CS 241 Honors
Kernel

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What to go over

- What does the (linux) kernel actually do?
- System Calls
- Linking and Loading
- Processes and Threads
- Completely Fair Scheduler
#include <pthread.h>

void* hello_thread(void *payload) {
    write(1, "Hello world!", 12);
    return NULL;
}

int main() {
    pthread_create(NULL, hello_thread,
                   NULL, NULL);
    pthread_exit();
}

Motivation

```c
#include <pthread.h> // Dynamic Linked Library

void* hello_thread(void* payload) {
    // Pthread
    write(1, "Hello world!", 12); // Sys Call
    return NULL;
}

int main() {
    // Process Start
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    pthread_exit() // Some kind of scheduling
}
```
Operates in ‘kernel space’ (Where kernel code runs in ring 0 - access to full CPU instruction set).

- The kernel can do anything (e.g. accessing devices and IO). Need a layer of security preventing unwanted changes in the state of the system, especially in undefined ways. Kernel space is also lower level - you don’t get the nice abstractions like `sbk(2)` or `write(2)`. The kernel has to route each of the requests to the appropriate drivers or handlers.

Exposed kernel calls are called system calls.
Some Kernel Calls Explained

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void * kmalloc(size_t size, int flags)

Flags allow to users to use special kernel actions
flags are one of many options the kernel handles.
  - GFP_ATOMIC - Cannot be interrupted, will not sleep. (Useful inside interrupt handlers)
  - GFP_NOIO - No disk I/O can be performed during request.

We can have an entire lecture on this one call so just believe that this call returns pages of memory that are greater than size. A page is usually 4KB, so it’ll be the smallest multiple of that.
mmap(void *addr, size_t length, int prot, int flags, int fd, off_t offset) Takes a file, puts it into memory.
Booting

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- Init does a lot of things. One important thing it does is initializing fork(), the magical library call that starts the entire process.
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- The first thing the kernel does is start init (the main process for your operating system).
- Init does a lot of things. One important thing it does is initializing fork(), the magical library call that starts the entire process.
- Then init checks run level and runs the appropriate startup scripts.
System Calls
#include <pthread.h> //Dynamic Linked Library

void* hello_thread(void* payload) { //Pthread
    write(1, "Hello world!", 12); //Sys Call
    return NULL;
}

int main() { //Process Start
    pthread_create(NULL, hello_thread, NULL, NULL);
    pthread_exit() //Some kind of scheduling
}
How do we call a system call?

Typically C library calls call system calls but here is some x86 to get the job done.

```assembly
_start:
  movl $4, %eax ; use the write syscall
  movl $1, %ebx ; write to stdout
  movl $msg, %ecx ; use string "Hello World"
  movl $12, %edx ; write 12 characters
  int $0x80 ; make syscall

  movl $1, %eax ; use the _exit syscall
  movl $0, %ebx ; error code 0
  int $0x80 ; make syscall
```
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- Kernel traps the signal, routes to the appropriate system call - executes the system call in Kernel space.
- We can load up to five of the system call parameters in registers (What if there are more?).
- Return value is stored in a register and returned back to userspace – we have a system call.
How do we call a system call?
The kernel has no restrictions, it can touch all memory in the system
Checking parameters

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Need to make sure that all memory accesses are within the bounds of the user’s virtual memory, do not point to kernel memory, and do not try to read or write from files they do not have permissions to.
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- If there was no checks on the arguments passed in, users could get systems calls like memcpy, read or write to get access to files or regions of memory they shouldn’t.
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- Other permissions accomplished via linux’s capabilities macros.
Checking parameters

- CAP_SYS_BOOT - Can reboot
- CAP_CHOWN - Can arbitrarily change file UIDs
- etc... see capabilities(7)
How to define a syscall?

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- Register the system call in the syscall table
- Define the syscall number in `<asm/unistd.h>`
- Compile the syscall into the kernel image
#ifndef __UAPI_ASM_IA64_UNISTD_H
#define __UAPI_ASM_IA64_UNISTD_H
#include <asm/break.h>
#define __BREAK_SYSCALL __IA64_BREAK_SYSCALL
#define __NR_ni_syscall 1024
#define __NR_exit 1025
#define __NR_read 1026
#define __NR_write 1027
#define __NR_open 1028
#define __NR_close 1029
#define __NR_creat 1030
#define __NR_link 1031
#define __NR_unlink 1032
#define __NR_execve 1033
Linking and Loading
#include <pthread.h> //Dynamic Linked Library

void* hello_thread(void *payload) { //Pthread
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int main(){ //Process Start
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What are we even talking about?

There are two types of libraries, those compiled with your programs and those that are linked dynamically at runtime. There are many benefits to use programs that get compiled with your program, but some drawbacks.
Benefits

- You have the source code/debug checking
- All code is in your code segment
- You can modify the library
Cost-Benefit Analysis: Compile-Time Libraries

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Drawbacks

- Updating is often tedious
- Your executable is bigger
- Your library cannot be reused by other applications
Solution: Dynamic Libraries

- What if we have one library that a bunch of programs can use (make it read only) and have it dynamically link the function calls in the program?
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- Updating your executable’s library is a piece of cake
- Reduce the size of your executable
- That library can be used by other applications.
Cool! But where are the library functions?
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• Have the functions in your code point to pointer where the functions are going to be.
Dynamic Lookup table?

- Cool! But where are the library functions?
- Any problem in computer science and be solved with another layer of abstraction.
- Have the functions in your code point to pointer where the functions are going to be.
- Have your code jump to the pointer and the pointer jump to the actual function
"In Unix-like systems that use ELF for executable images and dynamic libraries, such as Solaris, 64-bit versions of HP-UX, Linux, FreeBSD, NetBSD, OpenBSD, and DragonFly BSD, the path of the dynamic linker that should be used is embedded at link time into the .interp section of the executable’s PT_INTERP segment. In those systems, dynamically loaded shared libraries can be identified by the filename suffix .so (shared object)."
- Wikipedia
So what does that mean?

- Exec generates lookup-table (PT_INTERP segment)
- Calls to a library will cause a jump to the lookup table
- Lookup table entry will redirect the program to the library function
- After execution, returns back to your program
So about that library

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Else, mmap the library into memory. Set the executable bit (memory can either be executable or writeable) and then link the function. Cache this library’s location.
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Else, mmap the library into memory. Set the executable bit (memory can either be executable or writeable) and then link the function. Cache this library’s location.

When a process is done, reduce the reference count and return the page back to the system if need be.
So about that library
Drawbacks: Hacking

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- Perfect! Let’s dynamically link ALL THE THINGS!
- Not quite. You have to trust the library you are linking to. What if the library has been hacked?
- Some viruses redirect library calls (hint: LD_PRELOAD) thus, executing commands that the user is not aware of.
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Drawbacks: Hacking with Bugs

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- Example: libc had a buffer overflow bug (any application that uses libc was affected).
- But the pros outweigh the cons so DLLs are here to stay.
Demo time!
Processes and Threads
Processes
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- Imagine in the linux kernel there is a struct with all of this stuff – that is what a process essentially is.
Starting a process

Process Creation – Copy-on-Write

fork()
Only copy the page table

copy-on-write
Delay or altogether prevent copying of data
Now Exec-ing

- Exec takes an executable and uses the appropriate executable loader (ELF format for UNIX) to reorganize the file into memory. The kernel may mmap into new address spaces.
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The kernel then dynamically links libraries and destroys the pages that the old processes had.

The kernel resets registers and sets the stack pointer to the entry point of the main function. And finally, does the jump to the entrypoint. Your program is started!
Threads
Threads!

- Two types of threads - user space threads and kernel threads

- Kernel threads are used for things like system calls and monitoring. No need to context switch to user space!
- kswapd - 'kernel swap daemon' handles swaping to/from disk
- kwroker - handles ACPI signals from BIOS

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What do you mean?

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This abstraction is really cool – that is why in the systems literature/papers *everything* is a process.
Threading Start - pthread_create
After pthread initialization, set the attributes like detached state, stack address, and scheduling preferences.
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Then, allocate some stack space in the current program’s stack. Then the thread gets added to a table and a lightweight process is created using clone() [Think fork but no copying]
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Then the pthread is added to the pthread table, and returns out of the pthread function.
After pthread initialization, set the attributes like detached state, stack address, and scheduling preferences.

Then, allocate some stack space in the current program’s stack. Then the thread gets added to a table and a lightweight process is created using clone() [Think fork but no copying]

Then the pthread is added to the pthread table, and returns out of the pthread function.

Scheduling the process is left up to the completely fair scheduler.
Here’s a quick demo of clone!
Threading Start - pthread_create
Acts like another process, that’s why you can signal to it.
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You can sleep just like another process and use shared mutexes and whatnot because it resides in the same memory.
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Race conditions! All the fun stuff from processes
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- You can sleep just like another process and use shared mutexes and whatnot because it resides in the same memory.
- Race conditions! All the fun stuff from processes
- (The kernel does know it’s supposed to be treated as a thread and uses group scheduling for efficiency)
Pthread join

- Gets return values from the process
Pthread join

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- We get rid of the stack space and the entry from the table.
Pthread join

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- We get rid of the stack space and the entry from the table.
- Return the stack back to the program.
Completely Fair Scheduler
I promise last time.

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Okay let’s backtrack to threads and stuff

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- It is not a secret, we have more processes than CPUs – more threads than CPUs even.
- So how does the CPU run all these processes? It switches between them really fast using what we call a scheduler.
- This is essentially a dining philosopher problem that is solved by pre-emption. The kernel tells processes when they can hog resources like CPUs and tells them to stop whenever else.
Original implementation called the $O(1)$ scheduler
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Constant time calculation of timeslices and per-processor runqueues
Backstory

- Original implementation called the $O(1)$ scheduler
- Constant time calculation of timeslices and per-processor runqueues
- Scaled reasonably well
Original implementation called the $O(1)$ scheduler
Constant time calculation of timeslices and per-processor runqueues
Scaled reasonably well
Attempted to determine interactive vs non-interactive processes, got it wrong frequently.
 Processes are either IO-bound or Process-bound
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IO bound will spend most of its time waiting for IO

Needs to be run frequently or the system will appear to be annoyingly slow

Process bound spends a lot of time actually computing things
  - e.g. A text-editor vs computing a forward pass of a neural network
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All processes are equal...

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- What if we stopped thinking about timeslices?

- Use percentages instead! Assign a percentage of the CPU to a process.
  - This way when an IO-bound process sleeps, it has a high priority when it wakes up.
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This way when an IO-bound process sleeps, it has a high priority when it wakes up.

The CPU creates a Red-Black tree with the processes virtual runtime (runtime / nice_value) and sleeper fairness (if the process is waiting on something give it the CPU when it is done waiting). Since the red-black tree is self balancing pop operation is guaranteed $O(\log(n))$. 
But some are more equal than others

- Nice values are the kernel’s way of yielding resources

Run `top` to see examples!
Nice values are the kernel’s way of yielding resources
A higher nice value means that you are "nicer" and give up priority
But some are more equal than others

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- Run top to see examples!
Red-Black-Tree
self balancing
binary search tree
$O(\log N)$ operations

vruntime
used as key in
the RB-Tree

gravest
need for
CPU

virtual runtime
struct task_struct {
    volatile long state;
    void *stack;
    unsigned int flags;
    int pri, static_prio, normal_prio;
    const struct sched_class *sched_class;
    struct sched_entity se;
    ...
};

struct sched_entity {
    struct load_weight load;
    struct rb_node run_node;
    struct list_head group_node;
    ...
};

struct ofs_rq {
    ...
    struct rb_root tasks_timeline;
    ...
};

struct rb_node {
    unsigned long rb_parent_color;
    struct rb_node *rb_right;
    struct rb_node *rb_left;
};
Looking back to threads

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The CFS tends to schedule groups of processes together – taking advantage of cache coherency, open files, open sockets etc.

The CFS handles higher priority and long running processes fairly so no process fades away into the scheduling abyss.
Groups of processes that are scheduled may have imbalanced loads so the scheduler roughly distributes the load. When another CPU gets free it can only look at the average load of a group schedule not the individual cores. So the free CPU may not take the work from a CPU that is burning so long as the average is fine.
CFS Problems

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- If a group of processes is running, on non adjacent cores then there is a bug. If the two cores are more than a hop away, the load balancing algorithm won’t even consider that core. Meaning if a CPU is free and a CPU that is doing more work is more than a hop away, it won’t take the work (may have been patched).
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- After a thread goes to sleep on a subset of cores, when it wakes up it can only be scheduled on the cores that it was sleeping on. If those cores are now busy
Any questions? Thanks for sticking along!
Edit history

- Bhuvan Venkatesh
- Aneesh Durg
Sources

- Linux User’s Manual