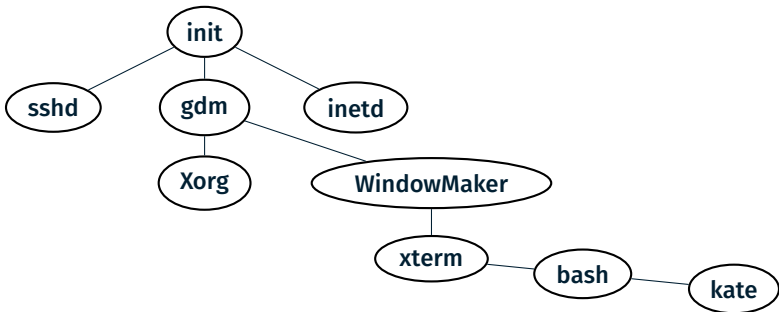
Processes



- Processes are an execution environment for programs
 - Have a process ID (PID, positive integer)
 - Execute a program
- Each process is assigned resources they need
 - Memory
 - Address space
 - Opened files
 - ...
- Visualization of processes: `ps(1)`, `ps tree(1)`, `htop(1)`



- Between all processes, a parent-child relation exists
 - The first process is started by the system kernel (e.g. *init*)
 - A tree of processes is created ~> process hierarchy



- **kate** is a child of **bash**, **bash** is a child of **xterm**



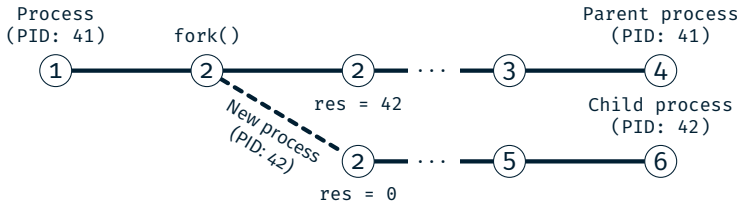
```
01 pid_t fork(void);
```

- Creates a new child process
- Exact copy of the parent process:
 - Data and stack segment (copy)
 - Text segment (shared use)
 - File descriptors (open files)
 - **Exception:** Process ID
- Parent and child process both return from the call to `fork(2)`
- Difference is the returned value of `fork(2)`
 - Parent: PID of the child
 - Child: 0
 - Error: -1

Create Child Processes (2)



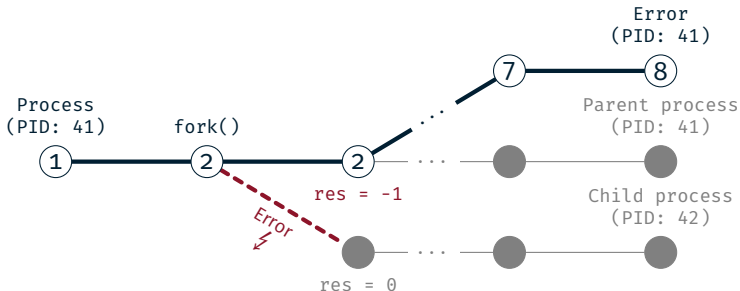
```
01 printf("Process (PID: %d)", getpid());
02 pid_t res = fork();
03 if(res > 0) {
04     printf("Parent process (PID: %d)", getpid());
05 } else if(res == 0) {
06     printf("Child process (PID: %d)", getpid());
07 } else {
08     printf("Error (PID: %d)", getpid());
09     // [...] Error handling
10 }
```



Create Child Processes (2)



```
01 printf("Process (PID: %d)", getpid());
02 pid_t res = fork(); // Has an error ⚡
03 if(res > 0) {
04     printf("Parent process (PID: %d)", getpid());
05 } else if(res == 0) {
06     printf("Child process (PID: %d)", getpid());
07 } else {
08     printf("Error (PID: %d)", getpid());
09     // [...] Error handling
10 }
```





```
01 pid_t wait(int *status);
```

- `wait(2)` is blocking until an arbitrary child process terminates
- Returns
 - > `0` Process ID of the child process
 - `-1` Error
- `status` contains the reason for the termination:
 - `WIFEXITED(status)` `exit(3)` or return from `main()`
 - `WIFSIGNALED(status)` Process terminated by signal
 - `WEXITSTATUS(status)` Exit status
 - `WTERMSIG(status)` Signal number
- Further macros: see documentation `wait(2)`



```
01 pid_t waitpid(pid_t pid, int *status, int options);
```

- `waitpid(2)` is blocking until a certain child process terminates
 - `pid > 0` Child process with process ID `pid`
 - `pid = -1` Arbitrary child process
 - ...
- Options:
 - WNOHANG** Returns immediately if no child terminated (not blocking)
 - ...
- Returns
 - `> 0` Process ID of the child process
 - `0` No process has terminated (when using `WNOHANG`)
 - `-1` Error – details see `waitpid(2)`



```
01 void exit(int status);
```

- Terminates the currently running process with the given exit status
- Frees all resources that were used by the process
 - Memory
 - File descriptors
 - Process management data
 - ...
- Process enters a so called *zombie* state
 - Makes it possible for the parent to react to its termination
 - Zombie processes still use some resources

⇒ Parent has to keep up with its zombies
- If the parent terminates before its child:
⇒ Passed on to the `init` process and cleared by it



```
01 int execl(const char *path, const char *arg0, ..., NULL);
02 int execv(const char *path, char *const argv[]);
```

- Replaces the currently running program within the process
 - **Is replaced:** text-, data- and stack segment
 - **Remains:** file descriptors, working directory, ...
- Calling parameters for `exec(3)`
 - Path of the new program
 - Arguments for the `main()` function
- Static number of arguments: `execl(3)`
- Dynamic number of arguments: `execv(3)`
- Last argument: NULL pointer
- `exec(3)` only returns in case of an error



- Finding executable programs using the PATH variable

```
01 $> cp dat dat-copy
02 $> ls
03 dat dat-copy                # no file 'cp'
04
05 $> echo $PATH                # PATH contains
06 /usr/local/bin:/usr/bin:/bin #   - /usr/local/bin/
07                               #   - /usr/bin/
08                               #   - /bin/
09 $> which cp
10 /bin/cp                      # 'cp' is in /bin/
11
12 $> ls /bin/                   # /bin/ contains many
13 [...]                         # more common programs
14 rm
15 cp
16 ls
17 [...]
```



```
01 int execlp(const char *file, const char *arg0, ..., NULL);
02 int execvp(const char *file, char *const argv[]);
```

- Like `execl(3)/execv(3)` and searching in `PATH`

Examples:

```
01 // absolute path and static list of arguments
02 execl("/bin/cp", "/bin/cp", "x.txt", "y.txt", NULL);
03
04 // Searching in PATH and static list of arguments
05 execlp("cp", "cp", "x.txt", "y.txt", NULL);
06
07 // Searching in PATH and dynamic list of arguments
08 char *args[] = { "cp", "dat", ..., "copy/", NULL };
09 execvp(args[0], args);
```

Example: fork(2), exec(3) and wait(2)

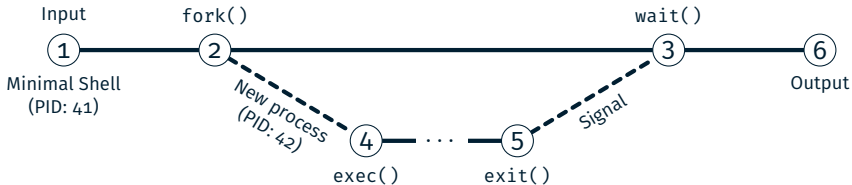


```
01 static void die(const char *reason) {
02     perror(reason); exit(EXIT_FAILURE);
03 }
04
05 // [...] Process runs
06 pid_t res = fork();
07 if(res > 0) { // Parent process
08     int status;
09     pid_t term_pid = wait(&status);
10     if(term_pid == -1) { // Error in wait()
11         die("wait");
12     } else {
13         printf("Child %d terminated\n", term_pid);
14     }
15 } else if(res == 0) { // Child process
16     execlp("cp", "cp", "dat", "dat-copy", NULL);
17     // Error in execlp(3)
18     die("execlp");
19 } else { // Error -- No child process created
20     die("fork");
21 }
```

Minimal Shell



1. Wait for the user input
2. Create a new process
3. Parent: wait for termination of the child
4. Child: start program
5. Child: program terminates
6. Parent: Output the exit status of the child





```
01 char *fgets(char *s, int size, FILE *stream);
```

- fgets(3) reads one line from the given channel
- '\n' is stored as well
- Maximum size-1 characters + final '\0'
- In case of an error or EOF, NULL is returned

⇒ Distinction using ferror(3) or feof(3)

```
01 char buf[23];
02 while (fgets(buf, 23, stdin) != NULL) {
03     // buf contains line
04 }
05
06 if(ferror(stdin)) { // Error
07     [...]
08 }
```

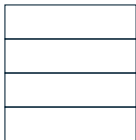


```
01 char *strtok(char *str, const char *delim);
```

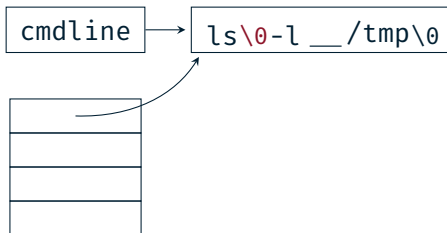
- strtok(3) breaks the string into tokens
- Tokens are separated by delimiters
- Each call returns a pointer to the next token
- delim: string that contains all delimiters (e.g. " \t\n")
- str:
 - **first call** pointer to the string
 - **all following calls** NULL
- Consecutive delimiters are skipped
- Delimiters after a token are replaced by '\0'
- At the end of the string: strtok(3) returns NULL



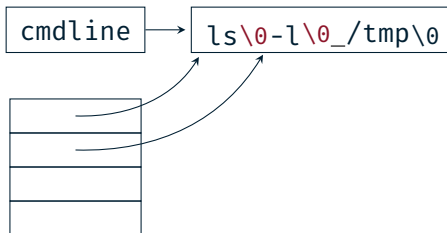
cmdline → ls -l __/tmp\0



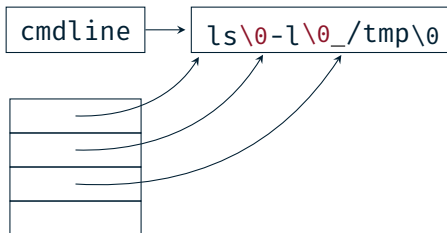
```
01 char cmdline[] = "ls -l /tmp";
02 char *a[4];
03 a[0] = strtok(cmdline, " ");
04 a[1] = strtok(NULL, " ");
05 a[2] = strtok(NULL, " ");
06 a[3] = strtok(NULL, " ");
```



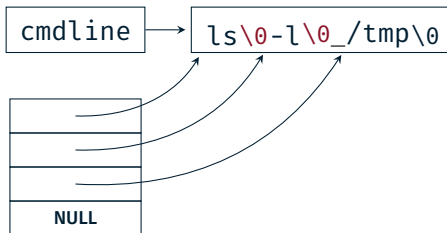
```
01 char cmdline[] = "ls -l /tmp";
02 char *a[4];
03 a[0] = strtok(cmdline, " ");
04 a[1] = strtok(NULL, " ");
05 a[2] = strtok(NULL, " ");
06 a[3] = strtok(NULL, " ");
```



```
01 char cmdline[] = "ls -l /tmp";
02 char *a[4];
03 a[0] = strtok(cmdline, " ");
04 a[1] = strtok(NULL, " ");
05 a[2] = strtok(NULL, " ");
06 a[3] = strtok(NULL, " ");
```



```
01 char cmdline[] = "ls -l /tmp";  
02 char *a[4];  
03 a[0] = strtok(cmdline, " ");  
04 a[1] = strtok(NULL, " ");  
05 a[2] = strtok(NULL, " ");  
06 a[3] = strtok(NULL, " ");
```



```
01 char cmdline[] = "ls -l /tmp";
02 char *a[4];
03 a[0] = strtok(cmdline, " ");
04 a[1] = strtok(NULL, " ");
05 a[2] = strtok(NULL, " ");
06 a[3] = strtok(NULL, " ");
```

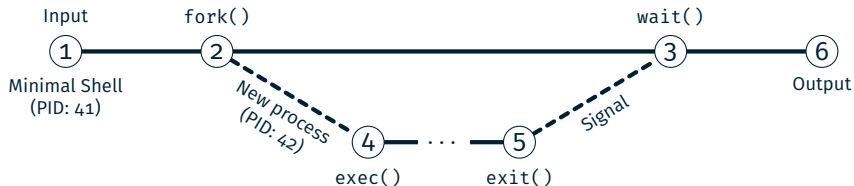
Assignment: mish



- Simple shell (**mini shell**) for executing commands
- Typical procedure:
 - Output a prompt
 - Wait for user input
 - Tokenize the input
 - Command name
 - Arguments
 - Create a new process
 - **parent**: waits for termination of the child
 - **child**: executes the command
 - Output the exit status



- Repeat: basic cycle of a minimal shell
 - Waiting for a input from the user
 - Creating a new process
 - Parent: Waiting for the termination of the child
 - Child: Starting the program
 - Child: Program terminates
 - Parent: Outputting the exit status of the child





Examples:

```
01 # Regular termination with Exit (Exitstatus = 0)
02 mish> ls -l
03 ...
04 Exit status [2110] = 0
05
06 # Invalid/empty input
07 mish>
08 mish> foo
09 foo: No such file or directory
10 Exit status [7342] = 1
11
12 # Termination by signal (here SIGINT = 2)
13 mish> sleep 10
14 Signal [1302] = 2
```



- Prompt does not contain a '\n'
 - Standard library buffers stdout line by line
- ⇒ The line buffer has to be flushed with fflush(3)



- Test programs: /proj/i4spic/<idm>/pub/aufgabe8/
- spic-wait (without parameter)

```
01 mish> /proj/i4spic/[...]/spic-wait
02 [...]
03 - send 'SIGPIPE' to this process
04 Command: kill -PIPE 3372
05 Expected Output: Signal [3372] = 13
06
07 [...]
08
09 Signal [3372] = 13
10 mish>
```

```
01
02
03
04
05
06
07
08 $> kill -PIPE 3372
09
10
```

- spic-wait (with parameter)

```
01 mish> /proj/i4spic/<idm>/pub/aufgabe8/spic-wait 15
02 Sending signal 15 (Terminated) to myself (PID: 4239)
03 Signal [4239] = 15
04 mish>
```



- Test programs: /proj/i4spic/<idm>/pub/aufgabe8/
- spic-wait (without paramter)

```
01 mish> /proj/i4spic/[...]/spic-wait
02 [...]
03 - send 'SIGPIPE' to this process
04   Command: kill -PIPE 3372
05   Expected Output: Signal [3372] = 13
06
07 [...]
08
09 Signal [3372] = 13
10 mish>
```

```
01
02
03
04
05
06
07
08 $> kill -PIPE 3372
09
10
```

- spic-wait (with parameter)

```
01 mish> /proj/i4spic/<idm>/pub/aufgabe8/spic-wait 15
02 Sending signal 15 (Terminated) to myself (PID: 4239)
03 Signal [4239] = 15
04 mish>
```



- Test programs: /proj/i4spic/<idm>/pub/aufgabe8/
- spic-wait (without paramter)

```
01 mish> /proj/i4spic/[...]/spic-wait
02 [...]
03 - send 'SIGPIPE' to this process
04   Command: kill -PIPE 3372
05   Expected Output: Signal [3372] = 13
06
07 [...]
08
09 Signal [3372] = 13
10 mish>
```

```
01
02
03
04
05
06
07
08 $> kill -PIPE 3372
09
10
```

- spic-wait (with parameter)

```
01 mish> /proj/i4spic/<idm>/pub/aufgabe8/spic-wait 15
02 Sending signal 15 (Terminated) to myself (PID: 4239)
03 Signal [4239] = 15
04 mish>
```



■ spic-exit

```
01 mish> /proj/i4spic/<idm>/pub/aufgabe8/spic-exit 12
02 Exiting with status 12
03 Exit status [6272] = 12
04 mish>
```



```
01 // DESCRIPTION:
02 //   printStatus() examines the termination of a process and
03 //   prints the source of the exit (signal or exit) and the
04 //   exit code or signal number, respectively.
05 //
06 // PARAMETER:
07 //   pid:   PID of the exited child process
08 //   status: Status bits as retrieved from waitpid(2)
09 //
10 static void printStatus(pid_t pid, int status) {
11     // TODO IMPLEMENT
12 }
```

- `/proj/i4spic/<idm>/pub/aufgabe8/mish_vorlage.c`
- Template does **not** contain:
 - all functions, variables, description of functionality, etc.
- Template does not replace own thoughts on the program structure
- During development, it could be useful to omit the flag `Werror` in the Makefile

Hands-on: run

Screencast: <https://www.video.uni-erlangen.de/clip/id/19832>



```
01 ./run <programm> <param0> [params...]
```

- run receives a program name and a list of parameters
 - Creates a new process for each parameter
 - Executes the given program with the passed parameter
 - Waits for the termination and continues with the handling of the next parameter
- Example call: `./run echo Car House Cat`
- Generated program calls:
 - `echo Car`
 - `echo House`
 - `echo Cat`
- (System-) Calls: `fork(2), exec(3), wait(2)`
- Keep in mind: error handling