Homework 2 Wet

Due Date: 22/12/2021 23:30

Teaching assistant in charge: Akiva Block

Important: the Q&A for the exercise will take place at a public forum Piazza only. Critical updates about the HW will be published in pinned notes in the piazza forum. These notes are mandatory and it is your responsibility to be updated. A number of guidelines to use the forum:

- Read previous Q&A carefully before asking the question; repeated questions will probably go without answers.
- Be polite, remember that course staff does this as a service for the students.
- You're not allowed to post any kind of solution and/or source code in the forum as a hint for other students; In case you feel that you have to discuss such a matter, please come to the reception hour.
- When posting questions regarding this assignment, put them in the "hw2-wet" folder.

Pay attention that in the dry part there are questions about the wet part, so it is recommended to review these questions before, and answer them gradually while working on the wet part.

Only the TA in charge, can authorize postponements. In case you need a postponement, please fill out the attached form:
https://forms.gle/575XhDwcwmfBWzEN7

1. Introduction

As we learned in class, serving user requests is an important role of the OS kernel. The kernel services are exposed to user applications through system calls. For example, C programs can create new processes and finish them via the `fork()` and `exit()` system calls, respectively.
The goal of this assignment is implementing a new set of services for managing a new feature called process weights. To this end, you will implement three new system calls.

But before diving in, we start with a detailed walk-through of Linux kernel development. You should work on the Ubuntu virtual machine that was installed in HW0.

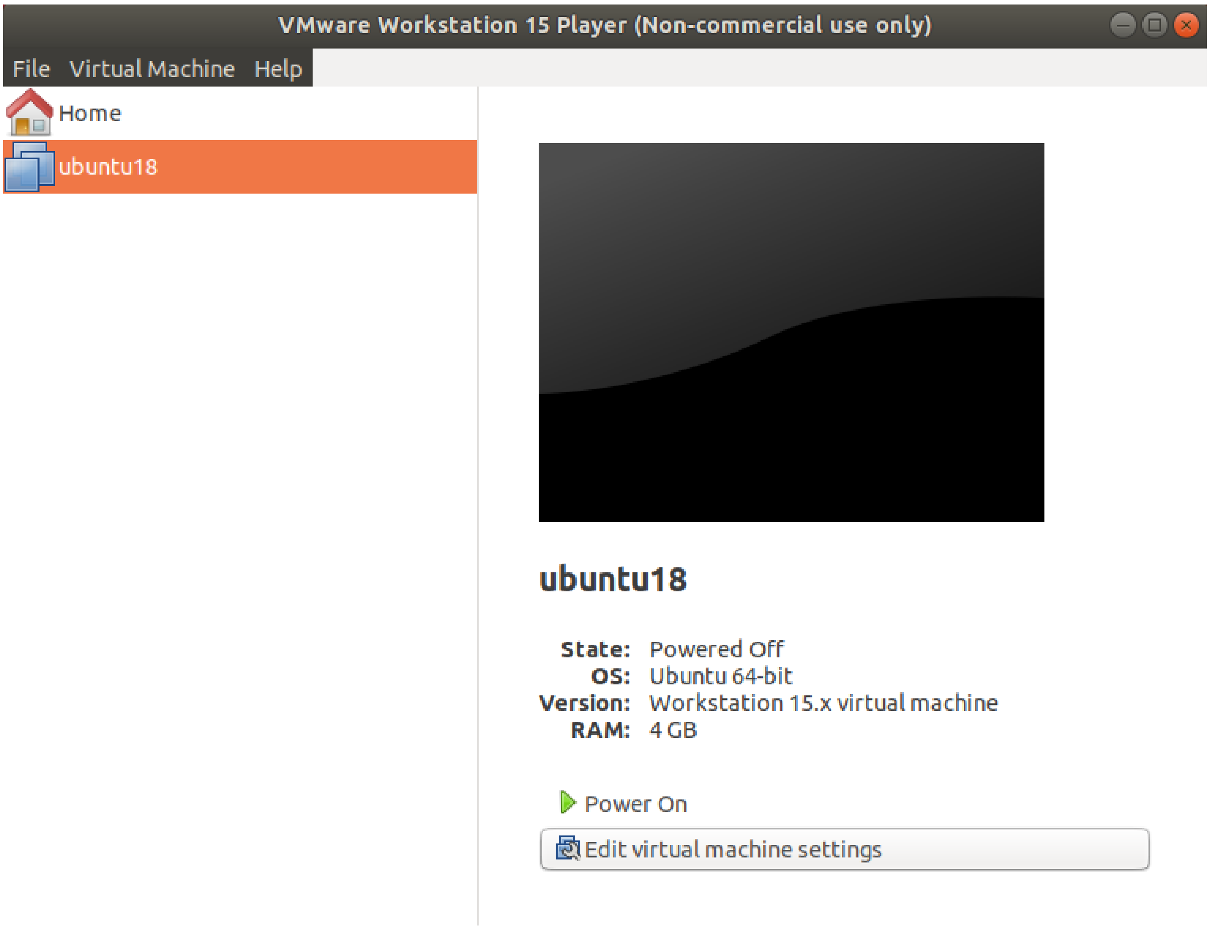
2. Minimum System Requirements

For this assignment, you will need at least:

- Processing: Intel/AMD 64-bit CPU.
- Memory: 4GB RAM.
- Storage: 50GB HDD or SSD.

If your PC has multiple cores, we recommend increasing the number of cores allocated to the VM to reduce the kernel build time (as explained in the next section):

1) Click “Edit virtual machine settings” on VMware main panel.

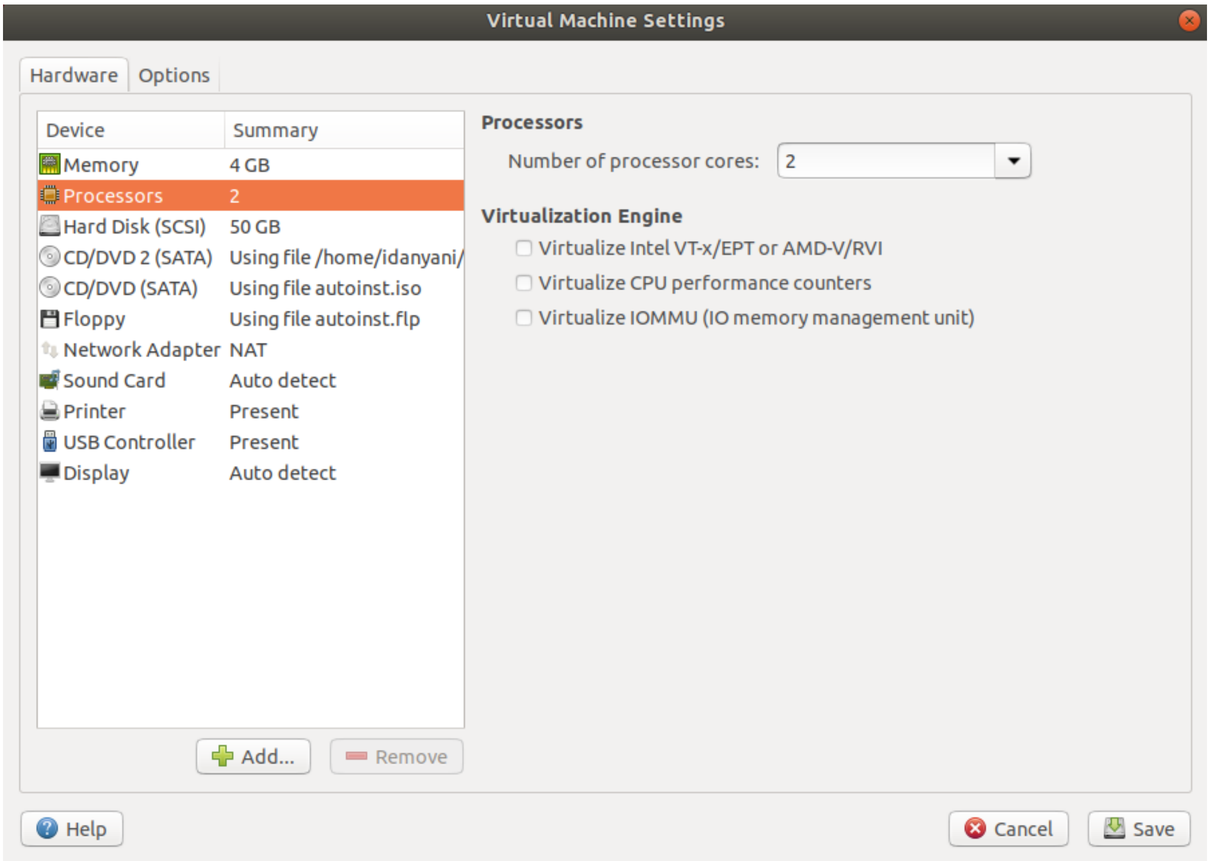


VMware Workstation 15 Player (Non-commercial use only)
File
Virtual Machine
Help
Home
ubuntu18
Power On
Edit virtual machine settings

ubuntu18

State: Powered Off
OS: Ubuntu 64-bit
Version: Workstation 15.x virtual machine
RAM: 4 GB

2) Navigate to the “Processors” tab and set the “number of cores” to $N - 1$, where N is the number of cores on your PC (we keep a free processor core for the host).



Device	Summary
Memory	4 GB
Processors	2
Hard Disk (SCSI)	50 GB
CD/DVD 2 (SATA)	Using file /home/idanyani/
CD/DVD (SATA)	Using file autoinst.iso
Floppy	Using file autoinst.flp
Network Adapter	NAT
Sound Card	Auto detect
Printer	Present
USB Controller	Present
Display	Auto detect

Processors

Number of processor cores: 2

Virtualization Engine

□ Virtualize Intel VT-x/EPT or AMD-V/RVI
□ Virtualize CPU performance counters
□ Virtualize IOMMU (IO memory management unit)

3) Save the settings and power on the VM.

3. Build the Linux Kernel

Estimated time: around 30 minutes on a VM with 2 cores.
Please follow the following instructions on your terminal:

1) Install prerequisites (software required for the next steps):

```
>> sudo sed -i "s/# deb-src/deb-src/g" /etc/apt/sources.list
>> sudo apt update -y
>> sudo apt install -y build-essential libncurses-dev bison flex
>> sudo apt install -y libssl-dev libelf-dev
```

APT (Advanced Package Tool) is a tool that simplifies software management on Ubuntu systems by automating the retrieval, configuration, installation and removal of software packages.

2) Download the Linux source code:

```
>> cd ~
>> apt source linux
```

3) Change permissions and rename the directory:

```
>> sudo chown -R student:student ~/linux-4.15.0/
>> mv ~/linux-4.15.0 ~/linux-4.15.18-custom
```

4) Configure the kernel build process (starting from an existing configuration file):

```
>> cd ~/linux-4.15.18-custom
>> cp -f /boot/config-$(uname -r) .config
>> geany .config # you may use any text editor you like
>> # search the CONFIG_LOCALVERSION parameter and set it to "-custom"
>> yes '' | make localmodconfig
>> yes '' | make oldconfig
```

The “make localmodconfig” command enables only the modules loaded in the currently running kernel. This step reduces the build time significantly (by ~80%). Note that we use the “yes” command with single quotes (two ‘ characters) that encloses nothing. Look at the man page of “yes” to see what it is doing.

5) Compile the kernel and its modules:

```
>> make -j $(nproc)
```

The “-j” flag specifies the number of “make” jobs to run simultaneously. In our case, we use all available cores.

6) Install the kernel modules:

```
>> sudo make modules_install
```

This command will copy the module objects under `/lib/modules/4.15.18-custom` .

7) Install the kernel image:

```
>> sudo make install
```

This command will copy the kernel bzImage from `arch/x86/boot/bzImage` to `/boot/vmlinuz-4.15.18-custom` and create a matching initramfs under `/boot` .

You can verify the installation by listing the installed files with:

```
>> ls /boot/*-custom
/boot/config-4.15.18-custom      /boot/System.map-4.15.18-custom
/boot/initrd.img-4.15.18-custom  /boot/vmlinuz-4.15.18-custom
```

8) Configure GRUB to boot from our custom kernel:

```
>> sudo geany /etc/default/grub
>> # search GRUB_DEFAULT and set it to: "Ubuntu, with Linux 4.15.18-custom"
>> # search GRUB_TIMEOUT_STYLE and set it to menu
>> # search GRUB_TIMEOUT and set it to 5
>> # add the line GRUB_DISABLE_SUBMENU=y at the end of the file
```

As we learned in class, GRUB is the default boot loader for our Ubuntu VM (and for most Linux operating systems). The GRUB settings are stored in `/etc/default/grub` .

9) Generate the GRUB configuration file and reboot:

```
>> sudo update-grub
>> sudo reboot
```

10) Make sure that you booted into the custom kernel:

```
>> uname -r
4.15.18-custom
```

4. Modify and Rebuild Your Kernel

As you probably noticed, downloading and building a Linux kernel from scratch requires some time and effort. Rebuilding a modified kernel, however, is easier and faster because the “make” utility rebuilds only the necessary object files and skips most of the work.

Enter the kernel source directory ~/linux-4.15.18-custom/ and edit init/main.c by inserting the following print statement in the run_init_process() function:

```
static int run_init_process(const char *init_filename)
{
      printk("Hello, Kernel!\n");
      argv_init[0] = init_filename;
      return do_execve(getname_kernel(init_filename),
            (const char __user *const __user *)argv_init,
            (const char __user *const __user *)envp_init);
}
```

Now rebuild and reinstall the modified kernel:

1) Recompile the kernel image (only bzImage, without the modules):

```
>> make -j $(nproc) bzImage
```

2) Copy the new bzImage to /boot (there's no need to modify the initramfs):

```
>> sudo cp -f arch/x86/boot/bzImage /boot/vmlinuz-4.15.18-custom
```

Note that "make install" will also work in this stage, but it will take a few more seconds and create another copy (which we don't need) of the old bzImage under /boot/vmlinuz-4.15.18-custom-old .

3) Reboot to load the modified kernel:

```
>> sudo reboot
```

4) Validate that your print appears in the kernel log:

```
>> dmesg | grep Hello
[    2.144190] Hello, Kernel!
```

If your modified kernel didn't boot properly, you can fix it from a working vanilla kernel.
Remember: GRUB lets you choose the kernel image to be loaded from the disk at boot stage.
The GRUB menu stays for only a few seconds on your screen, so be quick to catch it ;)

5. Background: System Calls in Linux/x86-64

Let us now recall what system calls are and how they are implemented in Linux on x86-64 machines. You should be familiar with this content because you already learned it in the “Computer Organization and Programming” course (234118), a.k.a. ATAM.

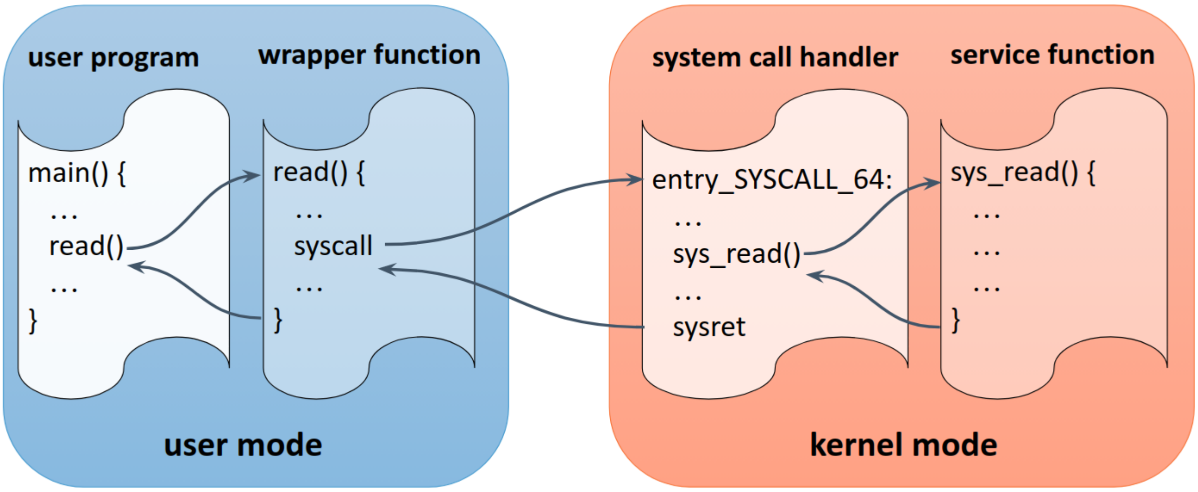
System calls are the way user code requests a service from the OS kernel. At first sight, a system call looks exactly like a typical function call in C. For example, the `read()` system call,

```
#include <unistd.h>
ssize_t read(int fd, void *buf, size_t count);
```

can be used by any C program to read `count` bytes from the file specified by `fd` to the buffer starting at address `buf`.

There is, however, a significant difference between system calls and function calls: system calls should run in a higher privilege level (kernel mode), whereas “regular” functions can be executed in a lower privilege level (user mode). This distinction is important to provide privacy and security: if we allowed “regular” functions to run in kernel mode, then user programs would be able to run privileged machine instructions and read any file on the disk.

System calls are implemented both in user space and in kernel space, as shown in the figure:



5.1 User-Side Implementation

User applications run user mode, which means the hardware restricts what applications can do. For example, an application running in user mode can’t access I/O devices (e.g., the disk) directly via the `in/out` machine instructions. User applications that want to access the disk, for example to read a file, should invoke the `read()` system call. When a program invokes the `read()` system call, it actually calls the wrapper function implemented in the standard C library, or `libc` in short.

The wrapper function is named so because it "wraps" the special machine instruction `syscall`. On x86-64 processors, this instruction transfers control (i.e., jumps) into the OS kernel while simultaneously raising the CPU privilege level. The wrapper function is also responsible to put the system call arguments in well-known locations (in specific registers) and to put the system-call number into a well-known location as well (in the RAX register). When the system call returns, the wrapper code unpacks the value returned from the kernel (in the RAX register) and returns control to the program that issued the system call. `libc` wrapper functions are coded in assembly, as they need to carefully follow convention in order to process arguments and return values correctly, as well as execute the hardware-specific `syscall` instruction. You can explore the libc code here, but beware: navigating through `libc` is very challenging as large parts of its code are auto-generated.

5.2 Kernel-Side Implementation

The `syscall` instruction makes a controlled transition into the OS. It points the RIP register to a pre-specified system call handler (which the OS sets up at boot time) and simultaneously raises the privilege level to kernel mode. The Linux system call handler is `entry_SYSCALL_64` is defined in the kernel source file `arch/x86/entry/entry_64.S` . The system call handler reads the system call number from the RAX register and dispatches the corresponding service function. All service functions are listed in the system call table (not shown in the above figure), which is defined in the kernel source file `arch/x86/entry/syscalls/syscall_64.tbl` . The `sys_read()` service function, for example, is stored in the first entry of this table because the number reserved for the `read()` system call is 0.

Service functions run in kernel mode, and as such have full access to the hardware of the system. The service functions are responsible for doing the "real" work, for example, initiating an I/O request or allocating more memory to a program. When the OS is done servicing the request, it passes control back to the user via the special `sysret` instruction, which reverts to user mode while simultaneously passing control back to where the application left off.

Note the clear borderline between user space and kernel space. User programs cannot include kernel headers in their code and cannot call kernel functions directly. In other words, your program can't simply call the `sys_read()` service function to read a file from the disk. Similarly, kernel code does not call user-space functions like `printf()`, does not include user-space header like `<stdio.h>` or `<iostream>`, and does not link against user-space libraries like `libc`. The only gate to kernel mode (and OS services) that's the user can use is the `syscall` instruction as described above.

6. Add Your First System Call

This section will take you through the steps required for implementing a new system call. Following the standard practice, you will implement an `hello()` system call, which simply dumps an "Hello, World!" message to the kernel log buffer.

6.1 Kernel-Side Implementation

Please take the following instructions in your terminal:

5) Enter the kernel source directory:

```
>> cd ~/linux-4.15.18-custom/
```

6) Declare the system call in `include/linux/syscalls.h` :

```
...
asmlinkage long sys_statx(int dfd, const char __user *path, unsigned
flags, unsigned mask, struct statx __user *buffer);
asmlinkage long sys_hello(void); // only add this

#endif
```

Reminder: “long” is a shorthand for “long int”, which is a 64-bit signed integer in Linux systems (according to the LP64 data model).

7) Reserve a service number in `arch/x86/entry/syscalls/syscall_64.tbl` :

```
...
332    common      statx              sys_statx
333    common      hello              sys_hello
...
```

The above line reserves the first available number in the “64-bit system call” list.

8) Create a new file called `kernel/hw2.c` and implement the system call there:

```
#include <linux/kernel.h>

asmlinkage long sys_hello(void) {
    printk("Hello, World!\n");
    return 0;
}
```

9) Add the new file (`kernel/hw2.c`) to the build process by listing it in `kernel/Makefile` :
(Add only what’s in bold)

```
# SPDX-License-Identifier: GPL-2.0
#
# Makefile for the linux kernel.
#

obj-y     = fork.o exec_domain.o panic.o \
          cpu.o exit.o softirq.o resource.o \
          sysctl.o sysctl_binary.o capability.o ptrace.o user.o \
          signal.o sys.o umh.o workqueue.o pid.o task_work.o \
          extable.o params.o \
          kthread.o sys_ni.o nsproxy.o \
          notifier.o ksysfs.o cred.o reboot.o \
          async.o range.o smpboot.o ucount.o hw2.o
...
```

10) Rebuild the modified kernel and reboot as explained in the previous section:

```
>> make -j $(nproc)
>> sudo cp -f arch/x86/boot/bzImage /boot/vmlinuz-4.15.18-custom
>> sudo reboot
```

6.2 User-Side Implementation

After the OS is loaded properly, we would like to test the system call from user-level code.

1) Write a simple C program under `~/test_hello.cxx` :

```
#include <iostream>
#include <unistd.h>

int main() {
    long r = syscall(333);
    std::cout << "sys_hello returned " << r << std::endl;
    return 0;
}
```

We stress that this user code is not part of the kernel source code; rather, this code will run in user privileges (CPL=3) and call the kernel `hello()` system call.

2) Build and run the user program:

```
>> g++ ~/test_hello.cxx -o ~/test_hello
>> ./test_hello
sys_hello returned 0
```

3) Validate that your “Hello, World!” was printed to the kernel log:

```
>> dmesg | grep Hello
[    2.144190] Hello, Kernel!
[   80.243584] Hello, World!
```

Note how we used the `syscall()` function in our `test_hello` program. This function provides an easy way for invoking a system call that has no `libc` wrapper function, like our new `hello()` system call. Make sure that you understand what `syscall()` does and how it works. How many parameters can `syscall()` get? Why do we pass `333` as an argument? Reading the “`man 2 syscall`” page is a good place to start.

7. Add Support for Process Weights

Now that we have the technical tools under our belt, we can start doing some real work. Your mission is to add a new functionality to the linux kernel called **process weights**.
We would like to assign to every process a user-specified weight (integer number) that represents how “heavy” this process is on the computer. When a process is forked, the child process should inherit its parent’s weight. The init process will have a weight of 0.
Before you start writing code, ask yourselves: where should we store each process weight?
To this end, you will implement three new system calls, as described below. You are required to implement these three system calls in `kernel/hw2.c` and submit this file, along with any other files you changed in the linux kernel.
We remind you that kernel functions that implement system calls should start with `sys_` , as was demonstrated in the implementation of the `hello()` system call from the previous section.

7.1 `int set_weight(int weight)`

System call number: 334.

Action: Sets the weight of the current process.

Arguments: `weight` - a non-negative number representing the user-specified process weight.

Return value:

- On success, return 0.
- On failure,
    - `-EINVAL` if the specified weight is negative.

We remind you that system calls report failures to user space by returning negative values. In such cases, the `libc` wrapper function will store the absolute return value in the `errno` global variable and return `-1` to the user-level code that invoked the system call.

7.2 `int get_weight(void)`

System call number: 335.

Action: Returns the weight of the current process.

Arguments: none.

Return value:

- On success, return the weight of the current process.
- This system call should never fail.

7.3 `int get_leaf_children_sum(void)`

System call number: 336.

Action: Returns the sum of the weights of all the current process' leaf descendants recursively. The sum includes the weights of all children of the current process that themselves are childless.
For example, if process A has children B and C, and C has a child D, this system call should return the sum of weights of B and D, when the current process is A.

Arguments: none.

Return value:

- On success, return the sum of weights of the leaf descendants as described above.
- On failure,
  - `-ECHILD` if the current process does not have any un-waited children.

7.4 `pid_t get_heaviest_ancestor(void)`

System call number: 337.

Action: Returns the pid (process id) of the ancestor of the current process with the heaviest weight among all the current process's ancestors (including itself). If there are 2 ancestors with the same maximal total weight, return any of them.
For example, consider this scenario: process A with weight 4 is the father of process B with weight 2, and process B is the father of process C with weight 1. This system call should return for all of these processes (A, B & C) the pid of process A.

Arguments: none.

Return value:

- On success, return the pid of the ancestor with the heaviest weight.
- This system call should never fail.

Important Notes and Tips

- It is important to remember that we do not require anything regarding the runtime complexity of your system call implementations, so there is no need to try and optimize your implementation if it runs correctly. Also bear in mind that you do not control the process tree, meaning that other kernel functions may change it without changing the fields you added.
- Notice that the default behavior of existing system calls such as `fork` and `execv` regarding the new process weight field is exactly the behavior that is required from you in this homework.
- Check out the macros `list_for_each` and `list_entry` from `include/linux/list.h`. They could be useful.
- We provided you with a simple testing framework for this HW assignment, which comprises the following files:
    - `makefile` - searches the current directory for source files that matches `test*.cxx`, compiles them into `test*.exe` files, and finally runs them with stdout and stderr redirected to `test*.out` .
    - `hw2_test.h , hw2_test.cxx` – user-level wrapper functions for our system calls.
    - `test1.cxx` - a simple test for the `set_weight` and `get_weight` system calls.

Submission Instructions

You should create a zip file (use zip only, not gzip, tar, rar, 7z or anything else) containing the following files:

a. The kernel source file `kernel/hw2.c`.
   This file should implement the four system calls described in this assignment: `hello()`, `set_weight()`, `get_weight()`, `get_leaf_children_sum()` and `get_heaviest_ancestor()`.
b. Any other kernel files you might have changed, including but not limited to: `kernel/Makefile` , `arch/x86/entry/syscalls/syscall_64.tbl` and `include/linux/syscalls.h.`
   Please keep the directory structure as it is in your zip file (for example, put `hw2.c` in the `kernel` directory).
c. A file named `submitters.txt` which includes the ID, name and email of the participating students. The following format should be used:

```
Linus Torvalds linus@gmail.com 234567890
Ken Thompson ken@belllabs.com 345678901
```

The zip should look like this:

```
final.zip -+
           +- kernel  -+
                       +- hw2.c
                       +- ...
           +- include -+
                       +- linux -+
                                 +- syscalls.h
                                 +- ...
           +- ...
           +- submitters.txt
```

Important Note: when you submit, keep your confirmation code and a copy of the file(s), in case of technical failure. Your confirmation code is the only valid proof that you submitted your assignment when you did.

Have a Successful Journey,
The course staff