System Level Programming

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2021-10-01

Course Organization

Motivation

Last year, you took introductory C/C++ courses

- Einführung in die Strukturierte Programmierung
- Softwareentwicklung Praktikum

Time to apply your knowledge...

- Interaction with the operating system (Posix API)
- Processes, Threads
- Memory management

Learning Goals

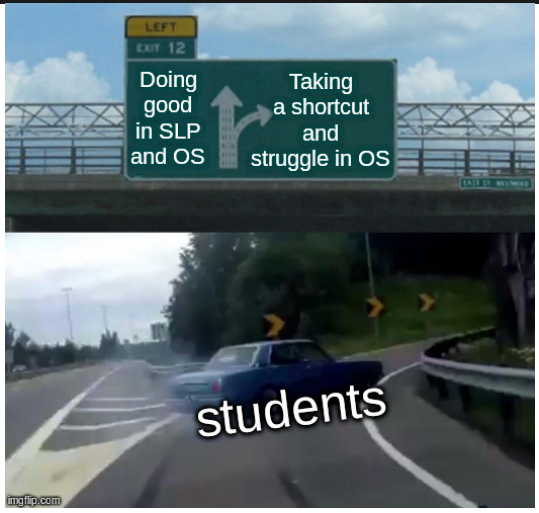
Learn how C and C++ does things

- Learn how the operating system manages your programs
- Learn to read and understand code
- Practice writing, fixing and adapting code snippets
- Practice or learn debugging!

Side effect:

- Preparation for the operating systems course

Take this course seriously

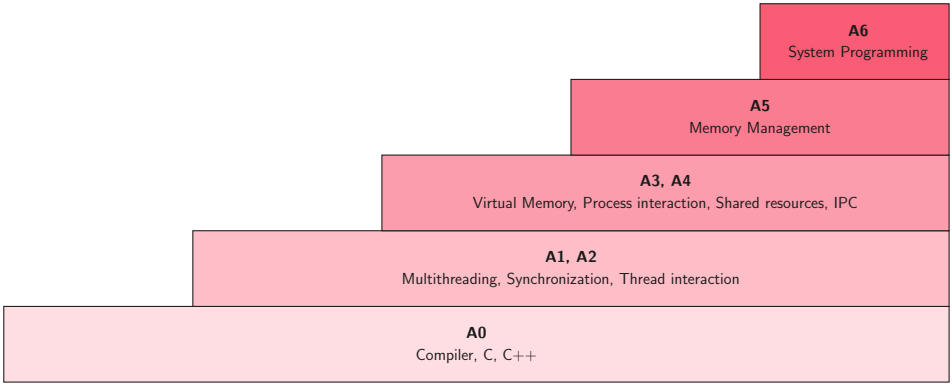


Registration and Related Issues

- Registration **closed**
- You obtain a grade if you are enrolled
  - as soon you submit a single assignment.
  - **A0 does not count** $\rightarrow$ self-assessment

  You will receive an email containing information
  - on your GIT repository, and
  - on your account in the test-system
- You will work individually on all assignments.
- Mandatory exam

Course Outline - Assignments

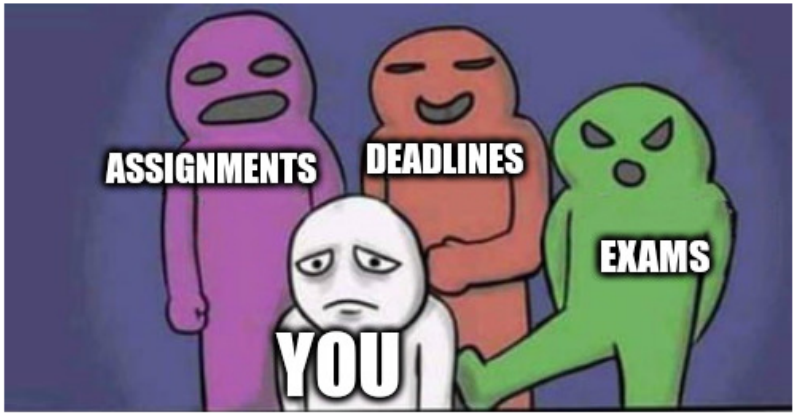


Course Outline - Lectures

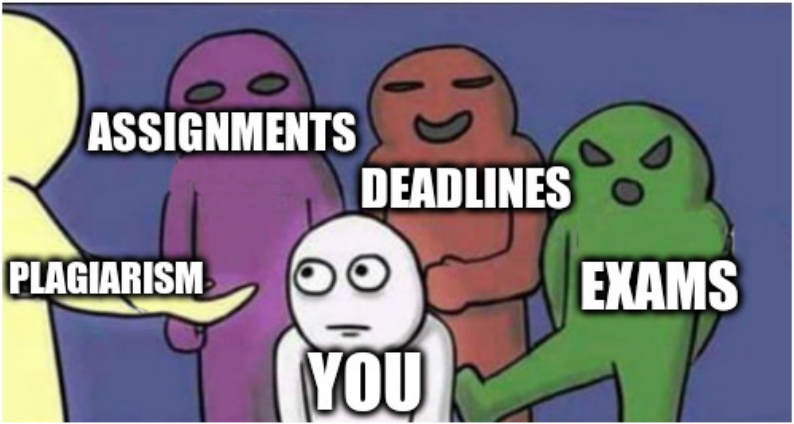
Three types of lectures

- Regular lectures
  - Theory
  - Examples
- Assignment presentations
  - Kick offs
  - Organisatorial details
  - Some basic theory
- Weekly question hours (0.5hr)
  - Discord!
  - for current + next assignment
  - Multiple tutors present

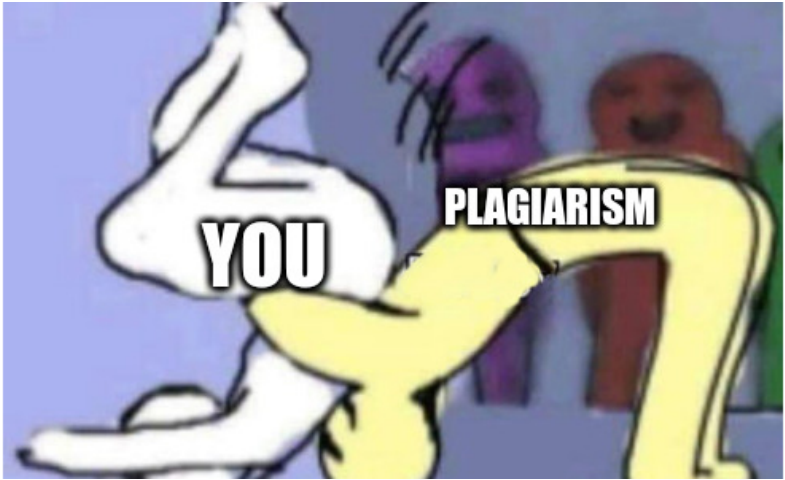
Do not



think that we won't find



Attempts of plagiarism



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- Shuffling code snippets $\rightarrow$ will have no effect!
- NO EXCEPTIONS!
- All people involved have to take the consequences

Working on Assignments

What are your tasks

- Read the assignment rules!
- Join the IAIK Discord: https://discord.gg/DCpzjqWBD3
- Pull from upstream before you begin.
- Understand the assignment specification,

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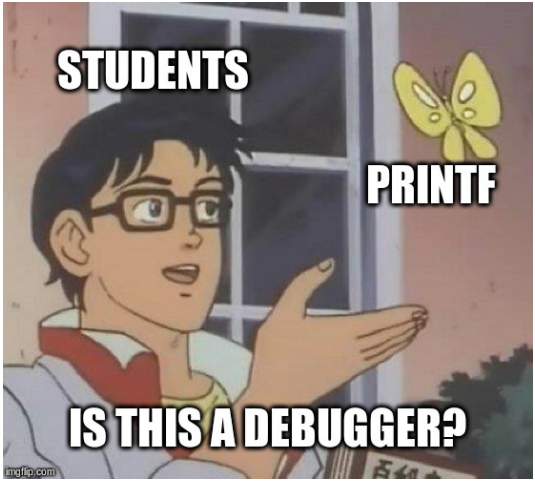
- Pull from upstream before you begin.
- Understand the assignment specification,
- Have an in-depth understanding of your solution, and
- implement your solution *yourself*.
- Do not remove tags, after the deadline!!!
- pro advice: use gdb for debugging and valgrind for memory checks

Debugging using a debugger



Assignment grading contd'

Each assignment graded individually with the help of the test system

- 105 points reachable
- stable solutions that are in line with the rules
- If you are not sure about something: *ask*

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Your submissions are tested automatically

- Subset of tests is revealed (=sanity checks)
- Passing all sanity checks does *not* mean 100% on all tests

Assignment Grading contd'

Interviews

- after the last exercise
- you can select a time-slot by yourself
- we will appoint you a **random** tutor.
- Three parts with different tutors
  - A1, A2
  - A3, A4
  - A5, A6
- points can be lost, but
- you can be awarded additional points

Assignment Grading contd'

Magic coins

- A0 rewards you with up to 100 coins when completed
- Assignment handed in an hour early: $+1$ Coin
- For each 10 min late: -1 Coin
- Max 48 hrs for a late submission
- Coins can be converted into bonus points
- Exchange rate: 1pt/50coins

Exam and Overview of grading

- mandatory
- 30 pts reachable
- $\geq$50% of points needed

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Positive grade:

- Exam: $\geq$ 15 pts
- Assignments: $\geq$55 pts
- but overall score has to be over $\geq$50%

Success

In numbers:

- Grading (max. 135 points):
  - $\geq$ 118 points $\rightarrow$ 1
  - $\geq$ 101 points $\rightarrow$ 2
  - $\geq$ 84 points $\rightarrow$ 3
  - $\geq$ 75 points $\rightarrow$ 4

Working Environment

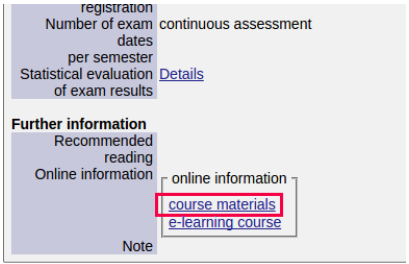
We recommend to use Linux

- e.g., Ubuntu
- use gcc/g++, gdb and valgrind

Support Channels & Feedback

Support

- Course website
- Discord: IAIK Discord
- studo



Give us feedback

- Anytime you think something could be improved
- Evaluation at the end of the course

Code-Fixing Challenge (A0)

The Challenge

- Not mandatory and for **self-assessment only**!
- Self-assessment – max. 1 hour.
- No grading, but coins as reward
- You can quit after A0, without getting graded
- The challenge is open on Wednesday (next week) from 7pm to 8pm.
- Pull from upstream

Multithreading (A1)

Assignment 1 Overview

What it's all about

- an ASCII computer game
- Collect artifacts from the ruins, avoid poisonous snakes, and zombie mummies
- because of a lazy tutor, you get a version without threads $\rightarrow$ not really playable
- TASK: fix it and make it fun to play

Synchronization (A2)

A2-First step

- Pull from upstream
- Try mkdir build && cd build; cmake ..; make and execute
- It will not work ;-)
- Fix it

A2-Note

- Changing core functionality/output of the program $\rightarrow$ 0 points
- Parts you may and should modify are marked with **STUDENT TODO**
- Do not make unnecessary changes

A2-What do we need?

- Locks:
  - Mutex
  - Semaphore
  - Condition variable
- Use Posix locks!
- Hint: there will be lectures on this topic

A2-Typical errors

- So, how to lock correctly?
- You need to hold the lock as long as you need the shared resource
- Carefully keep track of the sequence you've locked
- Always should be the same sequence

A2-Typical errors contd

Will work, but has a very bad performance. Maybe nothing can happen simultaneously because of the way it is locked.

A2-Typical errors contd

THREAD 1

```
// ...
lock(harddisk);
lock(floppy);
copySomething(floppy, harddisk);
unlock(floppy);
unlock(harddisk);
// ...
```

A2-Typical errors contd

THREAD 1

```
// ...
lock(harddisk);
lock(floppy);
copySomething(floppy, harddisk);
unlock(floppy);
unlock(harddisk);
// ...
```

THREAD 2

```
// ...
lock(floppy);
lock(harddisk);
copySomething(floppy, harddisk);
unlock(harddisk);
unlock(floppy);
// ...
```

A2-Typical errors contd

Results in a deadlock.

Program, Process, Thread

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Abstractions

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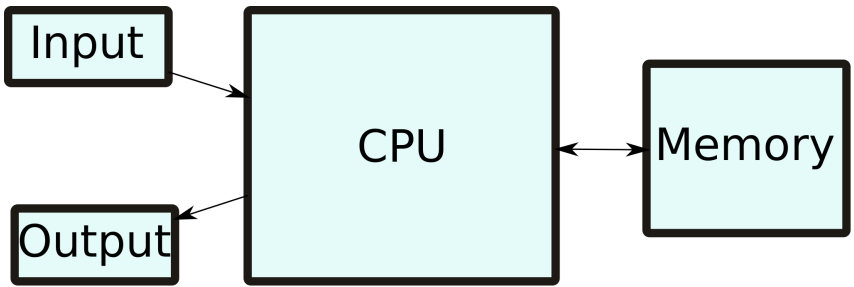
$\rightarrow$ Abstractions hide many details but provide the required capabilities

CPU vs. Process



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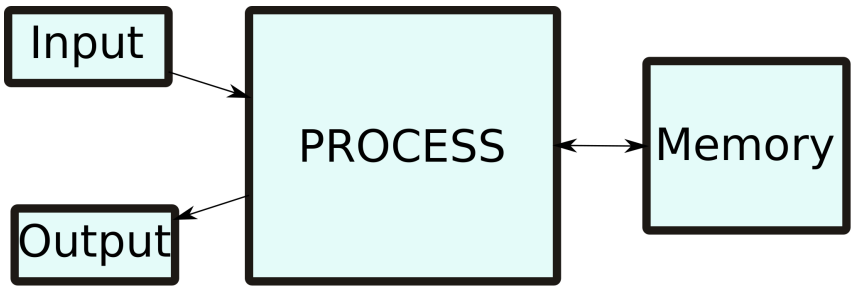

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- Process is an instance of a program

Threads

Process can have multiple threads

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Process can have multiple threads

- same program code and data

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Threads

Process can have multiple threads

- same program code and data
- own stack
- own registers (including instruction pointer)

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- **Process**: a container for threads and memory contents of a program
  - an instance of a program
  - restricted to its own boundaries and rights

Process Resources

A process is a container.

- Process ID

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- Process ID
- Filename

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- Process ID
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A process is a container.

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- Threads
- Child processes?

Thread Resources

A thread is a unit for execution.

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- A stack

Process and Thread Interaction

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Load program, create process, ...

- 1 initial thread
- executes the `main()`-function
- it's not a "main"-thread
- process may start further threads if required (how?)

```
ELF Header:
  Magic:   7f 45 4c 46 02 01 01 00 00 00 00 00 00 00 00 00
  Class:                             ELF64
  Data:                              2's complement, little endian
  Version:                           1 (current)
  OS/ABI:                            UNIX - System V
  ABI Version:                       0
  Type:                              DYN (Shared object file)
  Machine:                           Advanced Micro Devices X86-64
  Version:                           0x1
  Entry point address:               0x1050
  Start of program headers:          64 (bytes into file)
  Start of section headers:          14680 (bytes into file)
  Flags:                             0x0
  Size of this header:               64 (bytes)
  Size of program headers:           56 (bytes)
  Number of program headers:         11
  Size of section headers:           64 (bytes)
  Number of section headers:         29
  Section header string table index: 28
```

```
    43: 0000000000001000     0 FUNC    LOCAL  DEFAULT   11 _init
    44: 0000000000001200     1 FUNC    GLOBAL DEFAULT   14 __libc_csu_fini
    45: 0000000000000000     0 NOTYPE  WEAK   DEFAULT  UND _ITM_deregisterTMCloneTab
    46: 0000000000004000     0 NOTYPE  WEAK   DEFAULT   23 data_start
    47: 0000000000004010     0 NOTYPE  GLOBAL DEFAULT   23 _edata
    48: 0000000000001204     0 FUNC    GLOBAL HIDDEN    15 _fini
    49: 0000000000000000     0 FUNC    GLOBAL DEFAULT  UND __stack_chk_fail@@GLIBC_2
    50: 0000000000000000     0 FUNC    GLOBAL DEFAULT  UND __libc_start_main@@GLIBC_
    51: 0000000000004000     0 NOTYPE  GLOBAL DEFAULT   23 __data_start
    52: 0000000000000000     0 NOTYPE  WEAK   DEFAULT  UND __gmon_start__
    53: 0000000000004008     0 OBJECT  GLOBAL HIDDEN    23 __dso_handle
    54: 0000000000002000     4 OBJECT  GLOBAL DEFAULT   16 _IO_stdin_used
    55: 00000000000011a0    93 FUNC    GLOBAL DEFAULT   14 __libc_csu_init
    56: 0000000000004018     0 NOTYPE  GLOBAL DEFAULT   24 _end
    57: 0000000000001050    43 FUNC    GLOBAL DEFAULT   14 _start
    58: 0000000000004010     0 NOTYPE  GLOBAL DEFAULT   24 __bss_start
    59: 0000000000001155    65 FUNC    GLOBAL DEFAULT   14 main
    60: 0000000000001135    32 FUNC    GLOBAL DEFAULT   14 _Z8isdoubleOi
    61: 0000000000004010     0 OBJECT  GLOBAL HIDDEN    23 __TMC_END__
    62: 0000000000000000     0 NOTYPE  WEAK   DEFAULT  UND _ITM_registerTMCloneTable
    63: 0000000000000000     0 FUNC    WEAK   DEFAULT  UND __cxa_finalize@@GLIBC_2.2
```

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- at boot time (kernel threads, init processes)

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- **at request of a user (how?)**

Process Creation

- at boot time (kernel threads, init processes)
- **at request of a user (how?)**
  - also: start of a scheduled batch job (cronjob, how?)

Process Creation at request of a user

via Syscall!

- UNIX/Linux: `fork` (exact copy)

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- UNIX/Linux: `fork` (exact copy)
- Windows: `CreateProcess` (new image)


WHAT DOES THE FORK DO?

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```
pid_t fork(void);
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- shall be created with a single thread. If a multi-threaded process calls fork(), the new process shall contain a replica of the calling thread and its entire address space, possibly including the states of mutexes and other resources.
- parent and the child processes shall be capable of executing independently before either one terminates.
- ...

fork Return Value

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

Upon successful completion, fork() shall return 0 to the child process and shall return the process ID of the child process to the parent process. Both processes shall continue to execute from the fork() function. Otherwise, -1 shall be returned to the parent process, no child process shall be created, and errno shall be set to indicate the error.

Fork

```
pid_t child_pid;
child_pid = fork();
if (child_pid == -1) {
        printf("fork failed\n");
} else if (child_pid == 0) {
        printf("i'm the child\n")
            ;
} else {
        printf("i'm the parent\n"
            );
        waitpid(child_pid,0,0);
            // wait for child to
            die
}
```

- child does not know the parent

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- child does not know the parent
- parent knows the child
- parent waits for child to die (`waitpid`)


I never knew my real dad
I never knew my real dad
I never knew my real dad
VIA 9GAG.COM
We never knew our real dad

exec

```
int execl(const char *pathname, const char *arg, ... /* (char  *)
    NULL */);
int execlp(const char *file, const char *arg, ... /* (char  *)
    NULL */);
int execle(const char *pathname, const char *arg, ... /*, (char *)
     NULL, char * const envp[] */);
int execv(const char *pathname, char *const argv[]);
int execvp(const char *file, char *const argv[]);
int execvpe(const char *file, char *const argv[], char *const envp
    []);
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- replace running process by process defined by `file`

exec

```
int execvpe(const char *file, char *const argv[], char *const envp
    []);
```

- replace running process by process defined by `file`
- pass `argv`

exec

```
int execvpe(const char *file, char *const argv[], char *const envp
    []);
```

- replace running process by process defined by `file`
- pass `argv`
- use `envp` for environment variables (`PATH` etc.)

Process Termination

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- Killed by another process

Process Hierarchies

Some operating systems have hierarchies:

- implicit hierarchy from forking

Implicit parent-child hierarchy on Unix/Linux:

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Process Hierarchies

Some operating systems have hierarchies:

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- process groups in UNIX/Linux
- doesn't exist in Windows

Implicit parent-child hierarchy on Unix/Linux:

- when parent dies, all children, grand-children, grand-grand-children, ..., die aswell
- UNIX/Linux also cheats a bit: parent process typically inherits a processes' children, etc.

Process/Thread State

```
git grep TODO | sort
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- do we actually block the process?

Processes vs. Threads

- Threads are more lightweight than processes

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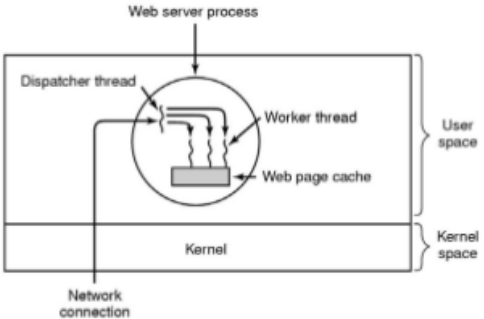
  - No need to reconfigure memory
- May achieve better performance

Example


Web server process
Dispatcher thread
Worker thread
Web page cache
User space
Kernel
Kernel space
Network connection

Example

```
while (TRUE)
{
  get_next_request(&buf);
  handoff_work(&buf);
}
while (TRUE)
{
  wait_for_work(&buf);
  look_for_page_in_cache(&buf,&page);
  if (page_not_in_cache(&page))
    read_page_from_disk(&buf,&page);
  return_page(&page);
}
```

Without Threads

Without threads,

- just one thread

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- complicated program structure

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Without Threads

Without threads,

- just one thread
- complicated program structure
- read content from disk may block process
- non-blocking read (polling!) decreases performance

Non-Blocking Read

```
while (TRUE) { // VERY simplified
  get_next_event(&buf);
  if (is_request_event(&buf)) {
    if (page_not_in_cache(&page)) {
      request_page_from_disk(&buf,&page);
      save_request_in_table(&buf);
    } else {
      return_page(&page);
    }
  } else if (is_disk_event(&buf)) {
    find_request_in_table(&buf);
    mark_requeust_as_done(&buf);
    return_page(&page);
  } else if (is_...
```

Non-Blocking Read

- Finite-state-machine!

Non-Blocking Read

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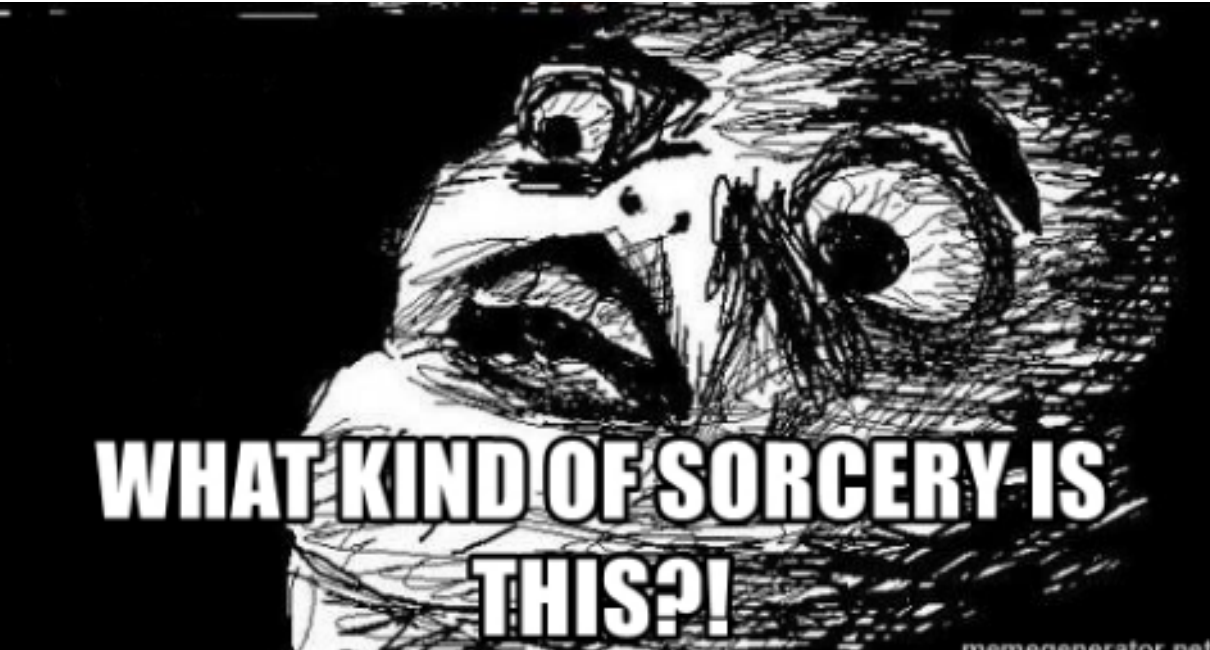
- Actually simulates threads

Non-Blocking Read

- Finite-state-machine!
- Actually simulates threads
- Better: use multithreading

How to use multithreading?

```
int pthread_create(pthread_t *thread, const pthread_attr_t *attr,
                   void *(*start_routine) (void *), void *arg);
```


WHAT KIND OF SORCERY IS THIS?!

Function Pointer

- `void *(*start_routine) (void *)`

Function Pointer

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- looks wrong...

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- `void* (*start_routine) (void*)`
- much better...

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- type: `void* (*) (void*)`
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- takes a `void*`
- returns a `void*`

Let's make a function pointer for `main`

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

- Function pointer: `(*)`

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- +second argument: `int (*)(int, char*[])`

Function Pointer

- `void* (*start_routine) (void*) = &main;`?

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Dangerous though ;)

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The `pthread_create()` function starts a new thread in the calling process. The new thread starts execution by invoking `start_routine()`; `arg` is passed as the sole argument of `start_routine()`.

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Before returning, a successful call to `pthread_create()` stores the ID of the new thread in the buffer pointed to by `thread`; this identifier is used to refer to the thread in subsequent calls to other pthreads functions.

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- `pthread_t*`?

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- `pthread_t` = thread ID
- `pthread_t*`? call by reference

How do pthreads terminate?

The new thread terminates in one of the following ways:

- It calls `pthread_exit`, specifying an exit status value that is available to another thread in the same process that calls `pthread_join`.

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- It is canceled (see `pthread_cancel`).
- Any of the threads in the process calls `exit`, or the main thread performs a return from `main()`. This causes the termination of all threads in the process.

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- After the last thread in a process terminates, the process terminates as by calling `exit` with an exit status of zero; [...]

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- The `pthread_join()` function waits for the thread specified by `thread` to terminate. If that thread has already terminated, then `pthread_join()` returns immediately.
- If retval is not `NULL`, then `pthread_join()` copies the exit status of the target thread into the location pointed to by `retval`. If the target thread was canceled, then `PTHREAD_CANCELED` is placed in the location pointed to by `retval`.

Killing threads

```
int pthread_cancel(pthread_t thread);
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Killing threads

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- The `pthread_cancel()` function sends a cancellation request to the thread `thread`.

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- Processes divide resources amongst themselves (except processor time)
- Threads divide processor time amongst themselves (and a few resources)
- Sometimes processes are more appropriate, sometimes threads