A practical course on

Advanced systems programming in C/Rust

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Today's topic!

Kernel and System calls

Kernel

The kernel is the core component of a computer system that:

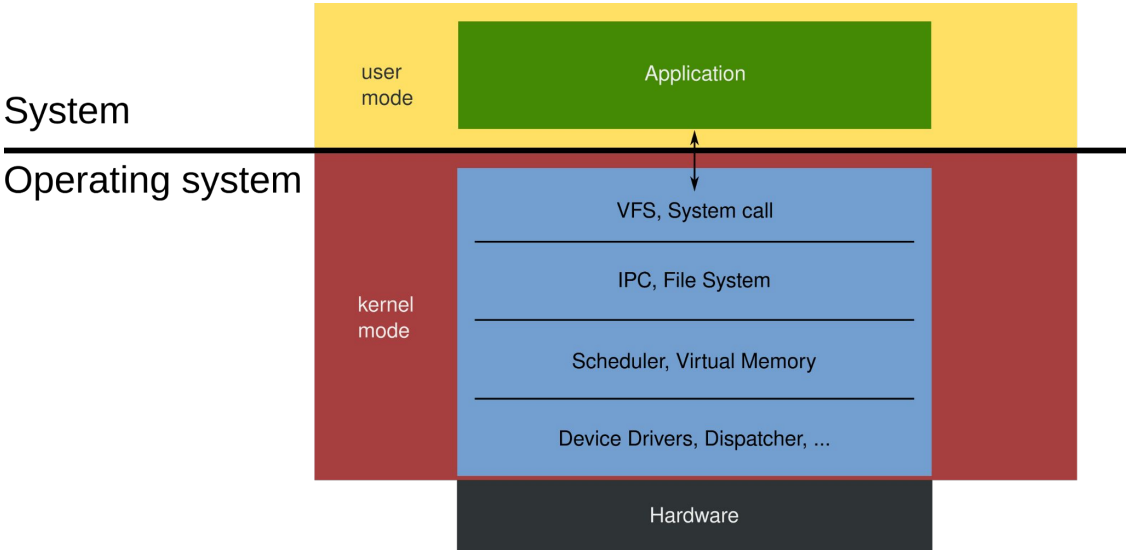
- manages resources (memory, threads, I/O devices, etc. . .)
- facilitates communication between applications (IPC)

It is executed in a privileged mode that gives it complete control over everything.

Various kernel designs define the boundary between privileged/unprivileged modes.

Monolithic Kernels

All OS services live in the kernel, in a single address space.
Single binary, modules can be added at run time.



Pros:

Performance: mode switches are relatively rare

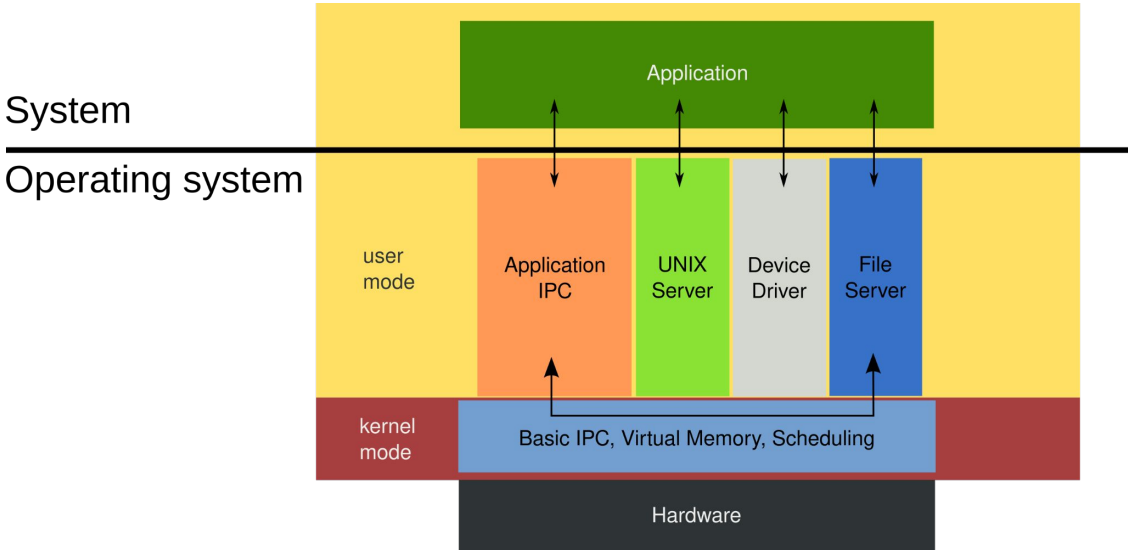
Cons:

Reliability: failure of a kernel service crashes the system

Examples: Linux, *BSD, MS-DOS, ...

Micro Kernels

Minimal services live in the kernel. Non essential services run in user mode.
If a user service crashes, it can be restarted without crashing the system.



Pros:

Reliability: services can crash and restart
Safety: easier to formalize

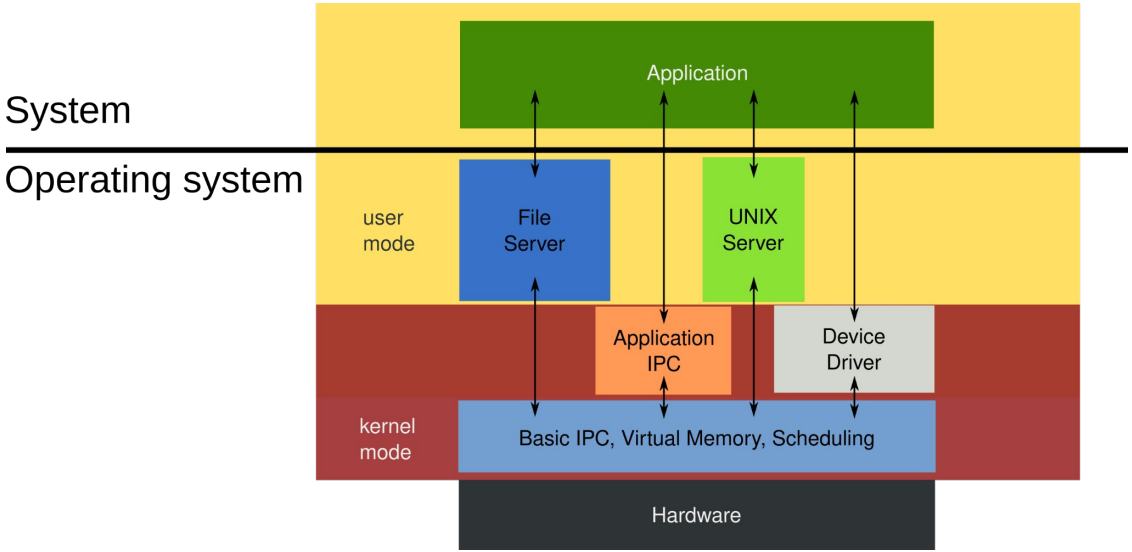
Cons:

Performance: lots of mode switches and communication

Examples: MINIX, Mach, ...

Hybrid Kernels

Between monolithic and micro kernels.
Performance-critical services live in the kernel, others run in user mode.

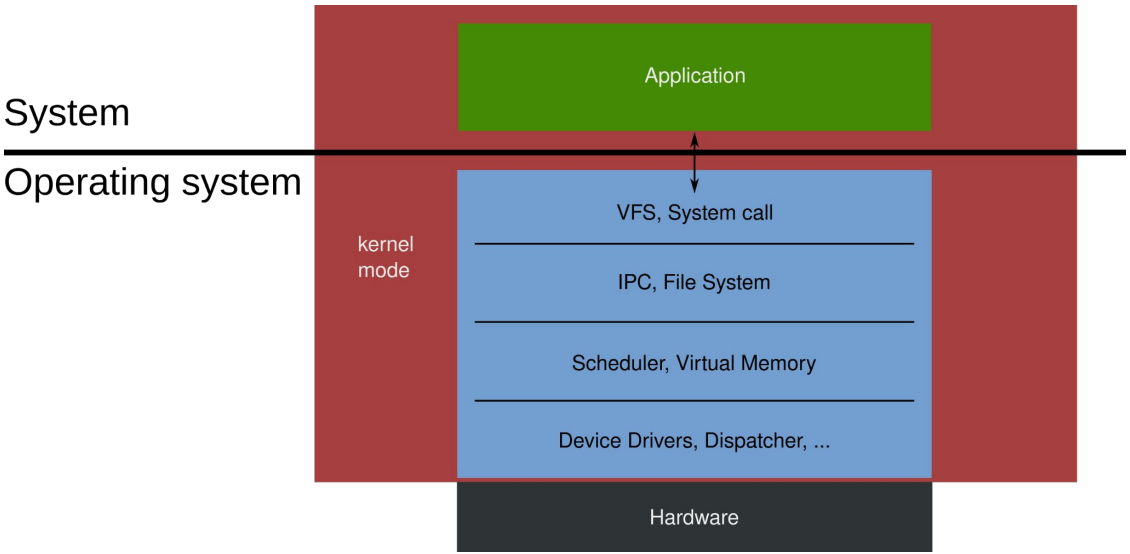


Depending on how *monolithic* or *micro* the kernel is, performance and reliability are on a spectrum between both designs.

Examples: NT, XNU, ReactOS, ...

UniKernels

Everything lives in the kernel, even applications.
Usually tailored for a particular application.



Pros:

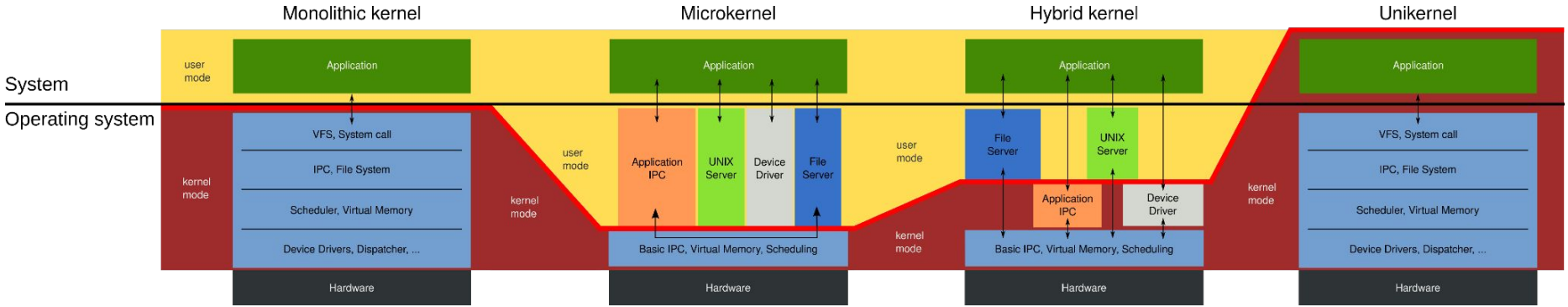
Performance: no mode switches, tailored to application.

Cons:

Usability: hard to Create, single purpose

Examples: ClickOS, MirageOS, Graphene, ...

~~Fifty~~ Four Shades of Kernel

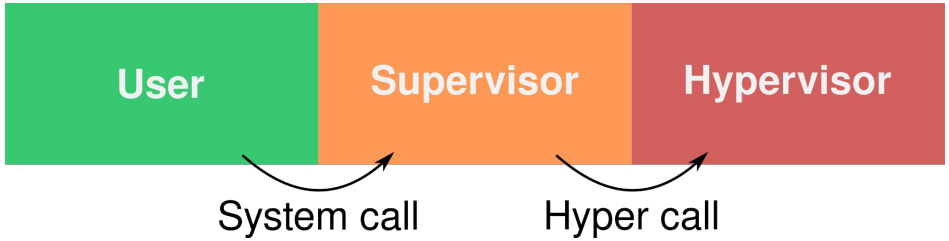


Privilege Levels

The privilege level determines what a piece of code can do on the system.

- **User mode**: Restricted access to hardware
  => Used by applications
- **Supervisor mode**: Access to privileged instructions, registers, management hardware
  => Used by the kernel
- **Hypervisor mode**: Access to virtualization-specific instructions
  => Used by hypervisors

Switching between privilege requires specific instructions.



System Calls

System calls allow applications to execute privileged code to perform certain tasks:

- I/Os (disk, network)
- Resource management (threads, memory)
- Communication (signals, IPCs)
- Access to specific hardware

They are the API of the kernel for user applications.
We'll only focus on **Linux** system calls here.

System Calls Wrappers

Programmers rarely directly use system calls. They usually use `libc` functions that perform system calls.

Example: The `ssize_t write(int, void*, size_t)` function is **not** an actual system call, but a wrapper from the `libc`.

Wrappers can make some argument checks and error handling (i.e. `errno`).

Some wrappers may do more, e.g. memory allocation can reuse previously freed memory without going through the kernel.

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System calls are just a software interrupt:

1. Place the system call number in a register

eax := SYS_read

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<place args>
int 0x80
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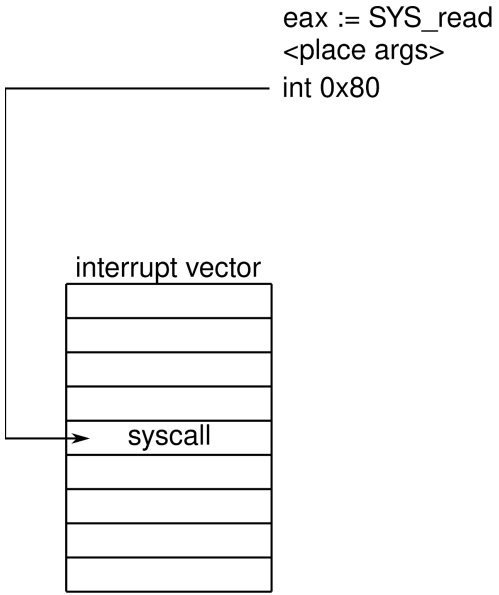

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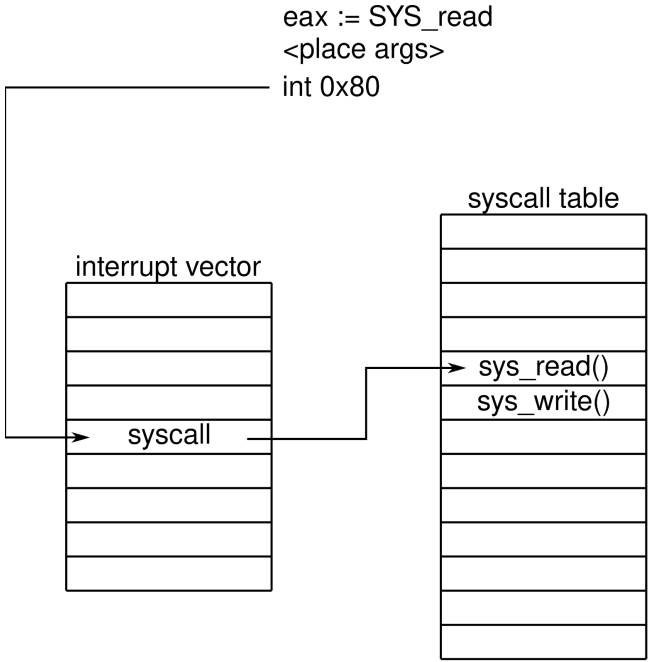

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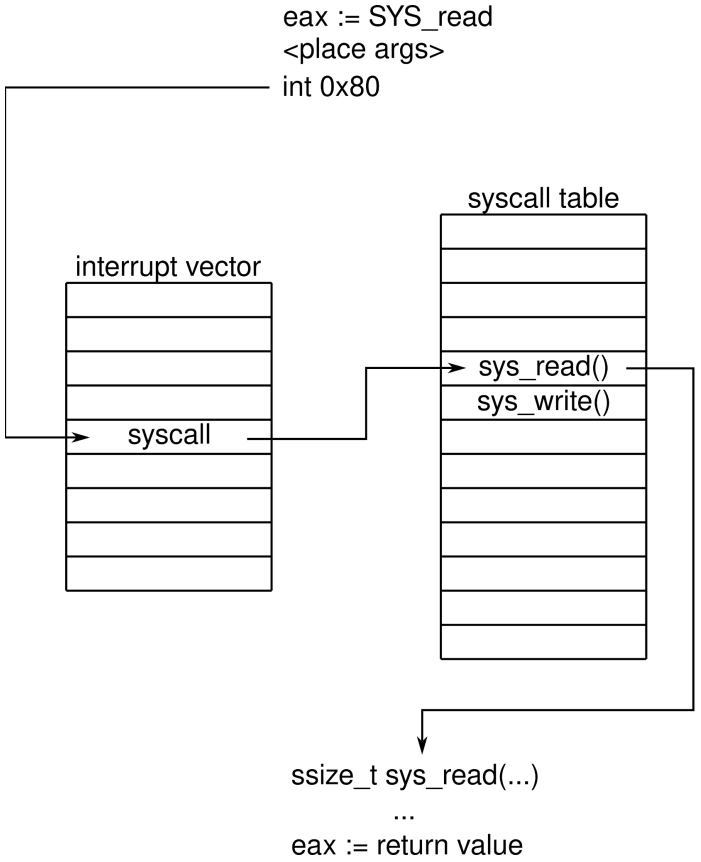

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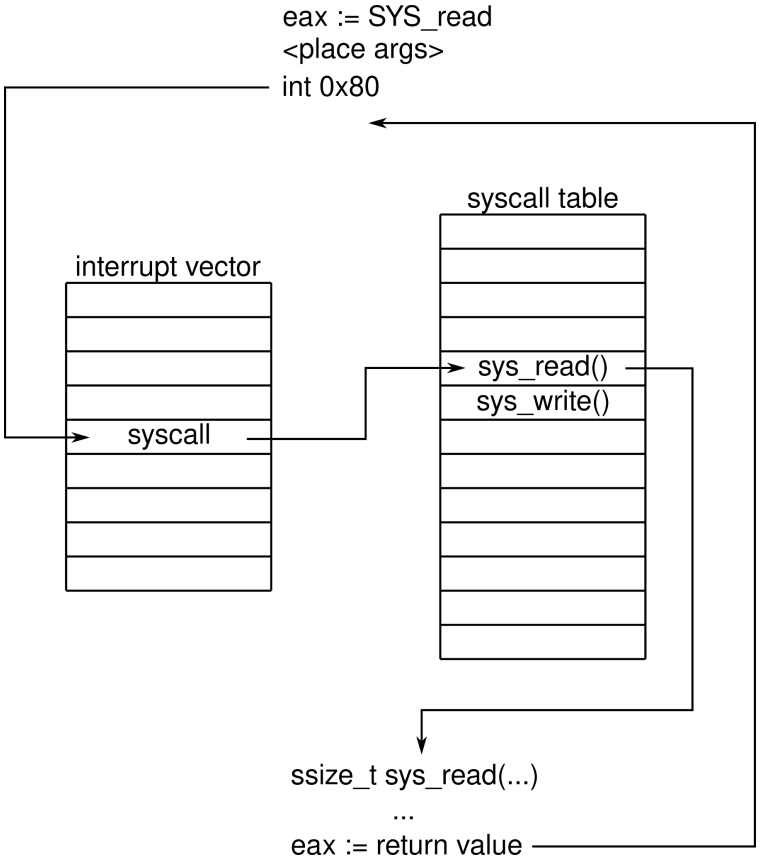

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3. Use the "system call" instruction

```
eax := SYS_read
<place args>
syscall
```

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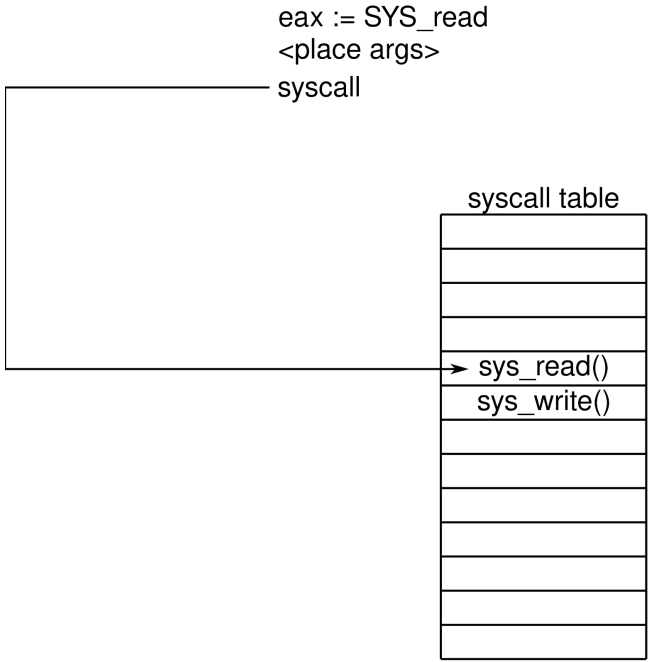

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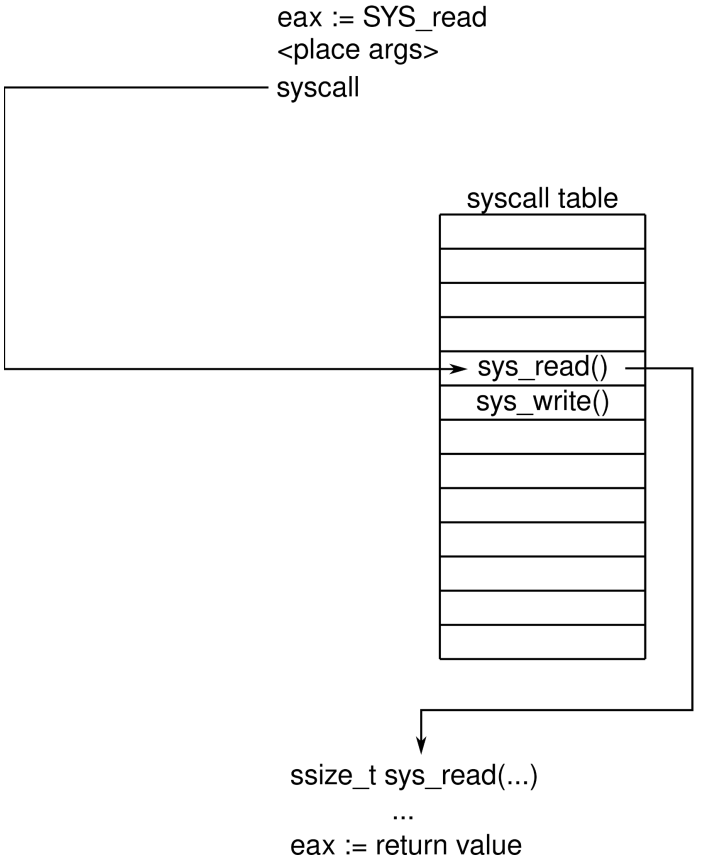

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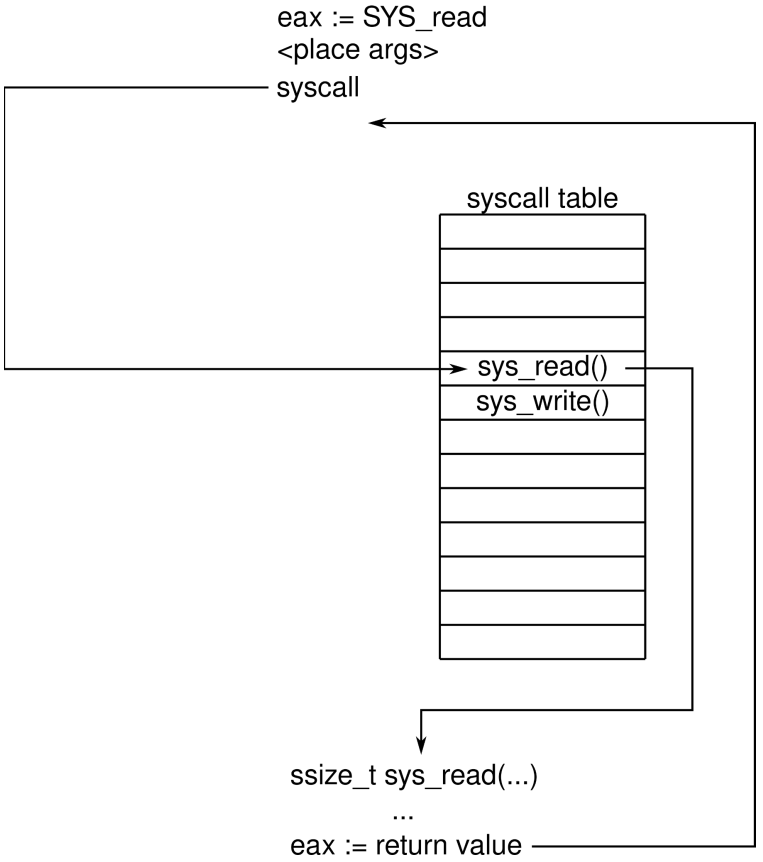
One level of indirection is bypassed.



Application Binary Interface

API: High-level interface for programmers (function prototypes, data types, …)

ABI: Low-level interface for compilers/OS (calling conventions, architecture-specific)

Arch	syscall#	retval	arg1	arg2	arg3	arg4	arg5	arg6	arg7
Arm EABI	r7	r0	r0	r1	r2	r3	r4	r5	r6
arm64	w8	x0	x0	x1	x2	x3	x4	x5	-
mips	v0	v0	a1	a1	a2	a3	a4	a5	-
riscv	a7	a0	a0	a1	a2	a3	a4	a5	-
x86-64	rax	rax	rdi	rsi	rdx	r10	r8	r9	-

Note: Linux allows at most 6 arguments for system calls. More examples at `man syscall`.

Note 2: Conforming to the ABI is the job of the `long syscall(long nr, ...)` function from the `libc`.

This Week's Tasks

Training exercises:

- Invoke a system call with the syscall libc function
- Invoke a system call in assembly

Main exercise:

- Implement a system call tracer

Going further (not graded):

- Implement a new system call in the Linux kernel

Hijacking System Calls (sort of …)

For the training exercises

System call wrappers (libc) are usually provided through a shared library.

```
redha@tum:~$ ldd /usr/bin/echo
linux-vdso.so.1 (0x00007ffd71f08000)
libc.so.6 => /usr/lib/libc.so.6 (0x00007f1af627a000)
/lib64/ld-linux-x86-64.so.2 => /usr/lib64/ld-linux-x86-64.so.2 (0x00007f1af6475000)
redha@tum:~$
```

The addresses of these functions are resolved at runtime by the linker (`ld-linux-x86-64.so.2`).

You can override a system shared library with your version with the `LD_PRELOAD` environment variable.

Tracing System Calls with `strace`

For the main exercise

`strace` is a tool used to trace system calls and signals. It relies on the `ptrace()` system call.

```
redha@tum:~$ strace -e execve,brk,open,read,write echo foo bar > /tmp/toto
execve("/usr/bin/echo", ["echo", "foo", "bar"], 0x7fff7460ee10 /* 48 vars */) = 0
brk(NULL)                               = 0x55d47d60c000
read(3, "\177ELF\2\1\1\3\0\0\0\0\0\0\0\0\3\0>\0\1\0\0\0`|\2\0\0\0\0\0"..., 832) = 832
brk(NULL)                               = 0x55d47d60c000
brk(0x55d47d62d000)                     = 0x55d47d62d000
write(1, "foo bar\n", 8)                = 8
+++ exited with 0 +++

redha@tum:~$
```

See you at the Q&A on Thursday!