

ECE353 Lectures

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Summary: Lecture slides have all the content, lectures are just a summary of the slides, cheatsheet is a summary of the lectures.

1 Review

1.1 Converting Between Binary, Hexadecimal, and Decimal

Process:

1. **Binary to Decimal:**
 - (a) Write down the binary number.
 - (b) Assign place values, starting from 2^0 on the rightmost digit.
 - (c) Multiply each binary digit by its corresponding power of 2.
 - (d) Add all the results together to get the decimal equivalent.
2. **Decimal to Binary:**
 - (a) Divide the decimal number by 2.
 - (b) Record the remainder (0 or 1).
 - (c) Repeat the division process with the quotient until the quotient is 0.
 - (d) Write the remainders in reverse order to obtain the binary equivalent.
3. **Binary to Hexadecimal:**
 - (a) Group the binary number into groups of 4 digits, starting from the right. Add leading zeros if necessary.
 - (b) Convert each 4-digit binary group to its hexadecimal equivalent using the binary-to-hex mapping (e.g., 0000 = 0, 0001 = 1, 1110 = E).
 - (c) Combine the hexadecimal digits to get the hexadecimal equivalent.
4. **Hexadecimal to Binary:**
 - (a) Write down each hexadecimal digit.
 - (b) Replace each hexadecimal digit with its 4-bit binary equivalent.
 - (c) Combine the binary groups to get the binary equivalent.
5. **Decimal to Hexadecimal:**
 - (a) Divide the decimal number by 16.
 - (b) Record the remainder as a hexadecimal digit (0–9 or A–F).
 - (c) Repeat the division process with the quotient until the quotient is 0.
 - (d) Write the remainders in reverse order to obtain the hexadecimal equivalent.
6. **Hexadecimal to Decimal:**
 - (a) Write down the hexadecimal number.
 - (b) Assign place values, starting from 16^0 on the rightmost digit.
 - (c) Multiply each hexadecimal digit by its corresponding power of 16, converting any letters (A–F) to decimal values (A=10, B=11, etc.).
 - (d) Add all the results together to get the decimal equivalent.

1.2 Little-endian and Big-endian

Definition:

- **Little-endian:** In the little-endian format, the least significant byte (LSB) of a multi-byte data value is stored at the lowest memory address, and the most significant byte (MSB) is stored at the highest memory address.
- **Big-endian:** In the big-endian format, the most significant byte (MSB) of a multi-byte data value is stored at the lowest memory address, and the least significant byte (LSB) is stored at the highest memory address.

Example:

- For example, the hexadecimal value 0x12345678 would be stored in memory as:

78 56 34 12

- For example, the hexadecimal value 0x12345678 would be stored in memory as:

12 34 56 78

1.3 Memory

Summary: Table, int*, &a, int**a, *a, int[5], etc.

2 Why Systems Software? Kernels

Summary:

2.1 Useful Terminal Commands

Summary:

- `./hello-world-linux-aarch64` to run hello world.
- `readelf -a <FILE>` to see the ELF header.
- `strace <PROGRAM>` to trace all the system calls a process makes on Linux.

2.2 Three OS Concepts

Definition:

1. **Virtualization:** Share one resource by mimicking multiple independent copies.
2. **Concurrency:** Handle multiple things happening at the same time.
3. **Persistence:** Retain data consistency even without power.

2.3 OS Manages Resources

Definition: Insert picture.

2.4 Program

Definition: A file containing all the instructions and data required to run.

2.5 Process:

Definition: An instance of running a program.

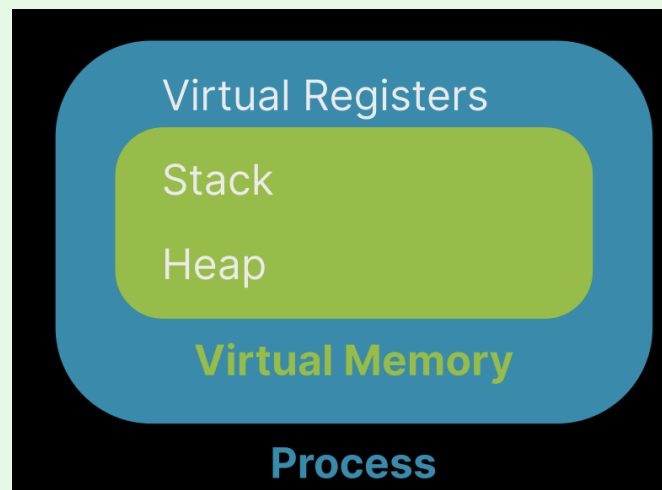


Figure 1: Process

2.5.1 Basic Requirements for a Process

Definition: Insert picture w/ virtual memory.

2.6 Process (Abstraction)

2.6.1 Static

Definition: Only able to use the global variable in the current C file.

2.6.2 Motivation for Virtualization

Motivation: How to run two different programs at the same time? Insert code.

- Was the address of local the same b/w 2 processes? Different address in physical memory b/w different processes.
- Was the address of global the same b/w 2 processes? Same address in physical memory b/w different processes, but uses virtual memory.
- What else may be needed for a process?

Warning: Local variables are stored on the stack.

2.6.3 Does the OS allocate different stacks for each process?

Definition: The stacks for each process need to be in physical memory. One option is the operating system just allocates any unused memory for the stack.

-

2.6.4 What about global variables?

Definition: The compiler needs to pick an address (random) for each variable when you compile.

- What if we had a global registry of addresses? Impossible (too much space and know memory addresses ahead of time).

Summary:

- The kernel is the part of the operating system (OS) that interacts with hardware (it runs in kernel mode).
- System calls are the interface between user and kernel mode:
 - Every program must use this interface!
- File format and instructions to define a simple “Hello world” (in 168 bytes):
 - Difference between API and ABI.
 - How to explore system calls.
- Different kernel architectures shift how much code runs in kernel mode.

FAQ:

- What is difference b/w printf and write?

2.7 File Descriptor (Abstraction)

Motivation: Since our processes are independent, we need an explicit way to transfer data.

Definition:

1. **IPC:** Inter-process communication is transferring data b/w two processes.

2. **File Descriptor:** A resource that users may either read bytes from or write bytes to (identified by an index stored in a process).
 - e.g. File or terminal.
 - e.g. 0 is standard input, 1 is standard output, and 2 is standard error.

2.8 System Calls

Definition: System calls are the interface b/w user and kernel mode.

2.8.1 System Calls Make Requests to the Operating System

Definition:

```
1 ssize_t write(int fd, const void *buf, size_t count);
```

- Description: writes bytes from a byte array to a file descriptor
 - fd: the file descriptor
 - buf: the address of the start of the byte array (called a buffer)
 - count: how many bytes to write from the buffer

```
1 void exit_group(int status);
```

- Description: exits the current process and sets an exit status code
 - status: the exit status code (0–255)

Example: Hypothetical "Hello World" Program

```
1 void _start(void) {
2     write(1, "Hello world\n", 12);
3     exit_group(0);
4 }
```

Warning: System calls uses registers, while C is stack based.

2.9 API Tells You What and ABI Tells You How

Definition:

- Application Programming Interface (API) abstracts the details and describes the arguments and return value of a function.
- Application Binary Interface (ABI) specifies the details, specifically how to pass arguments and where the return value is.

2.10 Magic

Definition: The "magic bytes" refer to the first 4 bytes of a file that uniquely identify the file format.

2.10.1 Programs on Linux Use the ELF File Format

Definition: Executable and Linkable Format (ELF) specifies both executables and libraries.

- Always starts with the 4 bytes: 0x7F 0x45 0x4C 0x46 or with ASCII encoding: DEL 'E' 'L' 'F'

Example: Hello World ELF File

1. 168 Byte Program:

- Tells the OS to load the entire executable file into memory at address 0x10000.
- The file header is 64 bytes, and the “program header” is 56 bytes (120 bytes total).
- The next 36 bytes are instructions, followed by 12 bytes for the string:
 - "Hello world\n"
 - Instructions start at 0x10078 (0x78 is 120).
 - The string (data) starts at 0x1009C (0x9C is 156).

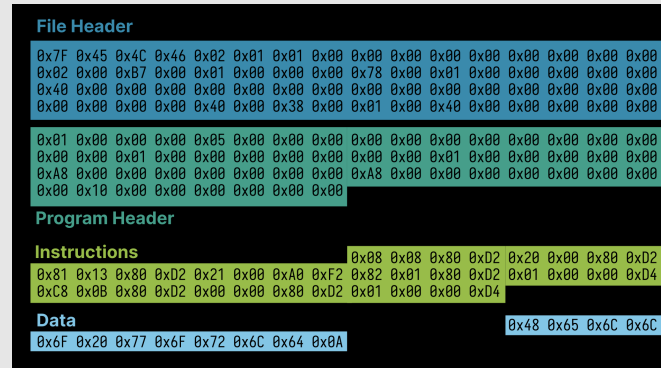


Figure 2: ELF File Division

2. **C Program:** Takes 500 bytes.
3. **Python Program:** Takes 2000 bytes.
4. **Java Program:** Takes 2000000 bytes.

2.11 Kernel

Definition: Kernel is a core part of the operating system that interacts with hardware that runs in kernel mode.

2.11.1 Kernel Mode

Definition: Kernel mode is a privilege level on your CPU that gives access to more instructions.

2.11.2 Levels of Privilege

Definition:

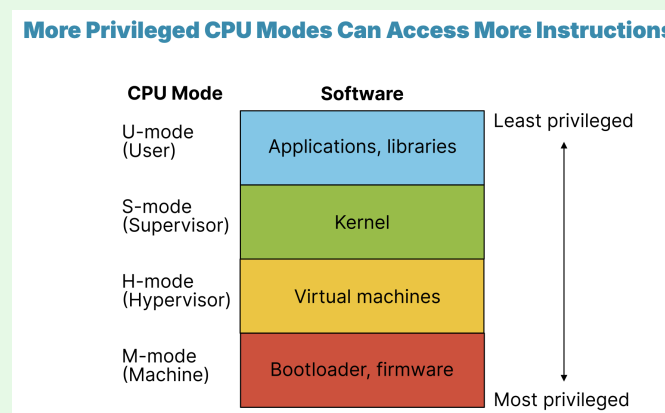


Figure 3: Levels of Privilege

2.11.3 System Calls Transition Between User and Kernel Mode

Definition:

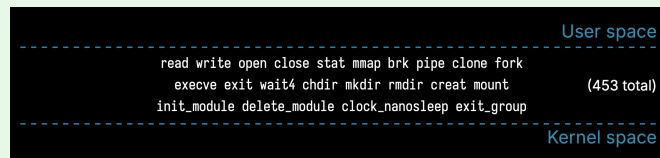


Figure 4: System Calls Transition

2.11.4 Different Types of Kernel Architectures

Definition:

- **Monolithic Kernel:** All the services are in the kernel.

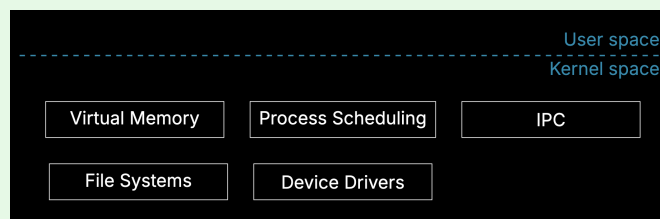


Figure 5: Monolithic Kernel

- **Microkernel:** Only the essential services are in the kernel.

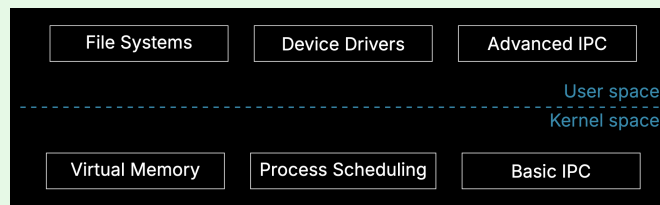


Figure 6: Microkernel

- **Hybrid Kernel:** A mix of monolithic and microkernel.
- **Nanokernel and picokernel:** Even smaller services than microkernel.

Warning: Short answer question.

3 Libraries

Summary:

- `ldd <executable>`: Shows which dynamic libraries are used by the executable.
- `-Db_sanitize=address`: Add the flag to Meson to detect memory leaks, which was built into the compiler, but you have to recompile.
- `valgrind <executable>`: Detect memory leaks from malloc and free.
 - **Warning:** GNU C library (libc.so) may allocate memory for its own uses, so it doesn't bother to free.
- Know the high-level rules of ABI changes without API changes.

FAQ:

3.1 What is an Operating System?

Definition: An operating system consists of a kernel and libraries required for your application.

Warning: OS have different libraries for different applications.

3.2 Normal Compilation in C

Definition:

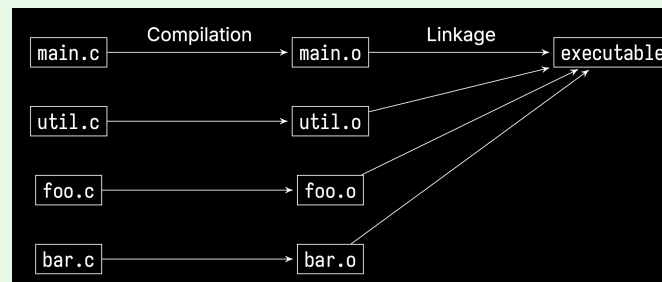


Figure 7:

Notes: Object files (.o) are ELF files with code for functions.

3.3 Static Libraries and Dynamic Libraries

3.3.1 Static Libraries

Definition:

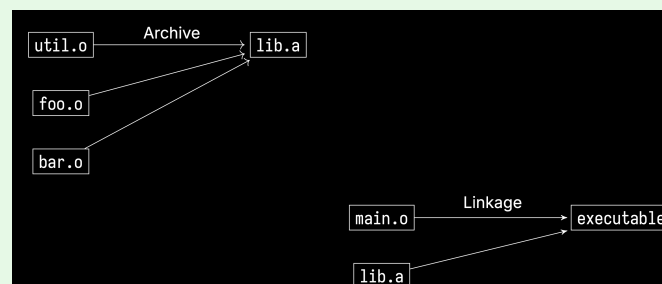


Figure 8:

- Static libraries are included at link time.

Notes:

- Put all .o files into a single .a file (i.e. library), then link the library with the application.

3.3.2 Dynamic Libraries

Motivation: C standard library (.so) is a dynamic library that is a collection of .o files containing function definitions.

Definition:

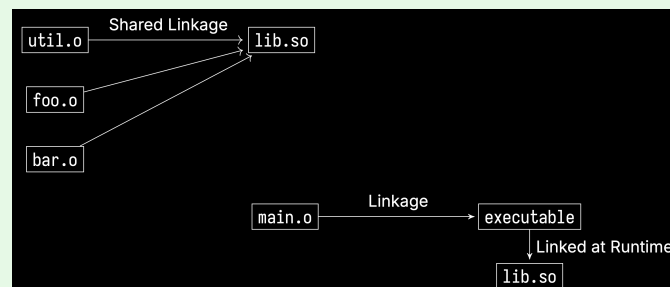


Figure 9:

- Dynamic libraries are included at runtime.
- Dynamic libraries are for reusable code. Multiple applications can use the same library.

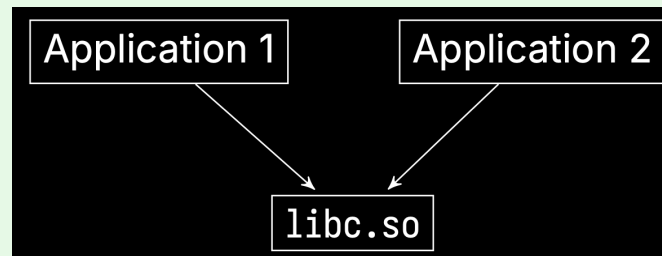


Figure 10:

- The operating system only loads `libc.so` in memory once, and shares it.
- Dynamic libraries allow easier debugging.
 - Control dynamic linking with environment variables `LD_LIBRARY_PATH` and `LD_PRELOAD`.

3.3.3 Comparison of Static and Dynamic Libraries

Notes:

- **Static:** Statically linking basically copies the .o files directly into the executable
 - Statically linking prevents re-using libraries (commonly used libraries have many duplicates)
 - Any updates to a static library requires the executable to be **recompiled**
- **Dynamic:** The executable has a reference to the dynamic library
 - Dynamic libraries updates can break executables.
 - * A dynamic library update may subtly change the ABI causing a crash.

Example:**1. Dynamic Library ABI Changes:**

- **Given:** Consider the following in a dynamic library:
 - A **struct** with multiple fields corresponding to a specific data layout (C ABI).
 - An executable accesses the fields of the **struct** used by a dynamic library.
- **Problem:** Now, if a dynamic library reorders the fields:
 - The executable uses the old offsets and is now wrong.
- **Note:** This is OK if the dynamic library never exposes the fields of a **struct**.

2. C Uses a Consistent ABI for Structs:

- **structs** are laid out in memory with the fields matching the declaration order.
- C compilers ensure the ABI (Application Binary Interface) of **structs** is consistent for an architecture.
- Consider the following structures:
 - Library v1:

```

1 struct point {
2     int y;
3     int x;
4 };
5

```

– Library v2:

```

1 struct point {
2     int x;
3     int y;
4 };
5

```

- For v1, the x field is offset by 4 bytes from the start of **struct point**'s base.
- For v2, it is offset by 0 bytes, and this difference will cause problems.

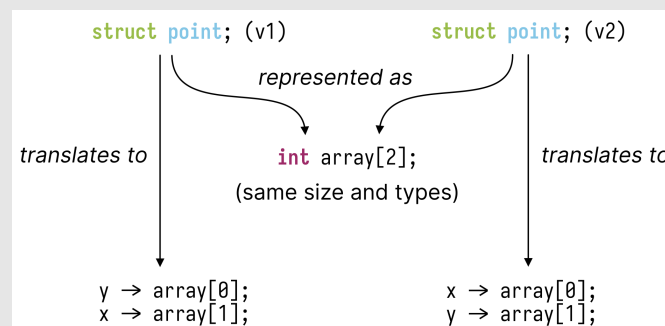
3. After Compilation the Translation Differs for Each Version:

Figure 11:

4. Point API Has 4 Functions:**libpoint.so**

```

struct point *point_create(int x, int y);
int point_get_x(struct point *p);
int point_get_y(struct point *p);
void point_destroy(struct point *p);

```

Figure 12:

5. ABI Stable Code Should Always Print "1,2" for Both Lines:

```

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

#include "point.h"

int main(void) {
    struct point *p = point_create(1, 2);

    printf("point (x, y) = %d, %d (using library)\n",
           point_get_x(p), point_get_y(p));

    printf("point (x, y) = %d, %d (using struct)\n", p->x, p->y);

    point_destroy(p);
    return 0;
}

```

Figure 13:

6. Mismatched Versions Don't Agree on the Location of X and Y:

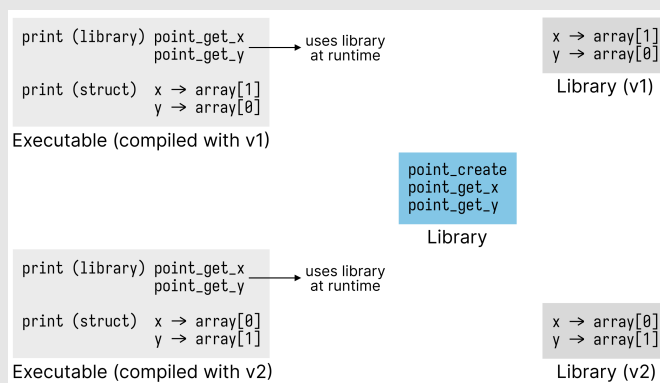


Figure 14:

7. Takeaways: The definition of struct point in both libraries is different. Order of x and y change.

- Our code works correctly if the compiled and linked versions match. If you expose a struct it becomes part of your ABI.
- A proper stable ABI would hide the struct from point.h

3.4 Semantic Versioning

Definition: Given a version number MAJOR.MINOR.PATCH, increment the:

- **MAJOR** version when you make incompatible API/ABI changes.
- **MINOR** version when you add functionality in a backwards-compatible manner.
- **PATCH** version when you make backwards-compatible bug fixes.

3.5 System Calls are Rare in C

Definition: Most system calls have corresponding function calls in C, but may:

- Set `errno`
- Buffer reads and writes (reduce the number of system calls)
- Simplify interfaces (function combines two system calls)
- Add new features

3.5.1 C exit

Definition:

- **System Call Exit (or exit_group):** Program stops at that point.
- **C Exit:** Feature to register functions to call on program exit (e.g. `atexit`).
 - i.e. Runs the function when the program exits.

Example:

```
1  #include <stdio.h>
2  #include <stdlib.h>
3
4  void fini(void) {
5      puts("Do fini");
6  }
7
8  int main(void) {
9      atexit(fini);
10     puts("Do main");
11     return 0;
12 }
```

- Return 0 is the same as calling `exit(0)`.

4 Processes

Summary:

- User space (applications, libraries) vs. kernel space (OS)
 - User space to kernel space: system calls
 - Libraries: Performs the system calls in this course.
- Open file descriptors: 0,1,2 go to Terminal (stdin, stdout, stderr)
- Process: Virtual registers, virtual memory (stacks, heap), open file descriptors.

FAQ:

- What does the terminal do with the open file descriptors?
- What does the file 1, file 2, and terminal do in the initial summary?
- Slide 3: What is PCB? Contains all the info about the process.
- Slide 3: What is a PID? Keeps track of a running process.
- Slide 4: What do the different componetns of the process state diagram mean? REWATCH
 - Created: Process is created.
 - Ready: Process is ready to run.
 - Running: Process is running, but it goes back to ready because it is waiting for something.
 - Blocked: Process is blocked, which goes to
- Slide 5: What is the proc filesystem?
 - The "proc" filesystem is a special filesystem in Unix-like operating systems that presents information about processes and other system information in a hierarchical file-like structure.
 - It is commonly mounted at '/proc'.
 - It allows users and applications to access kernel information in a structured and readable way.
- Slide 7: What is parent and child process?
 - Parent process: The original process that creates a new process.
 - Child process: The new process created by the parent process.
 - The child process is a copy of the parent process, but with a unique process ID.
- Slide 8: How to distinguish between parent and child process? 0 is returned in the child process, and the process ID of the child process is returned in the parent process.
- Slide 9: What is POSIX system? POSIX (Portable Operating System Interface) is a family of standards specified by the IEEE for maintaining compatibility between operating systems.
- Slide 9: What is man? is a command to display documentation, and use number.
- Slide 8: What happens when you call fork? Only the parent process calls the fork, and the child process is created.
- Slide 8: Will parent run first then child? No, since there two independent processes, the order of execution is not guaranteed.

4.1 Process: Adding onto the Process

Definition:

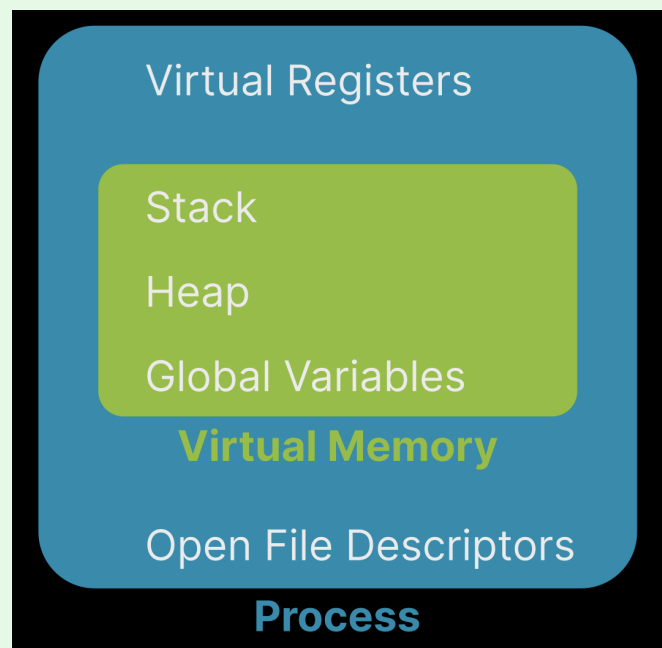


Figure 15: Process

4.2 Process Control Block (PCB)

Definition: Contains all information.

- Process state
- CPU registers
- Scheduling information
- Memory management information
- I/O status information
- Any other type of accounting information

Warning: Each process gets a unique process ID (pid) to keep track of it.

Example: In Linux, this is the `task_struct` structure.

4.3 Process State Diagram

Definition:

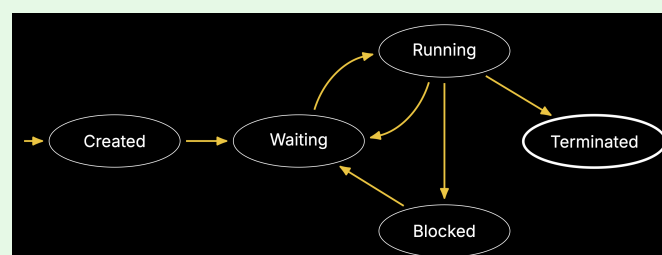


Figure 16: Process State Diagram

Notes: Waiting \iff Ready.

4.4 proc Filesystem

Definition: Read process state using the "proc" file system.

4.5 Create processes from scratch

4.5.1 Fork

Definition: `fork()` creates a new process, a copy of the current one.

```
1 int fork(void);
```

- Returns the process ID of the newly created child process:
 - -1: on failure
 - 0: in the child process
 - >0: in the parent process

4.6 Clone processes