# Operating Systems

## OS overview with BLITZ

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Operating system: a layer of software between applications and hardware

The OS provides an API to the applications above, and manages shared resources

# What is an operating system?

- The application developer’ s (or user’ s) view: “topdown”

  OS designed to provide an Application Programming Interface (API) to make using hardware resources easier (called system calls, or syscalls)

  Hides details via **good abstractions**

- The system’ s view: resource manager ( “bottomup” )

  OS manages possibly conflicting requests for resources, such as CPU cycles, memory, and storage

  It **virtualizes** physical resources

# OS as an API (a standard library)

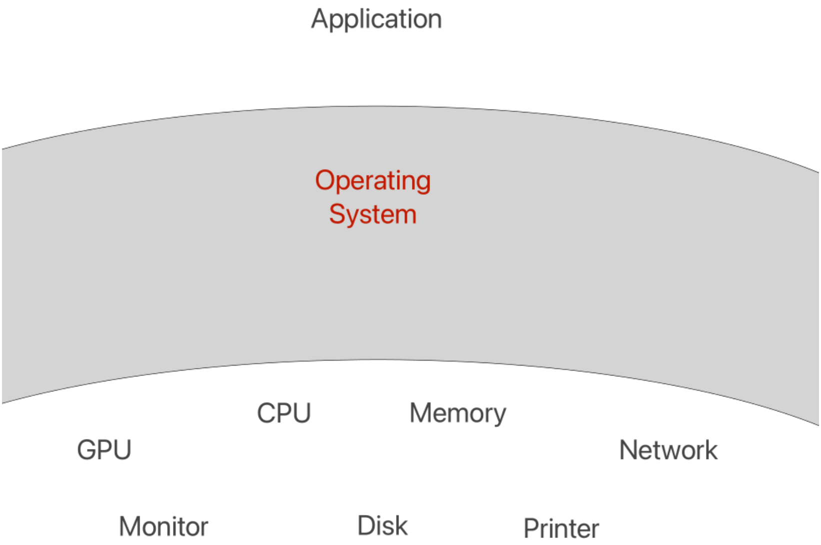
Why is such an abstraction important?

Otherwise, application writers must program all device accesses directly

- Load device command codes into device registers
- Handle initialization and timing for physical devices
- Interpret return codes

Hard to maintain and upgrade code

# Providing an API via system calls



# Providing an API via system calls

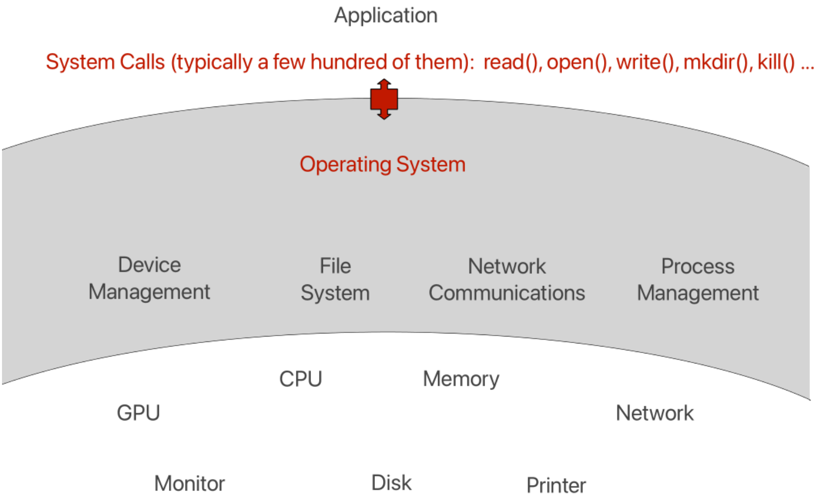



图 1: API via syscalls

# OS as a resource manager

- Shares resources across applications

  Sharing a resource (CPU) over time

  Sharing a resource (disk, memory) over space

- Makes efficient use of a limited resource

  Improves utilization and performance

  Minimizes overhead

- Protects applications from each other

  Enforces boundaries

*The OS* ***virtualizes*** *resources —the OS takes a physical resource (CPU, memory, or a disk)*
*and makes it easier to use.*

*Three important themes in this course:*
***virtualization***, ***concurrency***, *and* ***persistence***

# Theme #1: Virtualization

The OS takes a physical resource (CPU and memory) and transforms it into an easyto-use virtual form of itself

To the applications, the OS is a **virtual machine**

*The big question: how does the OS virtualize resources?*
*—mechanisms and policies*

*Demo: Virtualizing the CPU*

# Theme #2: Concurrency

The host of problems that must be solved when working on many things concurrently in the same program

*Demo: Concurrency with threads (functions that run in the same memory space as other functions)*

# Theme #3: Persistence

Storing data persistently using a file system

*Demo: I/O system calls*

*What problems will arise and how they are solved when the OS virtualizes the CPU?*

# Virtualizing the CPU

The OS needs to somehow share the physical CPU among many programs running seemingly at the same time

**Basic idea**: run one program for a little while, then switch to run another one, and so forth

Time-sharing the CPU —virtualization is achieved!

# But we have to care about performance

To minimize the overhead of running a program, we use a technique called limited direct execution

- Just run the program directly on the CPU!
- Sounds quite simple
- What may be a potential problem?

# Two problems

- If the OS directly runs the user program on the CPU, how can it make sure that the program doesn′ t do something it shouldn′ t be doing?
- When a user program is running, how can the OS run? (It′ s just a software program itself!)

# What we really need

*The OS needs to be in control, yet we don' t want to compromise performance!*

# Getting started

Let' s start with a brief review of how programs are executed on the CPU

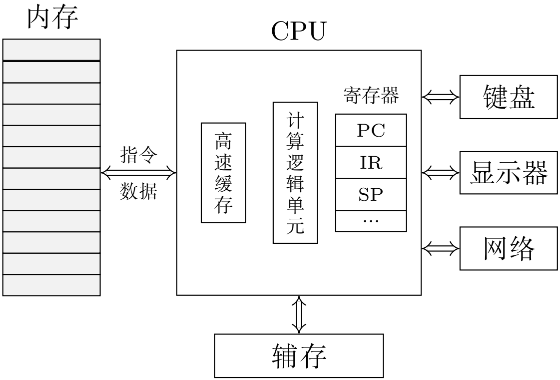



图 2: Components of a computer

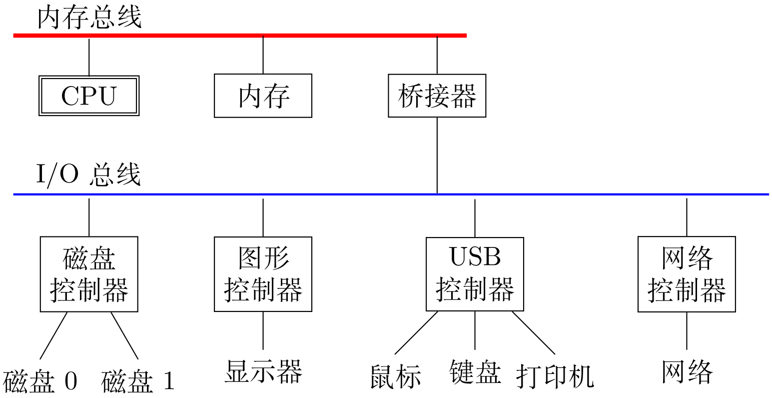



**图 3:** Different speeds

# A CPU’ s instruction set

Different for different CPU architectures

All have **load** and **store** instructions for moving items between memory and registers

- Load a word located at an address in memory into a register
- Store the contents of a register to a word located at an address in memory

Many instructions for comparing and combining values in registers and putting result into a register

# Basic anatomy on a CPU

Program Counter (PC)

holds the memory address of the **next** instruction

Instruction Register (IR)

holds the instruction currently being executed

General Registers (R1 ...Rn)

hold the environment of execution: temporary results

Arithmetic Logic Unit (ALU)

performs arithmetic functions and logic operations

# Basic anatomy on a CPU

The **Stack Pointer** (SP)

holds the memory address of a stack, with a frame for each active function' s parameters and local variables

The **Program Status Word** (PSW)

contains a few important control bits

# Program execution

All the CPU does is Fetch/Decode/Execute

- fetch next instruction pointed to by PC
- decode it to find its type and operands
- execute it
- repeat

```
PC = <start address>
while (halt_flag not set)
  IR = memory[PC]
  decode_and_execute(IR)
  PC = PC + 1
```

# The BLITZ architecture

The emulated CPU is a 32-bit architecture

16 general purpose **integer** registers with one word each (r0 -> r15)

16 **floating point** registers with a double precision floating point number each (64 bits) (f0 -> f15)

69 different instructions

# The Stack Pointer in BLITZ

Register r15 points to the top of the execution stack

The stack grows downwards from higher towards lower memory addresses

# Two problems, revisited

- If the OS directly runs the program on the CPU, how can it make sure that the program doesn′ t do something it shouldn′ t be doing?
- When a program is running, how can the OS run? (It′ s just a software program itself!)

# An intuitive solution

```
PC = <start address>
while (halt_flag not set)
  IR = memory[PC]
  if IR != special_instruction
  decode_and_execute(IR)
  else
  switch_to_the_OS_kernel()
  PC = PC + 1
```

*The OS needs help from **hardware** to accomplish these tasks!*

# Processor Modes

*CPUs have a mode bit in the PSW that defines the execution capability of a program*

**Kernel mode** (mode bit set)

- Executes any instruction
- called "System mode" in the BLITZ documentation

**User mode** (mode bit cleared)

- Executes a subset of instructions
- Instructions that execute only in the kernel mode are called **Privileged Instructions**

# What is an example of a privileged instruction?

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I/O operations to the disk

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I/O operations to the disk

The operation that sets the mode bit to 1!

# Processor modes: a summary

- OS operates in **kernel mode**

  has all privileges to access devices and memory Modules that run in kernel mode are called "the kernel"

- Applications operate in **user mode**

  Have limited privileges: limited access to memory, no access to I/O devices

- Now the OS is in control

  When applications need to run privileged instructions, they **must** enter the OS kernel

How can applications (user programs) enter the OS kernel?

Can an application just set the PC to the address of an OS instruction, and jump to that address?

How do we enforce that only the OS operates in the kernel mode?

# How can applications enter the OS kernel?

Applications, running in user mode, need to perform a **system call**

To perform a system call, a user program needs to execute an instruction called a **trap**

# The trap instruction

All it does is to jump into the kernel while simultaneously raising the privilege level to kernel mode

- the application calls a library procedure (in the standard C library) that includes the appropriate trap instruction
- fetch/decode/execute cycle then begins at a prespecified OS kernel entry point for a system call
- CPU is now running in kernel mode

# When the system call returns

We will need to return to the program making the system call

But at the same time, the mode bit will need to be cleared (reducing the privilege level back to user mode)

Again, the OS depends on some help from the CPU, by using another instruction, let' s call it **return-from-trap**

# What the hardware must do

- When executing a trap, the hardware will need to make sure to save the caller' s registers, the PC, and flags in the PSW
  - Because the hardware is responsible for returning correctly when the **return-from-trap** instruction is issued by the OS
- One way to do this (Intel x86) is to save them onto a kernel stack (so does KLITZ)
- The **return-from-trap** instruction will pop these values off the stack and resume the execution of the program in the user mode

*But there' s one more important problem:*
*How does the trap instruction know which code to run?*
*(there are, after all, hundreds of system calls.)*

# Which code to run?

Can the calling program specify an address to jump to?

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**No**. The kernel must carefully control what code executes upon a trap.

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**Solution**: The kernel sets up a trap table at boot time in kernel mode, and then let the hardware know where it is.

# Trap/Interrrupt

The trap table is also called the interrupt table/vector, because it has entries for hardware interrupts and exceptions too!

It turns out that trap is only one of the entries in the trap table.

The actual type of the system call is called the **syscall number**, and it can be stored at a wellknown location in the kernel stack.

# Interrupts

Interrupts are **asynchronous** (comes in at any arbitrary time)

- Caused by hardware events
- Timer interrupts
- I/O (such as keyboard or disk) interrupts

# Exceptions

Caused by programming errors in a user-mode program

Examples:

- an arithmetic exception (divide by zero)
- attempts to access memory that the program does not control
- attempts to execute a privileged instruction

# The trap (interrupt) table: an illustration

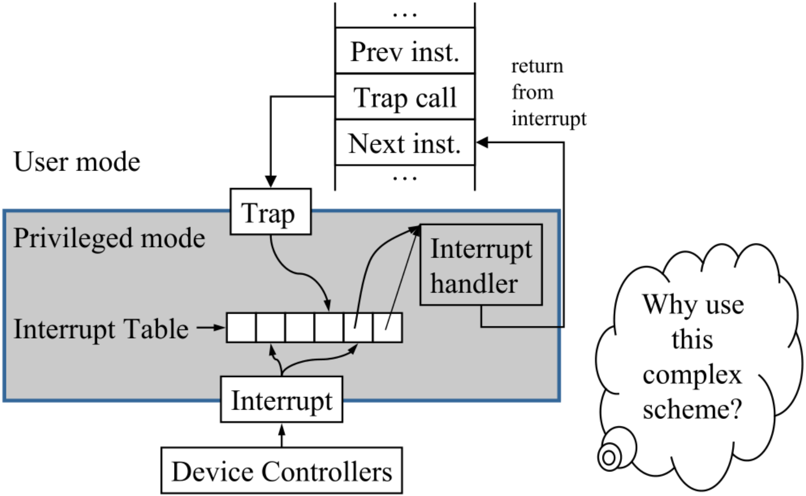


图 **4:** Trap table (Interrupt vector)

*Interrupt and Trap Processing in BLITZ ("The BLITZ Architecture," pages 22-25, 54)*

# The Program Status Word in BLITZ

Called the **Status Register** in BLITZ documentation

A special 32-bit register, but only 6 bits are used

Three condition codes are set during certain arithmetic operations: Z = Zero, V = Overflow, N = Negative

Privileged bits (can only be changed by the kernel in the System Mode)

- "I" bit: Interrupt Enabled (1) or Disabled (0)
- "S" bit: System Mode (1) vs. User Mode (0)
- "P" bit: Paging Enabled (1) or Disabled (0)

# Interrupt Types in BLITZ

Asynchronous interrupts (hardware)

- Timer Interrupt
- Disk Interrupt

Synchronous interrupts (during execution)

- Exceptions: Privileged Instruction; Arithmetic
- Trap: Syscall

# More about BLITZ registers

Two sets of integer registers: "system" (kernel) r0-r15 and "user" r0-r15

- When running in user mode, the user r0-r15 is used
- When running in kernel mode, the system r0-r15 is used
- In kernel mode, the kernel can read/write user registers

The use of two sets of integer registers allows kernel traps (such as system calls) to be executed quickly

- No registers need to be saved when trapping to the kernel
- But only one set of floating-point registers that are shared

# When an interrupt occurs and is serviced

The current executing instruction is finished

- PC points to the next instruction for hardware interrupts
- PC points to the offending instruction for exceptions
- PC points to the instruction following the "syscall" trap for system calls

An "Exception Info Word" is pushed onto the system stack (system register r15 used)

- Syscall trap: system call number
- All zeros for most other types of interrupts

Status Register (PSW) is pushed onto the system stack

Program Counter (PC) is pushed onto the system stack

# When a trap, interrupt, or exception occurs

Status Register changed

- Switch to System Mode
- Disable subsequent interrupts
- Disable paging (address translation via the page table)

PC is loaded with the corresponding address of one of the interrupt vector entries

- The entry contains a **jmp** instruction, which transfers control (again) to the interrupt handler
- 14 entries in the interrupt vector, in low memory, 56 bytes in total
- Some interrupts can be masked, some cannot

# if you want to know the details

Read blitz.c, singleStep() function, line 4997-6728

# Returning from a trap (interrupt) handler

The "Return from Interrupt" **reti** instruction in BLITZ

- First, restore the **PC** by popping the top value from the system stack and move it into the PC
- Second, restore the **Status Register** to the old value, by popping the next value from the system stack into the Status Register
- Third, pop and discard the next value from the system stack (the "Exception Info Word")

Instruction execution resumes in the interrupted program, as if nothing happened

None of the user registers are affected in an interrupted user program

# The trap table (called Interrupt Vector in BLITZ)

Interrupt Vector in Low Memory

| Address | Description |
|---|---|
| 000000 | Power On Reset |
| 000004 | Timer Interrupt |
| 000008 | Disk Interrupt |
| 00000C | Serial Interrupt |
| 000010 | Hardware Fault |
| 000014 | Illegal Instruction |
| 000018 | Arithmetic Exception |
| 00001C | Address Exception |
| 000020 | Page Invalid Exception |
| 000024 | Page Readonly Exception |
| 000028 | Privileged Instruction |
| 00002C | Alignment Exception |
| 000030 | Exception During Interrupt |
| 000034 | Syscall Trap |

# Runtime.s in Lab 1

- PowerOnReset: jmp RuntimeStartup
- TimerInterrupt: jmp TimerInterruptHandler
- DiskInterrupt: jmp DiskInterruptHandler
- SerialInterrupt: jmp SerialInterruptHandler
- HardwareFault: jmp HardwareFaultHandler
- IllegalInstruction: jmp IllegalInstructionHandler
- ArithmeticException: jmp ArithmeticExceptionHandler
- AddressException: jmp AddressExceptionHandler
- PageInvalidException: jmp PageInvalidExceptionHandler
- PageReadonlyException: jmp PageReadonlyExceptionHandler
- PrivilegedInstruction: jmp PrivilegedInstructionHandler
- AlignmentException: jmp AlignmentExceptionHandler
- ExceptionDuringInterrupt: jmp ExceptionDuringInterruptHandler
- SyscallTrap: jmp SyscallTrapHandler

# review our problems

With all these mechanisms, we still haven′ t solved the second problem yet.

When a program is running, how can the OS run? (It′ s just a software program itself!)

# review our problems

Can we trust the programs to behave reasonably, and just wait for a "**yield**" system call?

yield(): transfer control to the OS

We call this a "**cooperative**" approach —used by the original MacOS and Windows.

# review our problems

This is, obviously, not ideal —a malicious or buggy program can take over the CPU **indefinitely**.

How does the OS gain control of the CPU without cooperation?

# review our problems

Again, the OS depends on help from the **hardware**.

The solution: timer interrupts

# What We' ve Covered So Far

Required reading in the textbook: Chapter 1 and 2 in Operating Systems Concepts

Required reading in BLITZ:

- An Overview of the BLITZ System (7 pages)
- An Overview of the BLITZ Computer Hardware (8 pages)
- The BLITZ Architecture (67 Pages, esp. 1-9, 22-25, 54)

- 2018 年 10 月，我在瑞典一家国家戒毒所完成了 3 个月的康复计划。然后，失业了。没有毒品或其我恶习来消磨时间，日子似乎长得不可思议。我努力寻找活动来填补日子。最后我转向了编程，因为它一直是我生活中的一大兴趣。
- 期间我写了一个 ELF 解析器、Ext2 文件系统浏览器、以及一个带有事件循环的 GUI 框架。我之前的工作是开发网页浏览器 (苹果和诺基亚的 WebKit)。
- 一个操作系统开始成型。我选择 serenityos 这个名字是因为我想永远记住宁静的祈祷。当时我很担心我的未来，我觉得这个名字会帮助我走在正确的道路上。我的总体想法是建立自己梦想中的日常使用系统。它将是我最喜欢的两种计算范例的组合：上世纪 90 年代的 GUI 和 2000 年代后期的 Unix 的直截了当的命令行。

- 我们自己构建一切！从内核到 web 浏览器，以及介于两者之间的一切。所以我开始日复一日地开发。一周又一周。月复一月。这个项目成为了我的基石，因为我慢慢学会了重新驾驭生活。
- 我决定把我的一些节目录制下来，并上传到我的 YouTube 频道。一开始我很不舒服，但我坚持了下来，因为我喜欢做我自己，让人们看到我的感觉，而不是戴上面具假装一切都好。
- 越来越多的人发现了我的小项目（和我的频道），许多人发现了真正与他们产生共鸣的东西。从微不足道的开始，它已经成长为一个充满活力的开源社区，有来自世界各地的数百名贡献者。

- 从现在开始我会专注于 SerenityOS 的全职工作！多亏了 Patreon、GitHub 赞助商和 PayPal 的大力支持，这一切才得以实现！能得到这么多人的信任和支持，我感到非常幸运。非常感谢你们！
- 在撰写本文时，我每月收到超过 2000 美元的捐款。YouTube 上也有少量收入 (比如每月 150 美元)，以及 SerenityOS 产品的销售 (另外 100 美元)。这还不足以完全支撑我和我的家人，但已经足够让我决定冒险一试，看看会发生什么！
- 你可能理解，我这样做并不是为了致富。我只是一个试图保持理智和健康的人，碰巧我的治疗/自我护理项目引起了成千上万人的共鸣，他们想要支持这个项目，看看它会发展到什么程度。
- 很庆幸能在这里找回我自己，我会继续努力。

Andreas Kling