Exercise 1: Files, Shared Memory, Semaphores

Operating Systems UE 2022W

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Outline

- Files
- Exchanging data via same memory
  - Memory Mappings
  - POSIX Shared Memory (SHM)
- Explicit synchronization of multiple processes
  - POSIX Semaphore
  - Synchronization tasks
- Guidelines for the programming assignments
- Exercise 1

Unix File I/O

File Descriptor

- Non-negative integer
- Reference to an entry (= index) in the table of open files (file descriptor table) of the process
- Standard I/O file descriptors: already present at program start

File desc.	Description	POSIX Name	stdio Stream
0	Standard input	STDIN_FILENO	stdin
1	Standard output	STDOUT_FILENO	stdout
2	Error output	STDERR_FILENO	stderr

- POSIX name is defined in `<unistd.h>`

Unix File I/O

System calls for file access (see man pages chapter 2)

int **open**(const char *pathname, int flags, mode_t mode)

Opens an existing file or creates a new file

- pathname: path to the file
- flags: One of `O_RDONLY`, `O_WRONLY`, `O_RDWR`
  - Additional flags can be added (via bitwise OR):
    - `O_CREAT`: create the file if it does not exist
    - `O_EXCL`: fail if the file already exists
- mode: specifies the file mode bits to be applied when a new file is created
- Returns a file descriptor or -1 on error

```c
int fd = open("~/data.txt", O_CREAT | O_EXCL | O_WRONLY);

if (fd < 0) {
    fprintf(stderr, "open failed: %s\n", strerror(errno));
    exit(EXIT_FAILURE);
}
```

Unix File I/O

System calls for file access (see man pages chapter 2)

ssize_t **read**(int fd, void *buf, size_t count)

Read up to count bytes from a file

- fd: file descriptor
- buf: buffer to be filled with the read data
- count: size of buffer (max number of bytes to read)
- Returns number of bytes effectively read or -1 on error

```
char buffer[80];

for (int pos = 0; pos < sizeof(buffer); ) {
    int numread = read(fd, buffer+pos, sizeof(buffer)-pos);

    if (numread < 0) {
        // error
    } else
        pos += numread;
}
```

Unix File I/O

System calls for file access (see man pages chapter 2)

ssize_t **write**(int fd, void *buf, size_t count)

Write up to count bytes to a file

- fd: file descriptor
- buf: buffer with the data to be written
- count: size of buffer (max number of bytes to write)
- Returns the number of bytes effectively written or -1

```
char buffer[80] = "Data to be written";

for (int pos = 0; pos < sizeof(buffer); ) {
    int n = write(fd, buffer+pos, sizeof(buffer)-pos);

    if (n < 0) {
        // error
    } else
        pos += n;
}
```

Unix File I/O

System calls for file access (see man pages chapter 2)

int **close**(int fd)

Close a file

- fd: file descriptor
- Returns 0 on success and -1 on error

```
if (close(fd) < 0) {
    fprintf(stderr, "close failed: %s\n", strerror(errno));
    exit(EXIT_FAILURE);
}
```

Unix File I/O

EINTR

- read() and write() can be interrupted by a signal
- In this case they return -1 and set errno to EINTR
- No bytes are read or written
- If this happens, just retry

read() with checking for EINTR:

```
char buffer[80];
int pos, numread;

for (pos = 0; pos < sizeof(buffer); ) {
    numread = read(fd, buffer + pos, sizeof(buffer) - pos);

    if (numread < 0) {
        if (errno != EINTR)
            // other error than EINTR
    } else
        pos += numread;
}
```

Unix File I/O

EINTR

- read() and write() can be interrupted by a signal
- In this case they return -1 and set errno to EINTR
- No bytes are read or written
- If this happens, just retry

write() with checking for EINTR:

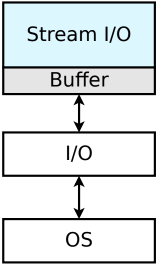
```
char buffer[80] = "Data to be written";
int pos, numwrit;

for (pos = 0; pos < sizeof(buffer); ) {
    numwrit = write(fd, buffer + pos, sizeof(buffer) - pos);

    if (numwrit < 0) {
        if (errno != EINTR)
            // other error than EINTR
    } else
        pos += numwrit;
}
```

Stream I/O in C

The functionality descends from a "portable I/O package" written by Mike Lesk at Bell Labs in the early 1970s. (Source: Wikipedia)

- Standard I/O library (portability)

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



- Buffered layer on top of the Unix I/O
- Stream data type: `FILE`, includes i.a. file descriptor, pointer to buffer, current position, EOF and error flags
- Predefined streams `stdin`, `stdout`, `stderr`
- Convention: functions start with "f": `fopen(3)`, `fdopen(3)`, `fwrite(3)`, `fprintf(3)`, ...

fopen(3)

FILE ***fopen**(const char *path, const char *mode)

- The file at `path` is opened, and associated with the returned stream
- Different I/O modes:
  - `"r"` : read-only
  - `"w"` : write-only (truncate to zero length first)
  - `"a"` : append-only
  - `"r+"` / `"w+"` / `"a+"` : read and write (update mode)
    Read from beginning / truncate to zero length / writing at EOF
- Returns NULL on failure ($\rightarrow$ errno)

```
FILE *input = fopen("data.txt", "r");

if (input == NULL) {
    fprintf(stderr, "fopen failed: %s\n", strerror(errno));
    exit(EXIT_FAILURE);
}
```

fdopen(3)

FILE ***fdopen**(int fd, const char *mode)

- Associates a stream with a file descriptor
  - `fd`: file descriptor
  - `mode`: I/O mode
- Returns NULL on failure (→ errno)

```
int fd = open(...);
if (fd < 0) {
    // error
}

FILE *f = fdopen(fd, "r");
if (f == NULL) {
    // error
}
```

Reading and Writing

Function	Description
fread	Reads *n* elements, each *s* bytes long
fgets	Reads a line (up to `'\n'`)
fgetc	Reads a character
fwrite	Writes *n* elements, each *s* bytes long
fputs	Writes a C-string
fputc	Writes a character
fprintf	Formatted printing
fseek	Set the file position indicator
Since POSIX.1-2008:	
getline	Reads a line into a dynamically allocated buffer

Stream Status

int **ferror**(FILE *stream)

- ferror tests the error indicator of the stream (0 = error flag not set).

int **feof**(FILE *stream)

- feof tests the end-of-file indicator of the stream (e.g. functions fgets and fgetc set this flag upon reaching the end of file)

int **clearerr**(FILE *stream)

- clearerr resets error and end-of-file indicators

int **fileno**(FILE *stream)

- fileno returns the file descriptor of a stream

e.g. fileno(stdout) $\rightarrow$ 1

fflush(3), fclose(3)

int **fflush**(FILE *stream)

- fflush enforces writing of buffered data

int **fclose**(FILE *stream)

- fclose calls fflush and closes the stream and the associated file descriptor.

Return 0 on success, EOF on failure ($\rightarrow$ errno)

Stream I/O Examples

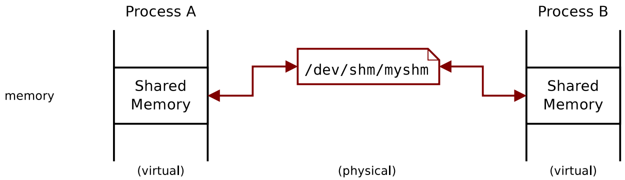
Read and write files

Read the content of an input file line by line and write it to an output file

```
char buffer[1024];
FILE *in, *out;

if ((in = fopen("input.txt", "r")) == NULL)
    // fopen failed

if ((out = fopen("output.txt", "w")) == NULL)
    // fopen failed

while (fgets(buffer, sizeof(buffer), in) != NULL) {
    if (fputs(buffer, out) == EOF)
        // fputs failed
}

if (ferror(in))
    // fgets failed

fclose(in);
fclose(out);
```

Shared Memory

- Common memory area: Multiple processes (related or unrelated) can access the same region in the physical memory (i.e., share data). This memory region is mapped into the address space of these processes.



- Read and modify by normal memory access operations
- Fast inter process communication[1]

Concurrent access!

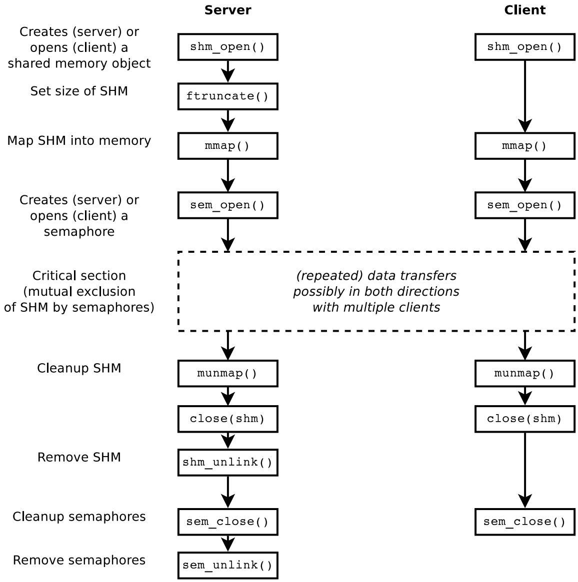
→ Explicit synchronization is necessary

[1] no intervention of the OS kernel/“zero-copy”, see http://www.linuxjournal.com/article/6345

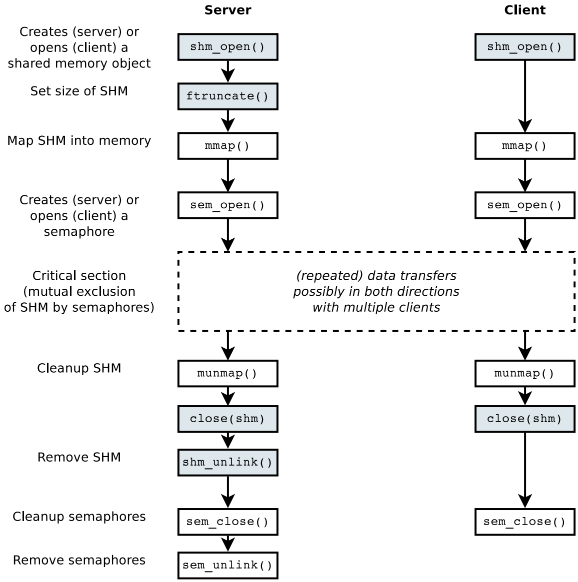
POSIX Shared Memory

- Makes it possible to create shared memory between non-related processes without creating a file
- Shared memory objects identified via names
- Created on file system for volatile memory: tmpfs
- Behaves as a usual file system (e.g. access rights)
- Available as long as system is running
- mmap is used to map it into the virtual memory of a process

Client-Server Example



Client-Server Example



Shared Memory API

Create/Open

- Create and/or open a new/existing object: shm_open(3)

```
#include <sys/mman.h>
#include <fcntl.h>     /* For O_* constants */

int shm_open(const char *name, int oflag,
             mode_t mode);
```

name Name like “/somename”

oflag Bit mask: O_RDONLY or O_RDWR and eventually…
  - O_CREAT: creates an object unless it is created
  - additionally O_EXCL: error if already created

mode Access rights at creation time, otherwise 0

- Return value: file descriptor on success, -1 on error (→ errno)
- Linux: Object at /dev/shm/somename created

Shared Memory API

Set Size

- The creating process normally sets the size (in bytes) based on the file descriptor: `ftruncate(2)`

```
#include <unistd.h>
#include <sys/types.h>

int ftruncate(int fd, off_t length);
```

- Return value: 0 on success, -1 on error ($\rightarrow$ errno)
- Then the file descriptor can be used to create a common mapping (mmap(2)) and finally it can be closed (close(2))

Shared Memory API

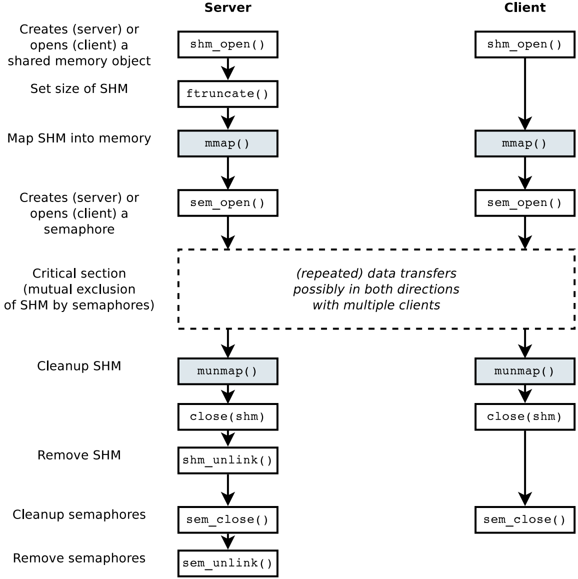
Remove

- Remove a shared memory object name: shm_unlink(3)

```
int shm_unlink(const char *name);
```

- Name, which was specified at creation
- Return value: 0 on success, -1 on error ($\rightarrow$ errno)
- Further shm_open() with the same name raises an error (unless a new object is created by specifying `O_CREAT`)
- The memory is released when the last process has closed the file descriptor with close() and released any mappings with munmap()
- Common commands (`ls`, `rm`) can be used to list and remove `/dev/shm/` (e.g. if program crashes)

Client-Server Example



Memory Mapping

Recall: mmap(2)

mmap(2)

= maps a file into the virtual memory of a process

- Multiple processes can access the underlying memory
- Shared memory is based on sharing a resource (a file) "shared file mapping"

Memory Mapping

Create

- Create a mapping: `mmap(2)`

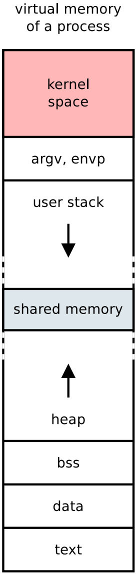
```
#include <sys/mman.h>

void *mmap(void *addr, size_t length, int prot,
           int flags, int fd, off_t offset);
```

addr	Suggestion for starting address, should be NULL
length	Size of the mapping in bytes, often the size of a file (see fstat(2))
prot	Bit mask for memory protection: PROT_NONE (no access allowed), PROT_READ, PROT_WRITE
flags	Bit mask, e.g., MAP_PRIVATE, MAP_SHARED, MAP_ANONYMOUS
fd	The file descriptor to be mapped
offset	Offset in the file (multiple of page size), 0

- Return value: Starting address of the mapping (aligned to page limit), MAP_FAILED on error (errno)

Memory Mapping

Virtual Address Space



- Mappings in different processes are created at different virtual addresses but point to the same physical address
- Take care by storing pointers!

Memory Mapping

Comments

- The file descriptor (e.g. of a shared memory) can be closed after the creation of the mapping
- In Linux, mappings are listed under `/proc/PID/maps`
- Disadvantages of actual file mappings (not a virtual file) for shared memory: Persistent → costs for disk I/O
- For related processes: shared, anonymous mappings (`MAP_SHARED | MAP_ANONYMOUS`)
  - No underlying file, not even a virtual file
  - Create mapping before fork():
    → child processes can access the mapping at the same address

Memory Mapping

Release

- Releasing a mapping: `munmap()`

```
#include <sys/mman.h>

int munmap(void *addr, size_t length);
```

- Removes whole memory pages from the given space, starting address has to be page-aligned
- Return value: 0 on success, -1 on error ($\rightarrow$ errno)

Example

Define Structure of the shared memory

```c
#include <fcntl.h>
#include <stdio.h>
#include <sys/mman.h>
#include <sys/types.h>
#include <unistd.h>

#define SHM_NAME "/myshm"
#define MAX_DATA (50)

struct myshm {
  unsigned int state;
  unsigned int data[MAX_DATA];
};
```

Example

Create and map the shared memory

```
// create and/or open the shared memory object:
int shmfd = shm_open(SHM_NAME, O_RDWR | O_CREAT, 0600);
if (shmfd == -1)
    ... // error

// set the size of the shared memory:
if (ftruncate(shmfd, sizeof(struct myshm)) < 0)
    ... // error

// map shared memory object:
struct myshm *myshm;
myshm = mmap(NULL, sizeof(*myshm), PROT_READ | PROT_WRITE,
             MAP_SHARED, shmfd, 0);

if (myshm == MAP_FAILED)
    ... // error

if (close(shmfd)) == -1)
    ... // error
```

Example

Cleanup

```
// unmap shared memory:
if (munmap(myshm, sizeof(*myshm)) == -1)
    ... // error

// remove shared memory object:
if (shm_unlink(SHM_NAME) == -1)
    ... // error
```

Semaphores

Synchronization

= control access of concurrent processes to a critical section

- Conditional synchronization: In which order is a critical section accessed: A before B? B before A?
- **Mut**ual **ex**clusion: Ensure that only one process is accessing a shared resource ().
  Not necessarily fair/alternating.

Example (1)

Thread A:

```
a1: print ‘‘yes’’
```

Thread B:

```
b1: print ‘‘no’’
```

- No deterministic sequence of “yes” and “no”. Depends on, e.g., the scheduler.
- Multiple calls might cause different outputs. Are other outputs possible?

Example (2)

Thread A:

```
a1: x = 5
a2: print x
```

Thread B:

```
b1: x = 7
```

- Path to output “5” and in the end $x = 5$?
- Path to output “7” and in the end $x = 7$?
- Path to output “5” and in the end $x = 7$?
- Path to output “7” and in the end $x = 5$?

Example (3)

Thread A:

```
a1: x = x + 1
```

Thread B:

```
b1: x = x + 1
```

- Assumption: x is initialized with 1. What are possible values for x after execution?
- Is `x++` atomic?

Semaphores

Functions

Semaphore

= "Shared variable" used for synchronization

- 3 basic operations:
  - S = Init(N)
    create semaphore S with value N
  - P(S), Wait(S), Down(S)
    decrement S and block when S gets negative
  - V(S), Post(S), Signal(S), Up(S)
    increment S and wake up waiting process

Example - Serialization

Thread A:

```
statement a1
```

Thread B:

```
statement b1
```

How to guarantee that a1 $<$ b1 (a1 before b1)?

Example - Serialization

Initialization:

```
S = Init(0)
```

Thread A:

```
statement a1
V(S) // post
```

Thread B:

```
P(S) // wait
statement b1
```

Example - Mutex

Thread A:

```
x = x + 1
```

Thread B:

```
x = x + 1
```

How to guarantee that only one thread is entering the critical section?

Example - Mutex

Initialization:

```
mutex = Init(1)
```

Thread A:

```
P(mutex) // wait
x = x + 1
V(mutex) // post
```

Thread B:

```
P(mutex) // wait
x = x + 1
V(mutex) // post
```

$\Rightarrow$ Critical section seems to be atomic

Example - Alternating Execution

Thread A:

```
for(;;) {
  x = x + 1
}
```

Thread B:

```
for(;;) {
  x = x + 1
}
```

How to achieve that A and B are called alternately?

Example - Alternating Execution

Initialization:

```
S1 = Init(1)
S2 = Init(0)
```

Thread A:

```
for(;;) {
  P(S1) // wait
  x = x + 1
  V(S2) // post
}
```

Thread B:

```
for(;;) {
  P(S2) // wait
  x = x + 1
  V(S1) // post
}
```

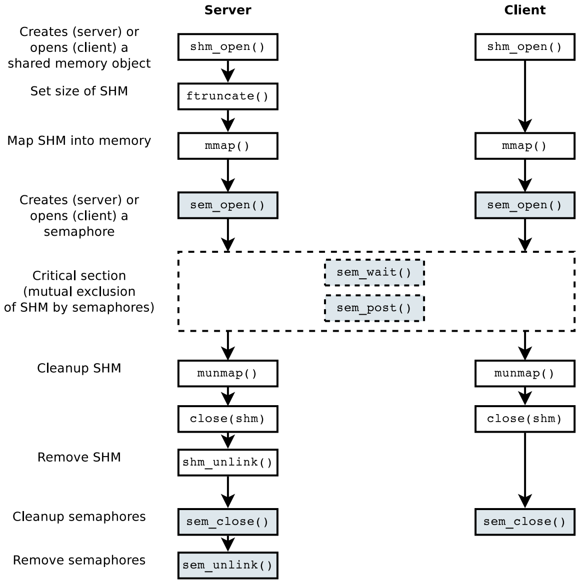
⇒ 2 semaphores are necessary!

How does the synchronization look like for 3 threads that should work alternately? How about N threads?

POSIX Semaphore

- Synchronization of processes
  - Non-related processes: named semaphores
  - (Related processes or threads within a process: unnamed semaphores)
- Similar to POSIX shared memory. . .
  - Identified by name
  - Created on dedicated file system for volatile memory: tmpfs
  - Lifetime limited to system runtime
- Linked with `-pthread`
- See also `sem_overview(7)`
- Linux: object is created at `/dev/shm/sem.`<u>`somename`</u>

Client-Server Example



Semaphore API

Create/Open

- Create/open a new/existing semaphore: sem_open(3)

```
#include <semaphore.h>
#include <fcntl.h>      /* For O_* constants */

/* create a new named semaphore */
sem_t *sem_open(const char *name, int oflag,
                mode_t mode, unsigned int value);

/* open an existing named semaphore */
sem_t *sem_open(const char *name, int oflag);
```

name Name of the form "/somename"
oflag Bit mask: O_CREAT, O_EXCL
mode Access rights (at creation time only)
value Initial value (when creating)

- Return value: Semaphore address on success, SEM_FAILED on error (→ errno)

Semaphore API

Close and Remove

- Close a semaphore: `sem_close(3)`

```
int sem_close(sem_t *sem);
```

- Remove a semaphore: `sem_unlink(3)`

```
int sem_unlink(const char *name);
```

Is released after all processes have closed it.

- Return value: 0 on success, -1 on error ($\rightarrow$ errno)

Semaphore API

Wait, P()

- Decrement a semaphore: `sem_wait(3)`

```
int sem_wait(sem_t *sem);
```

- If the value > 0, the method returns immediately
- It blocks the function until the value gets positive otherwise
- Return value: 0 on success, -1 on error ($\rightarrow$ errno) and the value of the semaphore is not changed

Signal Handling

The function `sem_wait()` can be interrupted by a signal (errno $==$ EINTR)!

Semaphore API

Post, V()

- Increment a semaphore: sem_post(3)

```
int sem_post(sem_t *sem);
```

- If the value of a semaphore gets positive, a blocked process will continue
- If multiple processes are waiting: the order is not defined (= weak semaphore)
- Return value: 0 on success, -1 on error (→ errno) and the semaphore value is not changed

Example - Alternating Execution

Process A (code without error handling)

```
#include <stdio.h>
#include <unistd.h>
#include <semaphore.h>
#include <fcntl.h>

#define SEM_1   "/sem_1"
#define SEM_2   "/sem_2"

int main(int argc, char **argv) {
  sem_t *s1 = sem_open(SEM_1, O_CREAT | O_EXCL, 0600, 1);
  sem_t *s2 = sem_open(SEM_2, O_CREAT | O_EXCL, 0600, 0);

  for(int i = 0; i < 3; ++i) {
    sem_wait(s1);
    printf("critical: %s: i = %d\n", argv[0], i);
    sleep(1);
    sem_post(s2);
  }
  sem_close(s1); sem_close(s2);

  return 0;
}
```

Example - Alternating Execution

Process B (code without error handling)

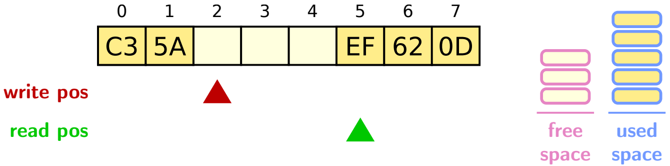
```
#include <stdio.h>
#include <unistd.h>
#include <semaphore.h>
#include <fcntl.h>

#define SEM_1   "/sem_1"
#define SEM_2   "/sem_2"

int main(int argc, char **argv) {
  sem_t *s1 = sem_open(SEM_1, 0);
  sem_t *s2 = sem_open(SEM_2, 0);

  for(int i = 0; i < 3; ++i) {
    sem_wait(s2);
    printf("critical: %s: i = %d\n", argv[0], i);
    sleep(1);
    sem_post(s1);
  }
  sem_close(s1); sem_close(s2);
  sem_unlink(SEM_1); sem_unlink(SEM_2);
  return 0;
}
```

Example - Handling Signals

```c
volatile sig_atomic_t quit = 0;

void handle_signal(int signal) { quit = 1; }

int main(void)
{
    sem_t *sem = sem_open(...);

    struct sigaction sa = { .sa_hander = handle_signal; };
    sigaction(SIGINT, &sa, NULL);

    while (!quit) {
        if (sem_wait(sem) == -1) {
            if (errno == EINTR) // interrupted by signal?
                continue;

            error_exit(); // other error
        }

        ...
    }
}
```

Circular Buffer

= simple FIFO implementation with shared memory and semaphores




```c
int wr_pos = 0;
void write(int val) {
   sem_wait(free_sem);
   buf[wr_pos] = val;
   sem_post(used_sem);
   wr_pos += 1;
   wr_pos %= sizeof(buf);
}
```

```c
int rd_pos = 0;
int read() {
   sem_wait(used_sem);
   int val = buf[rd_pos];
   sem_post(free_sem);
   rd_pos += 1;
   rd_pos %= sizeof(buf);
   return val;
}
```

Exercise guidelines

The full guidelines are appended to the exercise assignments and can be found on TUWEL!

Important

Failing to adhere to the formal coding guidelines leads to deductions! No points are awarded if the program does not compile or if it does not work as described by the testcases.

Most common mistakes

- Not tested in the TI-Lab
  ("But at home, it worked on my computer!" → use `ssh`)
- Failure to check return values
- Resources not de-allocated explicitly
- Missing usage message and insufficient argument handling (also check number of supplied arguments, surplus options, etc.)

Exercise guidelines

- Build: Write a Makefile
  - Targets **all** (first target; build your program) and **clean** (remove all files produced during the build process)
  - Compilation flags:

    ```
    $ gcc -std=c99 -pedantic -Wall -g -c filename.c
    -D_DEFAULT_SOURCE -D_BSD_SOURCE -D_SVID_SOURCE
    -D_POSIX_C_SOURCE=200809L
    ```
- Argument handling
  - Use `getopt(3)`
  - Usage message to show the correct invocation
- Error handling:
  - **If subsequent code depends on the successful execution of a function (e.g. resource allocation), then the return value must be checked.**
  - Print a meaningful error message to **stderr** and exit with **EXIT_FAILURE**

→ see lecture "Development in C"

Plagiarism

- Discussing possible approaches with colleagues is fine
- However, everyone must **implement** his/her **own solution independently**!
- Multiple students handing in the same solution or copying from eachother is not acceptable!
- Copying solutions from online sources is equally not acceptable!

Important

There will be a zero tolerance policy for cheating/copying solutions!

- First time you are caught: 0 points on the assignment
- Second time caught: Exclusion from the course with negative certificate

Plagiarism

- **Plagiarism can be detected with checker programs**
- There exist specialized checkers for source code
- Copying code and only altering it slightly (e.g. renaming variables) does not fool an automated checker!
- Neither do following examples:

```
if (x < y) {
    ...
}
```

```
if (!(x >= y)) {
    ...
}
```

```
switch (diff) {
    case 3:
        ...
        break;
    case 2:
        ...
        break;
    case 1:
        ...
}
```

```
if (diff == 3) {
    ...
}
if (diff == 2) {
    ...
}
if (diff == 1) {
    ...
}
```

Exercise 1

- 1a: Implement a simple Unix tool
  - Become acquainted with the C language
  - Argument handling
  - Learn to use Makefiles
- 1b: Producer/consumer example using a circular buffer
  - Producer(s) write(s) data to the circular buffer
  - Consumer reads from the circular buffer
  - Synchronization using semaphores

Summary

- Shared memory is a fast method for IPC
- Explicit synchronization with semaphores
- Synchronization tasks
- Strategies to resource (de-)allocation

Material

- Michael Kerrisk: A Linux and UNIX System Programming Handbook, No Starch Press, 2010.
- Linux implementation of shared memory/tmpfs: `http://www.technovelty.org/linux/shared-memory.html`
- Richard W. Stevens: UNIX Network Programming, Vol. 2: Interprocess Communications