CSE 220: Systems Programming

The Kernel and User Mode

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The Operating System Kernel

We have talked about the operating system or the kernel.

The operating system manages the hardware.

On our systems, it also:

- Supports the dedicated computer model
- Provides protection against misbehaving programs

The kernel is the code of the inner core of the OS.

In some sense the OS and Kernel are just programs.

User Mode Programs

Our programs run in user mode.

User mode programs appear to run on a dedicated computer.

This means that shared resources must be managed for them.

User mode programs ask the kernel for access to shared resources.

If the user mode program has a dedicated computer …where is the kernel?

Exceptions

Exceptions are another type of control flow.

Unlike `if`, `for`, *etc.*, they:

- Allow non-local (to another function or even program) transfer of control
- Can be asynchronous (triggered by an external event)

Exceptions may be caused by hardware or software.

The handling of exceptions requires both.

System Calls

A system call is a special kind of exception.

It allows a program to:

- "break out" of its dedicated computer, and
- contact the kernel

System calls are synchronous but non-local transfer of control.

The Kernel and Supervisor Mode

The kernel does not have a dedicated computer. ¶

The kernel has the real computer!

It runs in a special mode (often called supervisor mode).

It can:

- Access hardware directly
- Manipulate virtual memory mappings
- Modify process memory
- …

Protection Domains

This supervisor mode is a different protection domain.

Protection domains are a hardware capability.

User programs run in user mode, the kernel in supervisor mode.

The hardware enforces access restrictions on user mode.

Some hardware has more than two protection domains.

Changing Protection Domains

Changing protection domains is a supervisor mode operation.

This programs from breaking out of user mode.

It also means there must be a safe way to switch!

We will see how exceptions provide a controlled mode change.

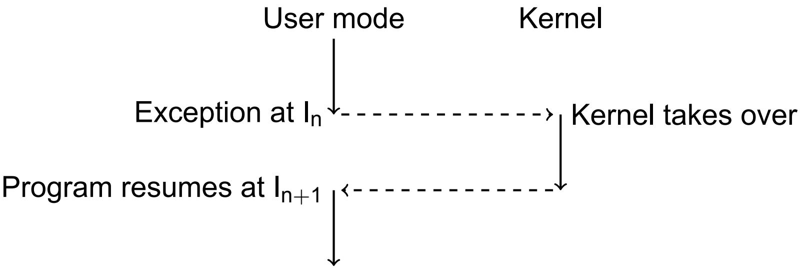
Changing protection domains can be slow and expensive.

Exception Flow

When an exception occurs, control passes to the kernel.

If control is already in the kernel, it changes location.

If control is in a user mode program, it switches contexts.



Types of Exceptions

There are four major types of exceptions:

- Interrupts are asynchronous notifications from hardware
- Traps are synchronous exceptions caused by software intentionally
- Faults are synchronous exceptions caused by software due to potentially recoverable errors
- Aborts are synchronous exceptions caused by unrecoverable errors outside of software control

We have only seen faults thus far (remember page faults?).

We are currently most interested in traps.

Interrupts

Interrupts are a way for hardware to signal the OS.

Examples:

- A network packet has arrived
- A clock has "ticked"
- A disk has completed a read

Interrupts are handled by the kernel.

Faults

We have already seen faults!

```
Segmentation fault (core dumped)
```

Faults are program errors that may be recoverable.

When a fault occurs, the kernel may:

- try to fix it
- notify the program

It may also terminate the program or shut down.

Fault Recovery

Some faults are not true errors:
e.g., page faults to bring in new pages.

Other faults may be recoverable by the program:

- Divide by zero
- Segmentation fault
- Bus error
- …

Each of these is an error, but might not be fatal.

For example, a calculation might usefully return some concrete value if it reaches a divide-by-zero.

Aborts

Aborts are relatively uninteresting to us.

They represent some unrecoverable error that often ends in:

- Rebooting the computer
- Shutting down the computer
- Terminating some or all processes
- *etc.*

Aborts are handled by the kernel.

Traps

Traps are software-generated exceptions.
(They are sometimes called software interrupts.)

They are generated by special instructions run by a program.

Their critical feature is:
Trap handlers are run by the kernel in supervisor mode.

This means that a user mode program can call into the kernel.

This provides a safe method of changing protection domains.

System Calls

System calls are:

- traps
- used by user-mode programs
- to invoke kernel functions

Many platforms have a dedicated hardware instruction for this:

- ARM: `svc`
- x86-64: `syscall`

System Call Handling

When the system call instruction runs, the hardware:

- Switches to supervisor mode
- Invokes a specific kernel routine

When the kernel receives a system call, it:

- Identifies what the program wants
- Verifies the program arguments
- Authenticates the request
- Performs the operation (or indicates failure)

This allows the kernel to decide whether a program can access something outside its “dedicated computer”.

The Implications of the Trap

The user mode program cannot decide what kernel code runs.

This is:

- controlled by the hardware
- configured by the kernel

This is how modern operating systems protect themselves from malicious or buggy programs.

Invoking a System call

We have invoked system calls!

`open()`, `sbrk()`, `mmap()`, *etc.* are system calls!

We never used the `syscall` instruction.

The C library makes system calls look like a C function.

All functions in manual section 2 are system calls.

Overhead

System calls are very slow.

They can take tens to hundreds of thousands of clock cycles.

This is due to:

- Changing protection domains
- Validating arguments
- Adjusting memory mappings
- Cache effects
- …

Programs should make fewer system calls when practical.

Summary

- Exceptions are special control flow
- Protection domains control access to hardware resources
- Exception handlers run in supervisor mode in the kernel
- Special trap exceptions can be used to implement system calls
- System calls allow user mode programs to request access to the kernel

References I

Required Readings

[1] Randal E. Bryant and David R. O'Hallaron. *Computer Science: A Programmer's Perspective*. Third Edition. Chapter 8: Intro, 8.1, 8.2. Pearson, 2016.

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