CS 351: Systems Programming — Reference Material
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1 C Programming

C is one of the lowest "high level" languages you can use today. It provides very minimal abstractions from hardware and assembly code, but allows you to relatively good typechecked code.

1.1 Memory Allocation

Because C is a language that does not provide many abstractions, it also requires the programmer to remember and manage their memory usage. So, **YOU** must be the one to manage the memory, there is **NO** built-in garbage collector for you to use.

Memory allocation is done on the heap of the program's execution space in memory. When you allocate memory in your program, you are actually requesting the operating system to give you the memory you want.

1.1.1 `malloc`

This is the simplest function of all possible memory allocation functions. `malloc`:

- Takes one argument:
  1. The number of bytes to allocate.
- Returns a **POINTER** to the front of the allocated memory.

`malloc` ***DOES NOT*** initialize memory, so it will be garbage.

1.1.2 `calloc`

This is quite similar to malloc. `calloc`:

- Takes 2 arguments:
  1. The number of spaces to allocate, for example the number of elements in an array.
  2. The number of bytes to allocate, for the type being stored.
- Returns a **POINTER** to the front of the allocated memory.

`calloc` ***ZEROS*** memory, so this does have a slight performance penalty.

1.1.3 `realloc`

`realloc` is used to **REALLOCATE** an existing memory location.

- Takes 2 arguments:
  1. The pointer to the memory location previously allocated with either `malloc` or `calloc`.
  2. The amount of memory to reallocate, in bytes.
- If the `NULL` pointer is passed to `realloc`, it will behave exactly like `malloc`.
- Returns a **POINTER** to the front of the reallocated memory

1.1.4 `free`

`free` is used to free memory that was previously allocated, removing from the programming space entirely.

- Takes 1 argument:
  1. A pointer to the memory to be deallocated.
- Returns `void`.

2 Processes

Processes are the fundamental unit of computation within an operating system.

Defn 1 (Process)**.** A *process* is a Program in execution. A process carries out the computation that we specify. A process contains:

- Code (`text`) of your program.
- Runtime data (Global, local, dynamic variables)
- Registers:
  - Program Counter (`PC`)
  - Stack Pointer (`SP`)
  - Frame Pointer (`FP`)
- Process Control Block

Defn 2 (Program)**.** A *program* is the binary image stored at some file location on the storage medium. The program is read into memory, and then is used to start a Process that runs that program.

Processes require both a **predictable** and **logical** control flow. This means:

- The Process must start somewhere, typically defined to be `main`.
- Nothing can disrupt a program mid-execution.
  - This is further discussed in Section 2.1.

2.1 Prevent Process Disruption

The easiest way to prevent a Process from having its control flow being interrupted is for the process to "own" the CPU for the entire duration of the process's execution. However, this means:

- No other process can run on this core
- This prevents efficient multi-Process/multitasking systems
- Malicious or poorly written program can "take over" the CPU
- An idle process (for example, waiting for user input) will underutilize the CPU

For the operating system to simulate this seamless logical control flow, we use all of the information used to make a Process, and need a Process Control Block.

Defn 3 (Process Control Block)**.** The *Process Control Block* (*PCB*) contains additional metadata about a Process. This includes:

- Process ID (`PID`)
- CPU Usage
- Memory Usage
- Pending Syscalls

The Process Control Block is sued to allow Processes to be interrupted, saved, and moved off a core. This allows the operating system to schedule processes according to some algorithm.

Defn 4 (Syscall)**.** A *syscall*, short for a *system call* is a way for a user-level Process to perform some computation that the operating system kernel restricts. Some common syscalls are:

- Opening a file
- Reading a file
- Writing a file
- Closing a file
- Creating a process
- Changing the process's binary
- Reading from the network
- Writing to the network

2.2 Required Hardware

Interrupting the execution of a Process requires some hardware support to be possible and efficient. We need 3 things:

1. A hardware mechanism to periodically interrupt the current Process to change execution to the operating system.
   - This is usually the *periodic clock interrupt*.
2. An operating system procedure to decide which processes to run, and in which order.
   - This is the operating system's Process Scheduler.
3. A routine for seamlessly switching between processes.
   - This is called a Context Switch.
   - Relatively speaking, these are expensive to perform.
   - **These are external to a Process's logical control flow**.
   - This forms part of the process of Exceptional Control Flow.
   - A Context Switch makes no guarantee about if and/or when this Process will start running again.
   - A Context Switch is the only way to invoke Syscalls.

To schedule Processes onto one of possibly many CPUs, there are programs called Process Schedulers.

Every time the Process Scheduler schedules a new Process, or when a process needs to perform a Syscall, or a kernel-level exception occurs, a Context Switch is made.

Defn 5 (Context Switch)**.** A *context switch* is the process of interrupting a Process, saving its current state, and scheduling something else to run on that CPU. This is done whenever a Syscall is made, and happens sometimes during a process's lifetime.

Context Switches form a core part of the Exceptional Control Flow.

2.3 Process Scheduling

Process scheduling is the process by which a process is put "scheduled" onto a particular CPU, according to some criteria. There are any number of scheduling algorithms, each of which optimizes for certain cases, and may yield a different order of process execution.

Defn 6 (Process Scheduler)**.** The *process scheduler* is an operating system component that chooses which Process to run next. It chooses this according to some algorithm, each of which might change the order of process execution.

One such Process Scheduler is the Priority Scheduling algorithm.

2.3.1 Priority Scheduling

Priority scheduling involves placing a priority on every Process that can be scheduled. Then, the process with the highest priority is chosen first, working our way down to the lowest priority. This is, partly, the setup most modern operating systems take today.

However, priority scheduling creates new issues that must be dealt with. One of these is Starvation.

Defn 7 (Starvation)**.** *Starvation* is when something that needs a resource to function does not receive this resource.

In this case, a lower-priority Process can experience Starvation if only higher-priority processes are present, and continually steal CPU execution time.

2.4 Exceptional Control Flow

To illustrate the power of Exceptional Control Flow, we will use an example piece of code, Listing 1.

Defn 8 (Exceptional Control Flow)**.** *Exceptional control flow* is designated by the fact that most of the computation involved is done in response to exceptions or special events. Which one depends on what "exceptional" means in that circumstance.

If there was an exception of any kind during the execution of the `while`-loop, then the process would be interrupted by the kernel, and Context Switched out. From there, the exception would be handled (if possible), and then the operating system would continue execution (if possible). While the execution of the Process was non-sequential, the process **is not aware** of this fact. **ALL** of the process's state is saved **before** the context switch, so that when the process is switched back in, it continues executing from the **same** spot as before.

There are 2 kinds of exceptions in operating systems today:

1. Synchronous Exceptions
2. Asynchronous Exceptions

```c
#include <stdio.h>

int main() {
        while (1) {
                printf("Hello world!\n");
        }
        return 0;
}
```

Listing 1: Exceptional Control Flow Example

2.4.1 Synchronous Exceptions

Defn 9 (Synchronous Exception)**.** A *synchronous exception* is one that is caused by the **currently executing** Process. These are usually things that the process wants to bring to attention, or to have handled.

2.4.1.1 Traps

Defn 10 (Trap)**.** A *trap* is a Synchronous Exception caused **by** the currently executing Process. A trap is caused by the process making a Syscall.

Remark 10.1 (Interaction with Scheduling)*.* A Trap will make the Process that made the Syscall Context Switch out of execution. The Process Scheduler makes **no** guarantees **when** the process will run again.

2.4.1.2 Faults

Defn 11 (Fault)**.** A *fault* is an unintentional failure in the Process and may or may not be recoverable.

A short list of common Faults includes:

- Segmentation Fault, Unrecoverable
- Protection Fault, may or may not be recoverable
- Page Fault, Recoverable
- Divide-by-zero, Possibly Recoverable

It's possible to recover from a Fault by having the fault handler fix the problem.
In addition, there may be a Context Switch after this action.

Unrecoverable : **Will** be a Context Switch, as this Process terminates.
Recoverable : **May** be a Context Switch, depending on the Process Scheduler.

2.4.1.3 Aborts

Defn 12 (Abort)**.** An *abort* is an **unintentional** and **unrecoverable** error. The Process is terminated by the operating system. If too many errors accumulate, the OS might terminate itself.

2.4.2 Asynchronous Exceptions

Defn 13 (Asynchronous Exception)**.** An *asynchronous exception*, typically called an *interrupt* is one caused by events **external** to the current Process. On older keyboards that used the PS/2 interface, pressing a key on the keyboard would generate an asynchronous exception. On modern computers, pressing `Ctrl+C` will produce a `SIGKILL` signal, which is another asynchronous exception.

These are typically associated with specific hardware pins on the CPU. A check for Asynchronous Exceptions is performed after **every** CPU cycle. These types of exceptions are handled with/by interrupt handlers.

Defn 14 (Interrupt Handler)**.** An *interrupt handler* takes the current state of the system and the Asynchronous Exception that was just raised, and handles the exception, then returns to another Process.
The steps involved are:

1. Save Context

2. Load OS Context
3. Execute the Interrupt Handler
4. Load context for the next process given by the scheduler
5. Return to the next process

Remark 14.1. These handlers are fairly lightweight, but having more and more interrupts **will** affect performance.

3 Process Management

In almost all modern systems today, there are many, many Processes running "simultaneously". That is in quotes because if you have multiple cores/Central Processing Units in a single package, you actually *can* run multiple processes at once. However, we choose to limit our discussion to single core packages, to simplify our discussions and remove a whole class of issues.

By default, there is only one Process running at the start of a computer's execution. We need ways to make more processes, change what Programs these processes are executing, and a way to wait for these processes to finish and pick up after them.

3.1 Making Processes, `fork`

`fork` creates a **copy** of the current Process. This is our *only* method of creating new processes. The child process is nearly an **exact** duplicate of the parent process, where only some process metadata in the Process Control Block is different. The function prototype for `fork` is shown in Listing 2.

After a `fork`, the parent and child share the same:

- Registers:
  - Program Counter `PC`. The child starts **at the same place in the program as the parent**.
  - Stack Pointer, `SP`
  - Frame Pointer, `FP`
- Open Files

```
1 #include <unistd.h>
2
3 /* typedef int pid_t */
4
5 pid_t fork();
6 /* Makes a system call to trap to the OS.
7  * This requests the OS to create a new process.
8  * This is mostly a duplicate of the original. */
```

Listing 2: `pid` Definition and `fork()` Declaration

`fork` returns **twice**.

- Once to the parent Process, with the `PID` of the child (> 0).
- Once to the child process, with the return code of `fork`. A returned value of `0` indicates success; it is a sentinel value.

`pid_t` is a system-wide unique Process IDentifier (`PID`). It is `typedef`-ed from an integer, so normal integer arithmetic and rules apply.

Listing 3 code will print `Hello World!` twice, but in no particular order. The reason that we don't have garbage being printed out to the screen is because the `STDOUT` stream has a lock associated with it, only allowing one Process to use the screen at a time.

Listing 4 will print `Hello World!` four times, but in no particular order. The main parent Process has 2 children, and the parent's **first** child makes another child.

3.1.1 Using Processes

There is usually a split in the logical control flow between the parent and child, making them take different actions. This is possible because the parent and child Processes receive different return values. A simple example of this is shown in Listing 5.

The results from Listing 5 executing is that both print statements are executed. But, you are not guaranteed the order in which they execute. Some orders that exist are:

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

int main(void) {
        fork();
        printf("Hello World!\n");
        return 0;
}
```

Listing 3: `fork()` Usage

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

int main(void) {
        fork();
        fork();
        printf("Hello World!\n");
        return 0;
}
```

Listing 4: `fork()` Usage

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

void fork0() {
        int pid = fork();
        if (pid == 0) {
                printf("Hello from child\n");
        } else {
                printf("Hello from parent\n");
        }

        return;
}

int main(void) {
        fork0();
        return 0;
}
```

Listing 5: Using `fork()`, Performing Separate Actions

- Child prints first, seen in Listing 6.

```
$ ./a.out
Hello from child
Hello from parent
```

Listing 6: Post- `fork` , Child Finishes First

- Parent prints first, seen in Listing 7.

```
$ ./a.out
Hello from parent
Hello from child
```

Listing 7: Post- `fork` , Parent Finishes First

- Child and parent print at the same time. But, there is a lock for the screen, blocking multiple Processes from printing out at the same time. This lock is what makes the output text appear in order.

3.1.2 `fork` Fails

`fork` , like most other Syscalls will return `-1` on a failure. The global variable `errno` is populated with the cause of the failure To access `errno`, refer to Listing 8.

```c
#include <errno.h>

extern int errno;
```

Listing 8: Using `errno` to get Error Return Codes

3.1.3 `fork` Bomb

A fork bomb just generates new Processes as fast as possible, overloading the system. A simplistic one is shown in Listing 9.

```c
#include <unistd.h>

int main() {
        while(1)
                fork();
        return 0;
}
```

Listing 9: `fork()` Bomb

3.2 Terminating Processes, `exit`

There are several possible ways for a Process to terminate.

- The simplest way to terminate a Process is for the main process to `return`. If we are being pedantic, the compiler actually implicitly inserts an `exit` in this case, making all possible exits from a process use `exit`.
- The `exit` Syscall.
  - This exits immediately
  - This may prevent a normal `return`

The standard UNIX **convention** is that exit status `0` is success, and any other value is some error code.

3.2.1 `atexit`

`int atexit (void (*fn)())` is a unique function. It registers a function that will be called after a Program has had `exit` called on it, but before it fully exits. This registration is achieved by passing a pointer to the function that shoudl be run. The registartion must happen some time before the `exit`. There is no particular place this registration **MUST** happen though.

In addition, these handlers are inherited by child Processes.

3.2.2 Zombie Processes

All processes become Zombie Process eventually, awaiting to be Reaped.

Defn 15 (Zombie Process)**.** A *zombie process* is one that is "dead", because it finished its execution, but is still tracked by the OS, because the parent has not used/Reaped/`wait`-ed them yet. This means:

- The `PID` remains in-use.
- The child Process's `exit` status can be queried.

ALL terminating/terminated processes turn into zombies.

Remark 15.1 (Processes Responsible for Reaping)*.* All processes are responsible for Reaping their own (immediate) children. If a program has 2 forks, the child of the child is **not** reaped by the original parent.

Remark 15.2 (Orphaned Process)*.* If a Process is completely *orphaned*, it transfers ownership to `PID = 1`, which will then Reap it.

If the parent Process did **NOT** Reap its children, the only way to remove these Zombie Processes is by **killing** the parent processes. Note that this is **not** the same as terminating the process.

Defn 16 (Reap)**.** To *reap* a Process is to clean up after the process. This means closing any files, freeing any resources used, then reading the `exit` code from the child (the one being reaped), and freeing the process itself.

Typically, this is done with the `wait` Syscall.

3.3 Getting Values from Processes, `wait`

The `wait` Syscall is the one that allows parent Processes to receive values back from their children. It is only called by a process with $>= 1$ children.

The `wait` Syscall:

1. Waits (if needed) for a child to terminate, and returns the `exit` status of the child. This informs the parent:
   - Termination cause
   - Normal/abnormal termination
   - Some macros are defined to find out the exit status of a process. There are **MANY** more than the ones below, I just listed a couple.

     `WIFEXITED(status)` **:** Did the process `exit` normally?

     `WEXITSTATUS(status)` **:** What was the `exit` status of the child?
2. Reaps the zombified child. If the number of Zombie Processes is ≥ 1, and no specific one was given to `wait`, then `wait` picks a child.
3. Returns the reaped child's `PID` and exit status via pointer (if non-`NULL`)

If `wait` is called by a Process with no children, `wait` returns `-1` and populates `errno` with an appropriate error code.

How to use `wait` is shown in Listing 10.

3.3.1 Synchronization Mechanism

`wait` also functions as a synchronization mechanism. If a parent Process `wait`-s for the child to finish, this synchronizes things between the parent and the child. An example, in code, is shown in Listing 11.

3.4 Changing the Running Program, `exec`

`exec` is almost never used directly. Instead, its family of syscalls is used, which all provide some amount of abstraction from the base `exec` call.

All of these are front-ends to `exec`.

1. `execl`

```c
#include <unistd.h>
#include <stdio.h>
#include <stdlib.h>
#include <sys/wait.h>

int main() {
        pid_t cpid;
        if (fork() == 0) {
                exit(0); /* Child -> Zombie */
        }
        else {
                cpid = wait(NULL); /* Reaping Parent */
        }

        printf("Parent pid = %d\n", getpid());
        printf("Child pid  = %d\n", cpid);
        while(1);
}
```

Listing 10: `wait()` Usage

```c
#include <stdlib.h>
#include <stdio.h>
#include <sys/wait.h>
#include <unistd.h>

void fork9() {
        if (fork() == 0) {
                printf("HC: hello from child\n");
        } else {
                printf("HP: hello form parent\n");
                wait(NULL);
                printf("CT: child has terminated\n");
        }
        printf("Child is dying. Bye\n");
}

int main() {
        fork9();
        return 0;
}
```

Listing 11: Using `wait()` as a Synchronization Tool

2. `execlp`
3. `execv`
4. `execvp`
5. `execve`

The variations in the families are denoted by the last letters in the function.

`l`: Arguments passed as list of strings to `main()`.
`v`: Arguments passed as array of strings to `main()`.
`p`: Path(s) to search for running program.
`e`: Environment (Environment variables and other state) specified by the caller.

Each of these can be mixed to some extent. The only constant between all of these is that the first argument, the name of the file to execute.

All of these execute a **new Program** within the **current Process context**, meaning **NO** new `PID` is given. When called, `exec` **never returns**, because it immediately starts the execution of the new program. This is because the binary image is replaced in-place.

How to use `exec` is shown in Listing 12.

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

int main() {
        execl("/bin/echo", "/bin/echo",
              "hello", "world", (void *)0);
        /* Everything below the execl becomes unreachable code, as the new
         * program REPLACES the original binary. */
        printf("Done exec-ing...\n");
        return 0;
}
```

Results:

```
$ ./a.out
hello world
```

Listing 12: `exec()` Usage

`exec` is a strong complement to `fork`, because we can make a new Process with `fork`, then change the new child to a new program with `exec`. An example of this, in code, is shown in Listing 13.

Results:

```
$ ./a.out
-rwxr-xr-x 1 ... a.out
-rwxr-xr-x 1 ... demo.c
Command completed
```

3.5 Signals

One way to pass information between Processes that are not constantly, directly communicating is through the use of Signals.

Defn 17 (Signal)**.** *Signal*s are messages delivered by the kernel to the user Processes. These can occur in the cases of:

- In response to OS events (segfault)
- The request of another process

Signals are delivered by a Signal Handler function in the **receiving process**.

```c
#include <unistd.h>
#include <sys/wait.h>
#include <stdio.h>
#include <stdlib.h>

int main() {
        if (fork() == 0) {
                execl("/bin/ls", "/bin/ls", "-l", (void *)0);
                exit(0);
        }
        wait(NULL);
        printf("Command Completed\n");
        return 0;
}
```

Listing 13: Using `fork()` and `exec()`

```c
#include <unistd.h>
#include <sys/wait.h>

int main() {
        int stat; /* stat is for the status of the child. */
        pid_t pid;
        if ((pid = fork()) == 0)
                while(1); /* Child goes into infinite while-loop. */
        else {
                kill(pid, SIGINT); /* Parent INTERRUPTs child with SIGINT*/
                wait(&stat);
                /* Signal handler in the parent to handle how a child handled a signal. */
                if (WIFSIGNALED(stat))
                        psignal(WTERMSIG(stat), "Child term due to:");
        }

        return 0;
}
```

Listing 14: Using Signals

An example of how Signals can be used is shown in Listing 14.
It can be useful to send a signal to multiple processes at once, in which case, the signal can be sent to a Process Group.

1. Signals can be delivered at *any time*
   - Interrupt **anything NONATOMIC**
   - Problematic if using global variables
   - Thus, minimize the use of global variables and their use in Signal Handlers
     - If global variables are needed, use data that can be read/written atomically.
2. A Signal Handler may execute in overlapping fashion (even with itself).
   - It does this when there are multiple signals to handle
   - Try to create separate Signal Handlers for different Signals.
     - Otherwise, signal handlers MUST be *Reentrant*
3. Execution of Signal Handlers for *separate* signals may overlap.
   - Any functions these Signal Handlers call may overlap as well
   - Thus, keep signal handlers simple
   - Minimize calls to other functions
4. Race conditions can be caused by this concurrency because we cannot predict when:
   - A child terminates
   - A Signal will arrive
   - We need to ensure that certain sequences *cannot be interrupted*

Defn 18 (Reentrant)**.** A *reentrant* program or function is one that is able to be called, repeatedly, while already executing.

3.5.1 Signal Lifecycle

1. Sending a signal to a process or a Process Group.
   - The `void kill(pid_t pid, int sig)` function is an example of a function that sends a Signal.
   - Give the process with `pid` the Signal `sig`.
   - There is a list of signals with names and values. The actual list is **MUCH** longer, but a few are shown below.
     1 `SIGHUP :` Terminate process, Terminal line hangup
     2 `SIGINT :` Terminate process, Interrupt program.
     3 `SIGQUIT :` Create core image/dump, quits program.
2. Registering a Signal Handler for a given Signal.
   - Some Signals cannot be caught by the Process.
   - The function `sig_t signal(int sig, sig_t func)` registers a function (`func`) to a particular signal (`sig`).
   - Children inherit their parent's signal handlers after a `fork`.
   - Children lose their parent's signal handlers when they `exec` to another Program.
3. Delivering a Signal to a Process (done by kernel).
   - 2 Bitmaps per Process
     (a) Pending
     (b) Blocked
   - There is no queue or counter for signals, as this functionality is not supported by a Bitmap
     - However, they are dealt with in a particular order
     - The order is from higher number to lower number, lower to higher priority (31 -¿ 0)
   - Some Signals cannot be delivered/blocked (`SIGKILL`, and others)
   - Newly `fork`-ed child inherits the parent's blocked bitmap, but pending vector is empty.
4. Designing a Signal Handler.
   - If the same signal is received while that signal handler is running
     - Nothing special happens.
     - The handler is already running, and when it finishes, the value in the Bitmap will be zeroed out, indicating completion.
   - If we receive a higher priority (lower-number) signal while handling a lower-priority (higher-number) one:
     - Preempt the lower priority handler with the higher one.
     - The higher priority will interrupt the higher priority and be run.

– If it is possible, the lower-priority signal will be handled after the higher priority one is complete.

Defn 19 (Bitmap)**.** A *bitmap* of *bitmask* is a data structure of finite size where each component element can either be a `0` or a `1`. These are used for keeping track of information about existence. They are done this way, because we can very easily check for the existence of something by performing a bitwise operation.

The kernel uses these Signal Bitmaps before a Process starts/resumes. Before resuming a process, the kernel computes `~pending & blocked`

- Remember that this is bitwise NOT (`~`) and bitwise AND (`&`).
- The result of this operation determines which signals get delivered to the process before the process begins regular execution.

The Signal Bitmaps are held in **kernel memory**.

3.5.2 Process Groups

Defn 20 (Process Group)**.** A *process group* is a way to logically group several Processes together. Child processes `fork`-ed inherit their process group ID `pgid` from their parent. This leads to the following properties:

(i) The founder of the group becomes the group leader.
(ii) The group leader is the Process where `pid == pgid` .
(iii) A Process can become a group leader by `setpgrp` .
(iv) The whole Process Group interacts with the Signals.
(v) If `kill` is given a negative value, it will kill the corresponding process group.

Remark. For most Processes started from a shell, they inherit the shell's Process Group ID. This can be changed through the `setpgrp` function. If this is done, any subsequent child processes started by this one will inherit that new `pgid`.

3.5.3 Registering Signal Handlers

Before we run our program, many Signal Handlers are registered to handle certain Signals in certain ways. However, we can choose to override them, or define new ones, if we so choose.

Defn 21 (Signal Handler)**.** A *signal handler* is a function that has been registered to handle one particular signal. These can be used to override some default handlers, but there are some handler functions, like the one for `SIGTERM` that are not allowed to be changed.

An example of the registration of a Signal Handler is shown in Listing 15.

3.5.4 Adjusting Signal Masks

If we want to modify the Signal state Bitmaps, we use the `sigprocmask` function.

`sigprocmask` has the following prototype: `int sigprocmask(int how, const sigset_t *set, sigset_t *oldset)` . The returned `int` is either `0`, for success, or `-1` for failure. The three parameters are:

`how` How to deal with the signals. There are three options here, defined as preprocessor constants in `signal.h`.
- `SIG_BLOCK` The set of blocked Signals is the union of the current set and the `set` argument.
- `SIG_UNBLOCK` The Signals in `set` are removed from the current set of blocked signals.
- `SIG_SETMASK` The set of blocked signals is set to the argument `set`.

`*set` The set of Signals to block that should be applied to the current set.
`*oldset` The previous set of blocked Signals. You do not **need** to pass something in here, but if you are interested in getting the signal mask at some point, you will want to have a variable to assign here.

By using `sigprocmask`, you are explicitly telling the system you want to block handling a particular set of Signals, until you unblock that particular set of signals.

4 Input/Output (I/O)

In UNIX, I/O devices include:

- Disk
- Terminal

```c
#include <unistd.h>
#include <sys/wait.h>

int main() {
        int stat; /* stat is for the status of the child. */
        pid_t pid;
        if ((pid = fork()) == 0)
                while(1); /* Child goes into infinite while-loop. */
        else {
                kill(pid, SIGINT); /* Parent INTERRUPTs child with SIGINT*/
                wait(&stat);
                /* Signal handler in the parent to handle how a child handled a signal. */
                if (WIFSIGNALED(stat))
                        psignal(WTERMSIG(stat), "Child term due to:");
        }

        return 0;
}
```

Results:

```
$ ./a.out
^CRelaying SIGINT to child
Child Dying
```

Listing 15: Registering Signal Handlers

```c
#include <stdlib.h>
#include <signal.h>

int main(void) {
        sigset_t mask;
        sigemptyset(&mask);
        sigaddset(&mask, SIGINT);
        sigaddset(&mask, SIGALRM);

/* Block the set of signals specified in `mask'
 * Do not collect the previous set of blocked signal by passing `NULL'*/
        sigprocmask(SIG_BLOCK, &mask, NULL);

        return 0;
}
```

Listing 16: Using `sigprocmask`

- Shared Memory
- Printer
- Network

This is mostly because UNIX made the design decision to try to view every component of a system as a File.

Due to the variety of I/O devices that need to be supported, there are a vast number of different mechanisms for using these devices. But, there are a few common mechanisms, requirements, and activities:

- Read/Write Ops
- Metadata:
  - Name
  - Position
  - Directory Name
  - Creation Date
  - Last Access Date
  - IP Address
  - MAC Address
  - TCP Packet Sequence Number
- Robustness
- Thread-safety

There are few general concerns that we need to have about the idea of viewing everything as a File.

- How are I/O endpoints represented?
  - File Descriptor
- How do we perform I/O?
  - Byte at a time
  - Give a chunk of memory and later check that the requested I/O completed?
- How do we perform I/O *efficiently*?
  - Efficiency depends on what we define efficient to be. Essentially, what are we optimizing for?

4.1 I/O Devices

There are 2 major types of I/O devices on UNIX systems:

1. Block Devices
2. Character Devices

Defn 22 (Block Device)**.** A *block device* is an I/O device that accesses and stores data in fixed-sized blocks. Typically, this also means they have fixed total size as well. This means they support seeking through their contents and random access for parts of their contents.

Some typical devices classified as this are:

- Disk
- Memory

Defn 23 (Character Device)**.** A *character device* is an I/O device that access and receives data as a stream. This means it receives "characters" as a stream, one-by-one. There is no support for seeking or random access of the stream, because we are getting the data as soon as it is being given.

Some typical devices in this category are:

- Network
- Mouse
- Keyboard

4.2 Filesystem

The filesystem acts as a namespace for devices, and allows for the efficient storage of data on Block Devices. A typical file system consists of two types of files:

1. *Regular files* consist of ASCII or binary data
   - Directories

2. *Special Files* may represent:
    - In-memory structures
    - Sockets
    - Raw Devices

4.3 Files

Defn 24 (File)**.** A *file* is an operating system abstraction over some other data. It allows us to interact with many different file systems and devices over a variety of protocols in a abstract and concise way. A file can be accessed by using a *fully qualified path*.

The only thing each file **MUST** have is a unique `inode`.

Defn 25 (`inode`)**.** The *inode* is a filesystem-unique number (Typically, there is one filesystem per device, so this is typically a per-device-unique number). The inode tracks:

- Ownership
- Permissions
- Size
- Type
- Location
- Number of Hard Links

Defn 26 (Hard Link)**.** A *hard link* is a link between `inode`s. Thus, they each point to the same data, and must have the same name. When one of the links is deleted, the total count for that inode decreases. Once the inode reaches `0` hard links, it is removed (deleted) from the system.

Defn 27 (Symlink)**.** A *symlink* (*symbolic link*, *soft link*) is a link between Files. Thus, the link points to the file, which then points to the data. The link is not required to have the same name as the original file. However, if the file that the symlink is pointing to is deleted, then we are left with a dangling pointer.

However, the items discussed above are held strictly in storage, hard drive, meaning they aren't good for regular use, as they are too slow.

Remark. Barring you doing something like setting up a portion of your RAM as a "hard drive", allowing for ridiculous performance.

Thus, we load and open an `inode` into Memory, and call this copy a `vnode`.

Defn 28 (`vnode`)**.** A *vnode* is a copy of the `inode` of the current file. Every currently open file has a **single** `vnode`.

Now that we have a way to efficiently access a file in-Memory, using the `vnode` structure, how can we "open" the same File multiple times? This is handled by the File Description structure.

Defn 29 (File Description)**.** The *file description* allows the kernel to track which Process has opened which File and trace them back to their `vnode`. For **each process**, the kernel maintains a table of pointers to its open file structures. This table points to each file descriptor, which then point to the backing `vnode`s.

The file description tracks:

- Position
- Access Mode
- Pointer to the backing vnode

There is an open file description for **each occurrence** of a File's opening.

However, all of the structures discussed above are in **kernel memory**, meaning user Processes cannot interact with them. This is where the File Descriptor comes in.

Defn 30 (File Descriptor)**.** The *file descriptor* is the index of this file in the File Description table. There are always three file descriptors defined at the beginning of a Program's execution.

1. FD `0` is STanDard INput (`STDIN`)
2. FD `1` is STanDard OUTput (`STDOUT`)
3. FD `2` is StanDard ERRor (`STDERR`)

After opening a file, **all** file operations are performed using File Descriptors. This obscures kernel I/O and filesystem implementation details from the user, allowing for an elegant and abstract I/O API.

4.4 System-Level I/O API

Input and output is one of the basic operations that a program of any use will have to do. Below, there is a list of common Syscalls for performing these operations. These Syscalls are the lowest-level I/O calls we can make for files

`int open(const char *path, int oflag, ...)` Opens a File.

- Loads `vnode` for File at `path`
- `oflag` is a bitwise OR of `O_RDONLY`, `O_WONLY`, ...
- Creates and initializes a new File Description in the table
- Returns the first unused File Descriptor available
- If you open the same file twice, then you get a new file descriptor (a new file description is made), but it points to the same `vnode`
- Process inherits parent's open files across a `fork`
- Process retains them after an `exec`
- Parent and child share:
  - File position
  - File Access mode
- Sharing this file description allows for coordinating between separate process
- You can mirror this inside of a single process by using the `dup` syscall.

`int fstat(int fd, struct stat *buf)` Query for file metadata

- `struct stat fstat.st_ino` Get inode number
- `struct stat fstat.st_size` Get file size
- `struct stat fstat.st_nlink` Get number of hard links

`int dup(int fd)` Duplicate the given File Descriptor and return a new file descriptor that points to the same File.

`int dup2(int fd1, int fd2)` Duplicate `fd1` such that `fd2` writes to the same `vnode`.

- We can use this to change the File Descriptor in use, allowing us to write to 2 locations at once.

`int close(int fd)` Close this File Descriptor.

- Delete the File Descriptor and deallocate the File Description.
- Once all File Descriptions of that point to this `vnode` are closed, the vnode is freed and the File is really closed.

`off_t lseek(int fd, off_t offset, int whence)`

`ssize_t read(int fd, void *buf, size_t nbytes)`

- Read up to `nbytes` from `fd` into the buffer `buf`.
- Blocks until at least one byte is available.
- Returns the number of bytes **actually** read.

`ssize_t write(int fd, void *buf, size_t nbytes)`

- Write up to `nbytes` into the open file at `fd` from `buf`.
- Returns the number of bytes **actually** written.

4.4.1 Why up to `nbytes`?

The `nbytes` parameters in `read` and `write` are necessary because the kernel attempts to maximize performance and minimize throughput. By knowing these terms, it makes it easier to schedule disk reads and writes, and allows for more efficient kernel buffering.

Each of the items in the list below are each valid reasons to have to specify the number of bytes to manipulate.

- `read`
  - `EOF`
  - Unreadablbe `fd`, for example when the disk is failing.
  - If the file is slow, this allows reading, a quick return to the Process ASAP and allow it to decide to read again or do something else.
  - Interrupt, for example from a Context Switch.

- `write`
  - Out of space, for example when the file is full, or when there is no more storage space on the backing media.
  - Unwritable `fd`
  - Slow File
  - Interrupt

A Computer Components

A.1 Central Processing Unit

Defn A.1.1 (Central Processing Unit)**.** The *Central Processing Unit*, *CPU*, is a chip that performs all actions in the computer. It calculates mathematical and logical values and acts based on them. It has several components built onto it, and can be thought of as the "brain" of the computer.

The design of a CPU determines some of the functionality it has. Therefore, more specialized processors can be made for special tasks, and more general processors can be built to handle a wide variety of calculations.

A.1.1 Registers

Defn A.1.2 (Register)**.** A *register* is a data storage mechanism built directly onto the Central Processing Unit. It is several hundred times faster than the system Memory. Registers are generally used when the currently running program is performing calculations. Since they are so fast, they are used as both source and destination operands in instructions.

Remark A.1.2.1. Depending on the Central Processing Unit architecture, there may be cases when Registers behave slightly differently between processors. This is something that can only be found by checking the Central Processing Unit manufacturer's documentation.

A.1.2 Program Counter

Defn A.1.3 (Program Counter)**.** The *program counter* is a Register that contains the value for the memory address of the next executing instruction. It does **NOT** hold the currently executing instruction's address in memory because that instruction is already in the Central Processing Unit. This keeps track of where the program is in execution and which instruction comes next.

A.1.3 Arithmetic Logic Unit

A.1.4 Cache

A.2 Memory

Defn A.2.1 (Memory)**.** *Memory*, or *RAM* (*Random Access Memory*), is a Volatile data storage mechanism. It is directly connected to the Central Processing Unit. This is the location that the Central Processing Unit writes to when it cannot or should not store something in the Central Processing Unit's Registers.

Remark A.2.1.1 (Volatility). Memory is volatile because each of the cells is a small capacitor. In between the clock cycles on the Central Processing Unit and Memory, the capacitors discharge. On the clock cycle, the capacitors are refreshed with electrical power, which does one of 2 things:

1. Keep the data bits the same, 1 to 1.
2. Update the data bits from 0 to 1.

Defn A.2.2 (Volatile)**.** If a data storage mechanism is called *volatile*, it means that once the storage mechanism loses power, the data is lost. This is in contrast to Non-Volatile data storage mechanisms.

A.2.1 Stack

Defn A.2.3 (Call Stack)**.** The *call stack* is an imaginary construct that resembles the traditional stack data structure. It is a way to visualize and organize the way memory is used during the execution of a program and its function/methods. It is filled with Stack Frames. This **does not** hold the code that is used in the function, rather it is everything that is needed for the function to be able to run.

Defn A.2.4 (Stack Frame)**.** A *stack frame*, *activation frame*, or *activation record* are objects that represent necessary portions of a function. These include:

- A Dynamic Link
- Local Variables
- Temporary Variables
- Static Links
- Function Arguments
- Return Address

Additionally, there are 2 registers used as pointers to move around and interact with the stack frame.

1. `FP` is in register `%rbp`. It is the Frame Pointer.
2. `SP` is in register `%rsp`. It is the Stack Pointer.

Defn A.2.5 (Dynamic Link)**.** The *dynamic link* or *dynlink* is a memory address pointer and sits at the bottom of a Stack Frame. It is a pointer back to the previous function's dynamic link. This ensures that any function can find its parent/calling function.

The dynamic link also serves as a means to access any variable that might be needed by this function. To access any variable in *this* function, you can subtract a byte multiple that you need to access the proper value. To access any variable in the calling function, you can add a byte multiple that would correspond to the proper variable.

In the `x86_ 64` architecture, instruction set, and convention that we used, the register `%rbp` was the dynamic link.

Remark A.2.5.1. Note: Due to the conventions we used, when accessing arguments passed to the function, we treated them as local variables, just further down in the call stack. This also means that we need to skip over the Return Address block in memory.

Remark A.2.5.2. Because we used the `%rbp` register to store our current Dynamic Link's address, the dynamic link might also be called the *base pointer*.

Defn A.2.6 (Local Variable)**.** *Local variables* are handled very simply. They get an appropriate amount of memory allocated to them on the stack, and that is it.

There is no way to give a variable a name in assembly. (Usually. Depends on the architecture and instruction set). However, there is no way to name something in memory. But, because the size of all the objects is known at compile-time, allocating the proper amount of memory required by each variable is possible.

Remark A.2.6.1. This holds true for strongly-typed, static, compiled languages, like Java, C, C++, etc. However, Python is slightly different in this regard, and handles it differently.

Defn A.2.7 (Temporary Variable)**.** A *temporary variable* is one that is allocated on this function's Stack Frame while calculating values. Once the calculations are completed, these values are deallocated. These temporary variables can also point to objects on the Heap. When the function has finished running, then these values are deallocated, along with all other Local Variables in use.

For example, since assembly-level addition only allows for 2 operands, but in general, addition can have more than 2 operands in use, there needs to be a way to store the value used in the addition. While we can accumulate and use that value in the addition, the values being added together are *not* modified.

Defn A.2.8 (Static Link)**.** The *static link* is an implicit argument, meaning it ***ALWAYS*** gets pushed onto the stack as a Function Argument, when appropriate.

Appropriate in this context could mean several things:

- When an object is alive, and when it is being acted on by a function.
  - In this case, the static link points to an instance of a class on the Heap.
- When a language allows for nested function declarations.
  - Then the static link points to the Dynamic Link of the outer function
  - This allows access to the outer function's Local Variables like normal, and allows us to go back later.

Defn A.2.9 (Function Argument)**.** *Function argument*s are handled very simply. If a function call takes an argument, then the argument is calculated, and then that argument is pushed onto the stack in *this* Stack Frame.

Remark A.2.9.1. If more than one argument is passed to a function, there are 2 ways to push values onto the Stack Frame:

1. In the order they are passed to the function
   - Say a function with 3 arguments is called, then the stack would have arguments in this order
     (a) argument0 (Lowest memory address)
     (b) argument1
     (c) argument2 (Highest memory address)
2. In reverse order
   - Say the same function is called with the same 3 arguments, then the stack would have arguments in this order
     (a) argument2 (Lowest memory address)
     (b) argument1
     (c) argument0 (Highest memory address)

When the values that were passed need to be accessed, and if the memory sizes of things are known at compile time, then we can calculate how far down we need to go in the stack to find the value. This is done by adding a positive value to the `%rbp`

Defn A.2.10 (Return Address)**.** The *return address* is used by the `%rip` register. It is calculated and pushed onto the Stack Frame stack when the `CALL` macro is used. It is the thing that allows us to jump around in the code from the `text` area of our program.

Remark A.2.10.1. The `%rip` register is the *register instruction pointer*. It holds the value of the *next* instruction to execute. Technically, it is the Program Counter's value.

Defn A.2.11 (Garbage Collection)**.** *Garbage collection* is the act of deallocating objects that may still be on the heap and organizing the heap. Since the heap allocates continuous "blocks" of memory required by an object, the heap may have the necessary memory to allocate an object, but in discontinuous locations.

Defn A.2.12 (Frame Pointer)**.** The *frame pointer* is a pointer that ***ALWAYS*** points to the current function's Dynamic Link. The frame pointer is commonly abbreviated as *FP*. This is the thing that allows us to access Local Variables, Function Arguments, and everything else inside of the Stack Frame. The value is held in the `%rbp` register.

Defn A.2.13 (Stack Pointer)**.** The *stack pointer* is a pointer that ***ALWAYS*** points to the top of the current Stack Frame. The stack pointer is commonly abbreviated as *SP*. This value is held in the `%rsp` register. This is the pointer that allows us to push and pop onto this function's Stack Frame.

Defn A.2.14 (Class Descriptor)**.** The *class descriptor* is a portion of memory set aside for the methods that are in an object.

A.2.2 Heap

Defn A.2.15 (Heap)**.** The *heap* is a memory organization construct that helps visualize the way memory is used during the execution of a program. It is ***SIGNIFICANTLY*** larger than the Call Stack.

In an object-oriented language, this is where instances of classes exist. These objects are allocated on a first-come first-serve basis. When the object is allocated, the amount of memory that the object requires is allocated ***in a continuous block***. The problem is that if the heap has been extensively used, then there might be enough total memory required to allocate an object, but because it is not in a continuous block, the object cannot be allocated.

This makes deallocation more complex, because when they are deallocated, the program might still view the memory as in-use. Additionally, because of the continuous block allocation nature of the heap, it must be organized every once in a while. This is called Garbage Collection.

Remark A.2.15.1. In an object-oriented language, like Java, when objects are stored on the heap, **ONLY** their class fields are stored there. The class methods are stored elsewhere, in the Class Descriptor.

A.3 Disk

Defn A.3.1 (Non-Volatile)**.** If a data storage mechanism is called *non-volatile*, it means that once the storage device loses power, the data is still safely stored. This is in contrast to Volatile data storage mechanisms.

A.4 Fetch-Execute Cycle