System Level Programming

Daniel Gruss

2022-03-01

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

Skillset Goals

- SLP is your booster for OS

Skillset Goals

- SLP is your booster for OS
- Everything, **Everything**, we teach, will matter for OS.

Skillset Goals

- SLP is your booster for OS
- Everything, **Everything**, we teach, will matter for OS.
- Seemingly useless staring at addresses? You will need this.

Skillset Goals

- SLP is your booster for OS
- Everything, **Everything**, we teach, will matter for OS.
- Seemingly useless staring at addresses? You will need this.
- Seemingly useless knowledge about program behavior? You will need this.

Skillset Goals

- SLP is your booster for OS
- Everything, **Everything**, we teach, will matter for OS.
- Seemingly useless staring at addresses? You will need this.
- Seemingly useless knowledge about program behavior? You will need this.
- Seemingly useless hours of debugging? You will need it this much.

Skillset Goals

- SLP is your booster for OS
- Everything, **Everything**, we teach, will matter for OS.
- Seemingly useless staring at addresses? You will need this.
- Seemingly useless knowledge about program behavior? You will need this.
- Seemingly useless hours of debugging? You will need it this much.
- Statistics show:

s

Skillset Goals

- SLP is your booster for OS
- Everything, **Everything**, we teach, will matter for OS.
- Seemingly useless staring at addresses? You will need this.
- Seemingly useless knowledge about program behavior? You will need this.
- Seemingly useless hours of debugging? You will need it this much.
- Statistics show:
  - without SLP (or barely passed) $\rightarrow$ average grade 5 in OS

s

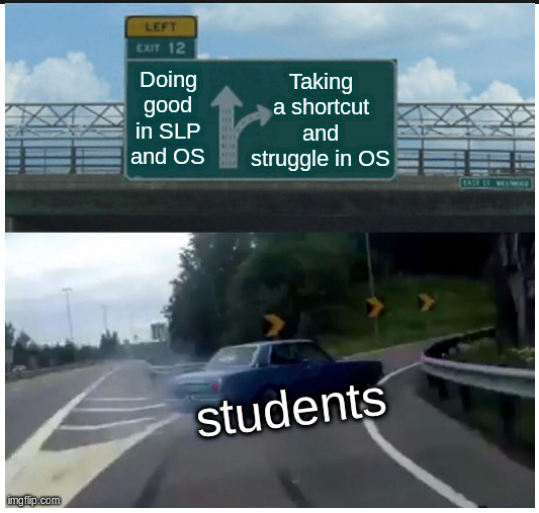
Skillset Goals

- SLP is your booster for OS
- Everything, **Everything**, we teach, will matter for OS.
- Seemingly useless staring at addresses? You will need this.
- Seemingly useless knowledge about program behavior? You will need this.
- Seemingly useless hours of debugging? You will need it this much.
- Statistics show:
  - without SLP (or barely passed) $\rightarrow$ average grade 5 in OS
  - with a good grade in SLP $\rightarrow$ average grade 1-2 in OS

s


THIS IS WHERE MY
SLP KNOWLEDGE WOUD BE
IF I HAD ONE

Take this course seriously

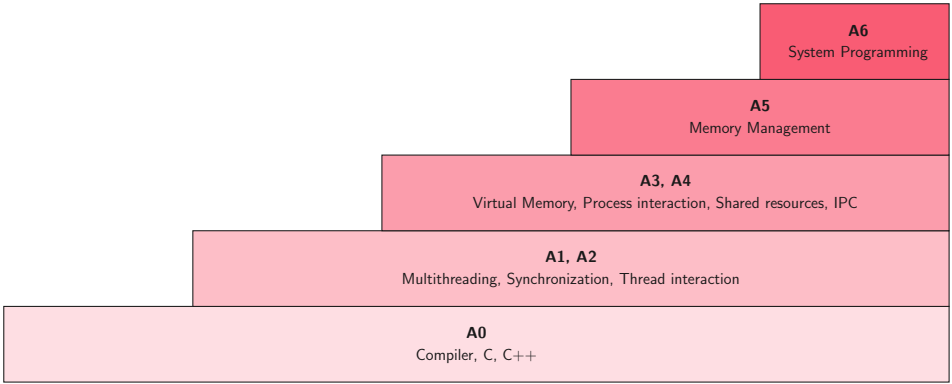


Registration and Related Issues

- 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

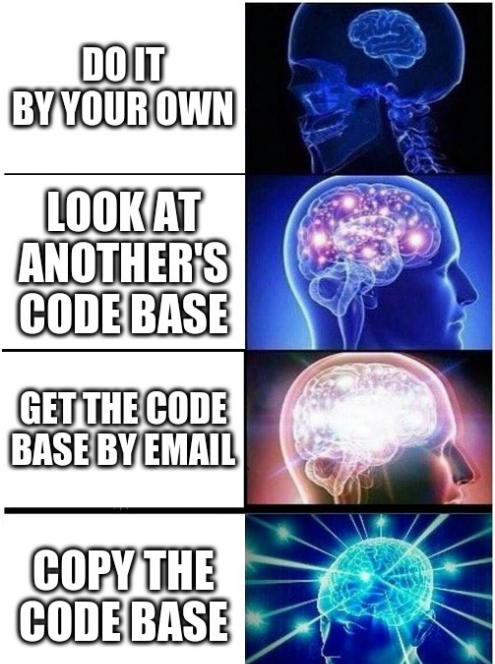
Course Outline - Assignments



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 IT
BY YOUR OWN
LOOK AT
ANOTHER'S
CODE BASE
GET THE CODE
BASE BY EMAIL
COPY THE
CODE BASE


sharing code
is plagiarism
CHANGE MY MIND

Student: copied code

Tutor: negative grade

Student:

Copycats

Plagiarism is strictly forbidden, so keep in mind that

- Every assignment will be checked

Copycats

Plagiarism is strictly forbidden, so keep in mind that

- Every assignment will be checked
  - ...once all assignments are completed.
- Different names for variables $\rightarrow$ will have no effect!

Copycats

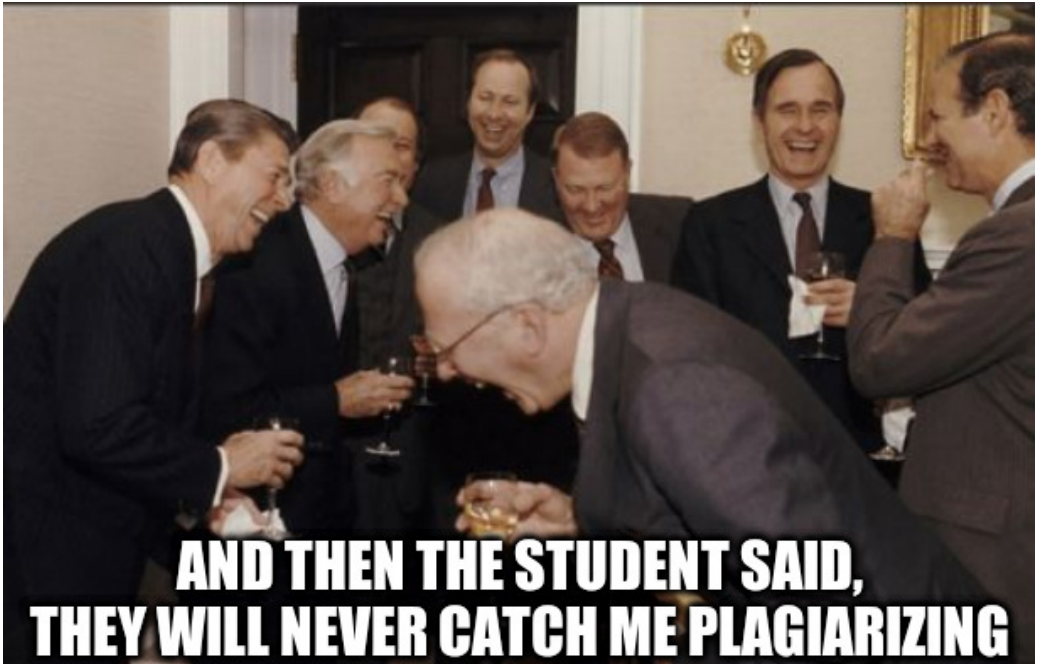
Plagiarism is strictly forbidden, so keep in mind that

- Every assignment will be checked
  - ...once all assignments are completed.
- Different names for variables $\rightarrow$ will have no effect!
- Shuffling code snippets $\rightarrow$ will have no effect!

Copycats

Plagiarism is strictly forbidden, so keep in mind that

- Every assignment will be checked
  - ...once all assignments are completed.
- Different names for variables $\rightarrow$ will have no effect!
- Shuffling code snippets $\rightarrow$ will have no effect!
- NO EXCEPTIONS!
- All people involved have to take the consequences


AND THEN THE STUDENT SAID,
THEY WILL NEVER CATCH ME PLAGIARIZING

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,

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,
- Have an in-depth understanding of your solution, and

Working on Assignments

What are your tasks

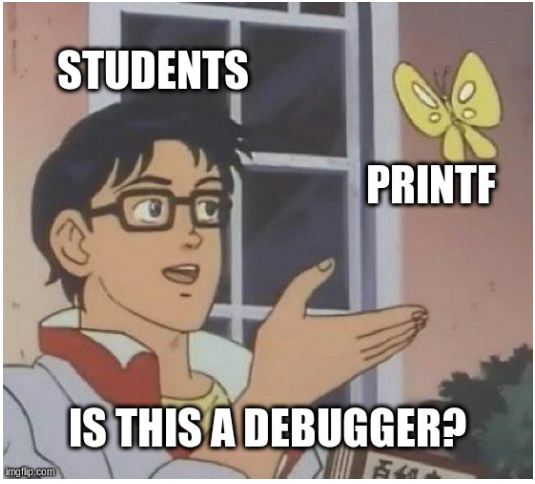
- Read the assignment rules!
- Join the IAIK Discord: https://discord.gg/DCpzjqWBD3
- Pull from upstream before you begin.
- Understand the assignment specification,
- Have an in-depth understanding of your solution, and
- implement your solution *yourself*.

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,
- 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*

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*

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

You may have to code something or be asked about many your own code with small variation

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

Exam and Overview of grading

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

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

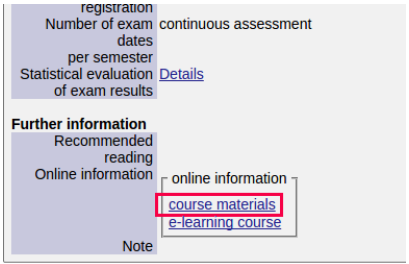
We recommend to use Linux

- 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

Changes this year

- offline again
- no recordings (our statistics show that grades suffer from lecture hall recordings)
- bonus tasks: locking examples from previous semesters

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

- A program: a binary file containing code and data

Program, Process, Thread

- A program: a binary file containing code and data
  - actions: write, compile, install, load

Program, Process, Thread

- A program: a binary file containing code and data
  - actions: write, compile, install, load
  - resources: file

Program, Process, Thread

- A program: a binary file containing code and data
  - actions: write, compile, install, load
  - resources: file
- A thread: an execution context

Program, Process, Thread

- A program: a binary file containing code and data
  - actions: write, compile, install, load
  - resources: file
- A thread: an execution context
  - actions: run, interrupt, stop

Program, Process, Thread

- A program: a binary file containing code and data
  - actions: write, compile, install, load
  - resources: file
- A thread: an execution context
  - actions: run, interrupt, stop
  - resources: CPU time, stack, registers

Program, Process, Thread

- A program: a binary file containing code and data
  - actions: write, compile, install, load
  - resources: file
- A thread: an execution context
  - actions: run, interrupt, stop
  - resources: CPU time, stack, registers
- A process: a container for threads and memory contents of a program

Program, Process, Thread

- A program: a binary file containing code and data
  - actions: write, compile, install, load
  - resources: file
- A thread: an execution context
  - actions: run, interrupt, stop
  - resources: CPU time, stack, registers
- A process: a container for threads and memory contents of a program
  - actions: create, start, terminate

Program, Process, Thread

- A program: a binary file containing code and data
  - actions: write, compile, install, load
  - resources: file
- A thread: an execution context
  - actions: run, interrupt, stop
  - resources: CPU time, stack, registers
- A process: a container for threads and memory contents of a program
  - actions: create, start, terminate
  - resources: threads, memory, program

Abstractions

- Process: abstraction of a computer

Abstractions

- Process: abstraction of a computer
- File: abstraction of a disk or a device

Abstractions

- Process: abstraction of a computer
- File: abstraction of a disk or a device
- Socket: abstraction of a network connection

Abstractions

- Process: abstraction of a computer
- File: abstraction of a disk or a device
- Socket: abstraction of a network connection
- Window: abstraction of a display

Abstractions

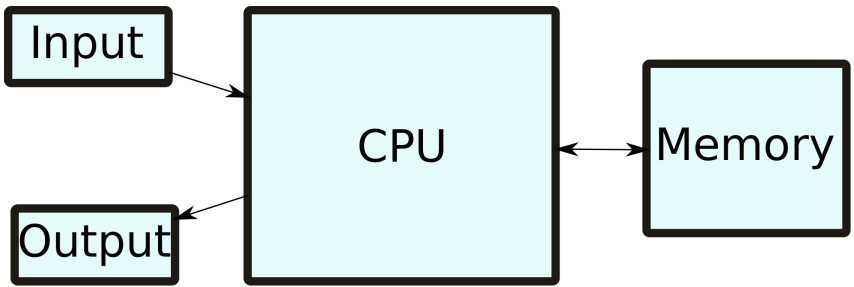
- Process: abstraction of a computer
- File: abstraction of a disk or a device
- Socket: abstraction of a network connection
- Window: abstraction of a display

Abstractions

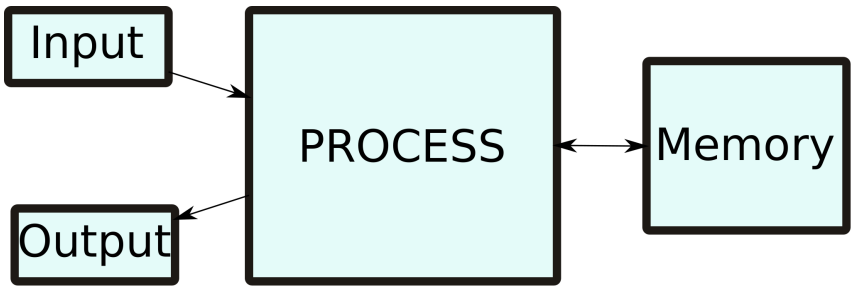
- Process: abstraction of a computer
- File: abstraction of a disk or a device
- Socket: abstraction of a network connection
- Window: abstraction of a display

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

CPU vs. Process



CPU vs. Process



Program, Process, Thread

- Once a program is loaded in memory, OS can start it(s first thread) by

Program, Process, Thread

- Once a program is loaded in memory, OS can start it(s first thread) by
  - setting up a stack and setting the stack pointer and

Program, Process, Thread

- Once a program is loaded in memory, OS can start it(s first thread) by
  - setting up a stack and setting the stack pointer and
  - setting the instruction pointer (of the first thread) to the programs first instruction

Program, Process, Thread

- Once a program is loaded in memory, OS can start it(s first thread) by
  - setting up a stack and setting the stack pointer and
  - setting the instruction pointer (of the first thread) to the programs first instruction
- Process is an instance of a program

Threads

Process can have multiple threads

Threads

Process can have multiple threads

- same program code and data

Threads

Process can have multiple threads

- same program code and data
- own stack

Threads

Process can have multiple threads

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

Program, Process, Thread

- **Program**: a binary file containing code and data

Program, Process, Thread

- **Program**: a binary file containing code and data
  - a mold for a process

Program, Process, Thread

- **Program**: a binary file containing code and data
  - a mold for a process
- **Thread**: an execution context

Program, Process, Thread

- **Program**: a binary file containing code and data
  - a mold for a process
- **Thread**: an execution context
  - a sequence of instructions

Program, Process, Thread

- **Program**: a binary file containing code and data
  - a mold for a process
- **Thread**: an execution context
  - a sequence of instructions
  - if part of a process: restricted to the boundaries of a process

Program, Process, Thread

- **Program**: a binary file containing code and data
  - a mold for a process
- **Thread**: an execution context
  - a sequence of instructions
  - if part of a process: restricted to the boundaries of a process
- **Process**: a container for threads and memory contents of a program

Program, Process, Thread

- **Program**: a binary file containing code and data
  - a mold for a process
- **Thread**: an execution context
  - a sequence of instructions
  - if part of a process: restricted to the boundaries of a process
- **Process**: a container for threads and memory contents of a program
  - an instance of a program

Program, Process, Thread

- **Program**: a binary file containing code and data
  - a mold for a process
- **Thread**: an execution context
  - a sequence of instructions
  - if part of a process: restricted to the boundaries of a process
- **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

Process Resources

A process is a container.

- Process ID
- Filename

Process Resources

A process is a container.

- Process ID
- Filename
- Program file

Process Resources

A process is a container.

- Process ID
- Filename
- Program file
- File descriptors

Process Resources

A process is a container.

- Process ID
- Filename
- Program file
- File descriptors
- Memory

Process Resources

A process is a container.

- Process ID
- Filename
- Program file
- File descriptors
- Memory
- Accounting

Process Resources

A process is a container.

- Process ID
- Filename
- Program file
- File descriptors
- Memory
- Accounting
- Threads

Process Resources

A process is a container.

- Process ID
- Filename
- Program file
- File descriptors
- Memory
- Accounting
- Threads
- Child processes?

Thread Resources

A thread is a unit for execution.

- Thread ID

Thread Resources

A thread is a unit for execution.

- Thread ID
- Thread state (Running, Sleeping, . . .)

Thread Resources

A thread is a unit for execution.

- Thread ID
- Thread state (Running, Sleeping, . . .)
- A set of register values

Thread Resources

A thread is a unit for execution.

- Thread ID
- Thread state (Running, Sleeping, . . .)
- A set of register values
- A stack

Process and Thread Interaction

Load program, create process, ...

Process and Thread Interaction

Load program, create process, ...

- 1 initial thread

Process and Thread Interaction

Load program, create process, ...

- 1 initial thread
- executes the `main()`-function

Process and Thread Interaction

Load program, create process, ...

- 1 initial thread
- executes the `main()`-function
- it's not a "main"-thread

Process and Thread Interaction

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
```

Process Creation

- at boot time (kernel threads, init processes)

Process Creation

- at boot time (kernel threads, init processes)
- **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)

Process Creation at request of a user

via Syscall!

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


WHAT DOES THE FORK DO?

Process Creation via fork (on Unix / Linux)

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

Process Creation via fork (on Unix / Linux)

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

The fork() function shall create a new process. The new process (child process) shall be an **exact copy** of the calling process (parent process) **except** as detailed below:

Process Creation via fork (on Unix / Linux)

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

The fork() function shall create a new process. The new process (child process) shall be an **exact copy** of the calling process (parent process) **except** as detailed below:

- unique PID

Process Creation via fork (on Unix / Linux)

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

The fork() function shall create a new process. The new process (child process) shall be an **exact copy** of the calling process (parent process) **except** as detailed below:

- unique PID
- copy of file descriptors

Process Creation via fork (on Unix / Linux)

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

The fork() function shall create a new process. The new process (child process) shall be an **exact copy** of the calling process (parent process) **except** as detailed below:

- unique PID
- copy of file descriptors
- semaphore state is copied

Process Creation via fork (on Unix / Linux)

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

The fork() function shall create a new process. The new process (child process) shall be an **exact copy** of the calling process (parent process) **except** as detailed below:

- unique PID
- copy of file descriptors
- semaphore state is copied
- 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.

Process Creation via fork (on Unix / Linux)

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

The fork() function shall create a new process. The new process (child process) shall be an **exact copy** of the calling process (parent process) **except** as detailed below:

- unique PID
- copy of file descriptors
- semaphore state is copied
- 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

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
- parent knows the child

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
- 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
    []);
```

exec

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

exec

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

- 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

- Normal exit (return value: zero)

Process Termination

- Normal exit (return value: zero)
- Error exit (return value: non-zero)

Process Termination

- Normal exit (return value: zero)
- Error exit (return value: non-zero)
- Fatal error (e.g. segmentation fault)

Process Termination

- Normal exit (return value: zero)
- Error exit (return value: non-zero)
- Fatal error (e.g. segmentation fault)
- Killed by another process

Process Hierarchies

Some operating systems have hierarchies:

- implicit hierarchy from forking

Implicit parent-child hierarchy on Unix/Linux:

Process Hierarchies

Some operating systems have hierarchies:

- implicit hierarchy from forking
- process groups in UNIX/Linux

Implicit parent-child hierarchy on Unix/Linux:

Process Hierarchies

Some operating systems have hierarchies:

- implicit hierarchy from forking
- process groups in UNIX/Linux
- doesn't exist in Windows

Implicit parent-child hierarchy on Unix/Linux:

Process Hierarchies

Some operating systems have hierarchies:

- implicit hierarchy from forking
- process groups in UNIX/Linux
- doesn't exist in Windows

Implicit parent-child hierarchy on Unix/Linux:

- when parent dies,

Process Hierarchies

Some operating systems have hierarchies:

- implicit hierarchy from forking
- process groups in UNIX/Linux
- doesn't exist in Windows

Implicit parent-child hierarchy on Unix/Linux:

- when parent dies,

Process Hierarchies

Some operating systems have hierarchies:

- implicit hierarchy from forking
- 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
```

Process/Thread State

```
git grep TODO | sort
```

- sort has to wait for input

Process/Thread State

```
git grep TODO | sort
```

- sort has to wait for input
- what does the sort do in the meantime?

Process/Thread State

```
git grep TODO | sort
```

- sort has to wait for input
- what does the sort do in the meantime?
  - loop and check (busy wait)

Process/Thread State

```
git grep TODO | sort
```

- sort has to wait for input
- what does the sort do in the meantime?
  - loop and check (busy wait)
  - sleep and get woken up

Process/Thread State

```
git grep TODO | sort
```

- sort has to wait for input
- what does the sort do in the meantime?
  - loop and check (busy wait)
  - sleep and get woken up
- blocking the process makes sense

Process/Thread State

```
git grep TODO | sort
```

- sort has to wait for input
- what does the sort do in the meantime?
  - loop and check (busy wait)
  - sleep and get woken up
- blocking the process makes sense
- do we actually block the process?

Processes vs. Threads

- Threads are more lightweight than processes

Processes vs. Threads

- Threads are more lightweight than processes
- Less independent than processes

Processes vs. Threads

- Threads are more lightweight than processes
- Less independent than processes
- No protection

Why threads?

- Things should happen in parallel - even within one application

Why threads?

- Things should happen in parallel - even within one application
- Example: text processing

Why threads?

- Things should happen in parallel - even within one application
- Example: text processing
  - typing

Why threads?

- Things should happen in parallel - even within one application
- Example: text processing
  - typing
  - spell checking

Why threads?

- Things should happen in parallel - even within one application
- Example: text processing
  - typing
  - spell checking
  - formatting on screen

Why threads?

- Things should happen in parallel - even within one application
- Example: text processing
  - typing
  - spell checking
  - formatting on screen
  - automatically saving

Why threads?

- Things should happen in parallel - even within one application
- Example: text processing
  - typing
  - spell checking
  - formatting on screen
  - automatically saving
- Some of these things may block

Why threads?

- Things should happen in parallel - even within one application
- Example: text processing
  - typing
  - spell checking
  - formatting on screen
  - automatically saving
- Some of these things may block
  - wait for mouse-click / keyboard press

Why threads?

- Things should happen in parallel - even within one application
- Example: text processing
  - typing
  - spell checking
  - formatting on screen
  - automatically saving
- Some of these things may block
  - wait for mouse-click / keyboard press
  - wait for disk

Why threads?

- Things should happen in parallel - even within one application
- Example: text processing
  - typing
  - spell checking
  - formatting on screen
  - automatically saving
- Some of these things may block
  - wait for mouse-click / keyboard press
  - wait for disk
  - etc.

Why threads

- Make programming easier

Why threads

- Make programming easier
  - Split tasks in different blocks

Why threads

- Make programming easier
  - Split tasks in different blocks
  - Like with processes

Why threads

- Make programming easier
  - Split tasks in different blocks
  - Like with processes
  - But they cooperate easily because of the shared address space

Why threads

- Make programming easier
  - Split tasks in different blocks
  - Like with processes
  - But they cooperate easily because of the shared address space
    - Consumes less memory

Why threads

- Make programming easier
  - Split tasks in different blocks
  - Like with processes
  - But they cooperate easily because of the shared address space
    - Consumes less memory
    - Attention: do not confuse *shared memory* (between processes) with *shared address space* (between threads)

Why threads

- Make programming easier
  - Split tasks in different blocks
  - Like with processes
  - But they cooperate easily because of the shared address space
    - Consumes less memory
    - Attention: do not confuse *shared memory* (between processes) with *shared address space* (between threads)
- Switching between threads can be faster

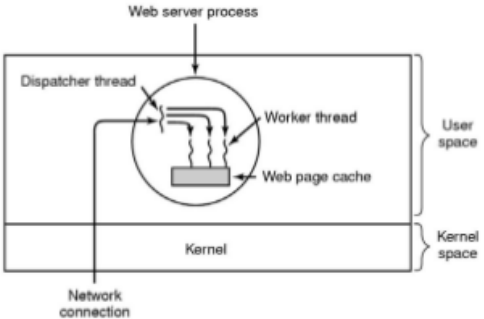
Why threads

- Make programming easier
  - Split tasks in different blocks
  - Like with processes
  - But they cooperate easily because of the shared address space
    - Consumes less memory
    - Attention: do not confuse *shared memory* (between processes) with *shared address space* (between threads)
- Switching between threads can be faster
  - No need to reconfigure memory

Why threads

- Make programming easier
  - Split tasks in different blocks
  - Like with processes
  - But they cooperate easily because of the shared address space
    - Consumes less memory
    - Attention: do not confuse *shared memory* (between processes) with *shared address space* (between threads)
- Switching between threads can be faster
  - 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

Without Threads

Without threads,

- just one thread
- complicated program structure

Without Threads

Without threads,

- just one thread
- complicated program structure
- read content from disk may block process

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

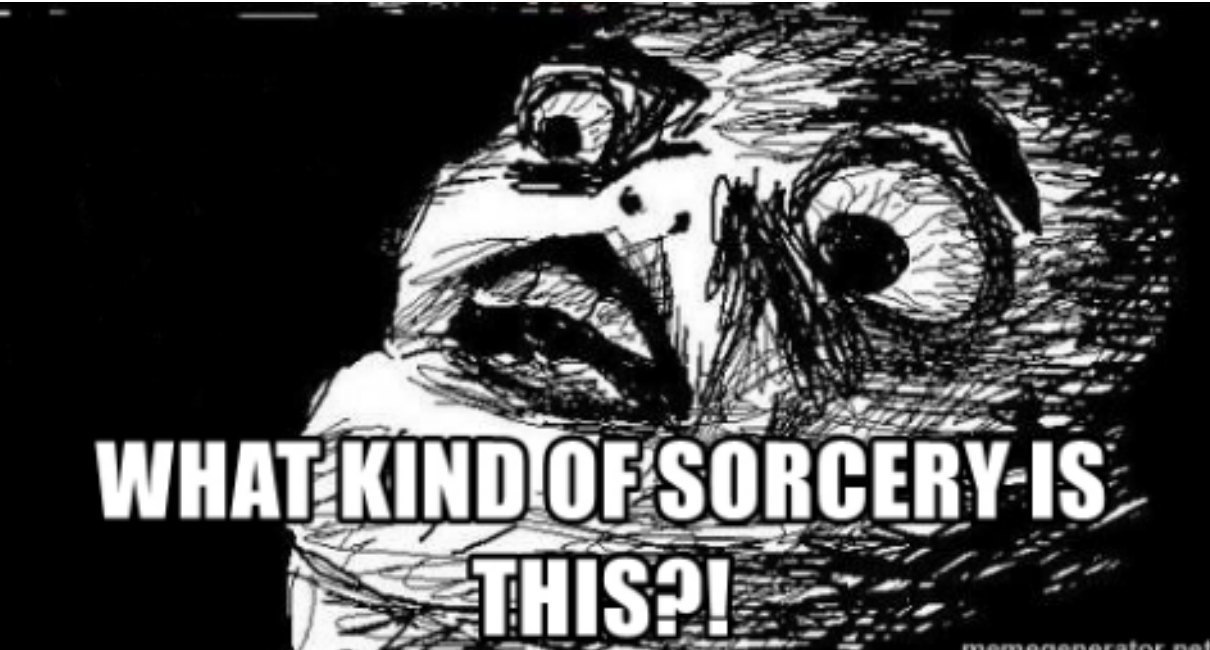
- Finite-state-machine!
- Actually simulates threads

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

- `void *(*start_routine) (void *)`
- looks wrong...

Function Pointer

- `void *(*start_routine) (void *)`
- looks wrong...
- `void* (*start_routine) (void*)`

Function Pointer

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

Function Pointer

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

Function Pointer

- `void* (*start_routine) (void*)`
- `start_routine` is the function pointer **name**

Function Pointer

- `void* (*start_routine) (void*)`
- `start_routine` is the function pointer **name**
- type: `void* (*) (void*)`

Function Pointer

- `void* (*start_routine) (void*)`
- `start_routine` is the function pointer **name**
- type: `void* (*) (void*)`
- `(*)` indicates **this is a function pointer**

Function Pointer

- `void* (*start_routine) (void*)`
- `start_routine` is the function pointer **name**
- type: `void* (*) (void*)`
- `(*)` indicates **this is a function pointer**
- takes a `void*`

Function Pointer

- `void* (*start_routine) (void*)`
- `start_routine` is the function pointer **name**
- type: `void* (*) (void*)`
- `(*)` indicates **this is a function pointer**
- takes a `void*`
- returns a `void*`

Let's make a function pointer for `main`

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

- Function pointer: `(*)`

Let's make a function pointer for `main`

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

- Function pointer: `(*)`
- +argument parenthesis:

Let's make a function pointer for `main`

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

- Function pointer: `(*)`
- +argument parenthesis:

Let's make a function pointer for `main`

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

- Function pointer: `(*)`
- +argument parenthesis: `(*)()`
- +return type:

Let's make a function pointer for `main`

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

- Function pointer: `(*)`
- +argument parenthesis: `(*)()`
- +return type:

Let's make a function pointer for `main`

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

- Function pointer: `(*)`
- +argument parenthesis: `(*)()`
- +return type: `int (*)()`
- +first argument:

Let's make a function pointer for `main`

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

- Function pointer: `(*)`
- +argument parenthesis: `(*)()`
- +return type: `int (*)()`
- +first argument:

Let's make a function pointer for `main`

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

- Function pointer: `(*)`
- +argument parenthesis: `(*)()`
- +return type: `int (*)()`
- +first argument: `int (*)(int)`
- +second argument:

Let's make a function pointer for `main`

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

- Function pointer: `(*)`
- +argument parenthesis: `(*)()`
- +return type: `int (*)()`
- +first argument: `int (*)(int)`
- +second argument:

Let's make a function pointer for `main`

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

- Function pointer: `(*)`
- +argument parenthesis: `(*)()`
- +return type: `int (*)()`
- +first argument: `int (*)(int)`
- +second argument: `int (*)(int, char*[])`

Function Pointer

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

Function Pointer

- `void* (*start_routine) (void*) = &main;`?
- type doesn't match... what now?

Function Pointer

- `void* (*start_routine) (void*) = &main;`?
- type doesn't match... what now?
- cast:

Function Pointer

- `void* (*start_routine) (void*) = &main;`?
- type doesn't match... what now?
- cast:

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

Function Pointer

- `void* (*start_routine) (void*) = &main;`?
- type doesn't match... what now?
- cast:

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

Dangerous though ;)

How to use multithreading?

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

How to use multithreading?

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

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()`.

How to use multithreading?

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

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()`.

The `attr` argument points to a `pthread_attr_t` structure whose contents are used at thread creation time to determine attributes for the new thread; this structure is initialized using `pthread_attr_init` and related functions. If `attr` is `NULL`, then the thread is created with default attributes.

How to use multithreading?

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

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()`.

The `attr` argument points to a `pthread_attr_t` structure whose contents are used at thread creation time to determine attributes for the new thread; this structure is initialized using `pthread_attr_init` and related functions. If `attr` is `NULL`, then the thread is created with default attributes.

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.

How to use multithreading?

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

How to use multithreading?

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

- `pthread_t` = thread ID

How to use multithreading?

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

- `pthread_t` = thread ID
- `pthread_t*`?

How to use multithreading?

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

- `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`.

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`.
- It returns from `start_routine()`. This is equivalent to calling `pthread_exit` with the value supplied in the return statement.

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`.
- It returns from `start_routine()`. This is equivalent to calling `pthread_exit` with the value supplied in the return statement.
- It is canceled (see `pthread_cancel`).

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`.
- It returns from `start_routine()`. This is equivalent to calling `pthread_exit` with the value supplied in the return statement.
- 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.

How do pthreads terminate?

```
void pthread_exit(void *retval);
```

How do pthreads terminate?

```
void pthread_exit(void *retval);
```

- The `pthread_exit()` function terminates the calling thread and returns a value via `retval` that (if the thread is joinable) is available to another thread in the same process that calls `pthread_join`.

How do pthreads terminate?

```
void pthread_exit(void *retval);
```

- The `pthread_exit()` function terminates the calling thread and returns a value via `retval` that (if the thread is joinable) is available to another thread in the same process that calls `pthread_join`.
- After the last thread in a process terminates, the process terminates as by calling `exit` with an exit status of zero; [...]

Waiting for threads

```
int pthread_join(pthread_t thread, void **retval);
```

Waiting for threads

```
int pthread_join(pthread_t thread, void **retval);
```

- The `pthread_join()` function waits for the thread specified by `thread` to terminate. If that thread has already terminated, then `pthread_join()` returns immediately.

Waiting for threads

```
int pthread_join(pthread_t thread, void **retval);
```

- 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);
```

Killing threads

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

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

Take Aways

- Processes divide resources amongst themselves (except processor time)

Take Aways

- Processes divide resources amongst themselves (except processor time)
- Threads divide processor time amongst themselves (and a few resources)

Take Aways

- 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