# Principles of Operating Systems

## Introduction

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2024

# References

- These slides are adapted from the slides of Renaud Lachaize
- Chapters of *Operating Systems: Three Easy Pieces*
  - Chater 2: Introduction
  - Chapter 6: Direct Execution

# Course goals

- **Introduce you to operating system concepts**
  - Hard to use a computer without interacting with the OS
  - Understanding the OS makes you a better (more effective) programmer
- **Cover important system concepts in general**
  - Caching, concurrency, memory management, I/O, protection, ...
- Teach you to deal with larger software systems
- Prepare you to take other classes related to OS concepts
  - M1 Principles of computer networks, M1/M2 Distributed systems, M2 Parallel systems, M2 Advanced OS & Cloud infrastructure, …

# Outline

- What is an operating system?
- Some history
- Abstractions: processes and address spaces
- Protection and resource management

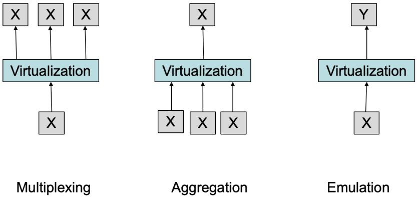
# What is an operating system?

- *An operating system (OS) is a (software) layer between the hardware and the applications*

- Two key roles: **virtualization** and **resource management**

# What is an operating system?

- **Virtualization**
  – *The OS makes it easier to write and run programs on a machine*
    - Hides the low-level interface of the hardware and replaces it with higher-level abstractions
    - Hides the physical limitations of a machine and the differences between machines (size of the main memory, number of processors)
    - Hides the sharing of resources between applications/users
  – Thus, we sometimes refer to the OS as a *"virtual machine"*



# What is an operating system? (continued)

- **Resource management**
  - The OS is in charge of managing the resources of a computer system
    - **Physical resources**: memory, processor, devices, ...
    - **Logical resources**: programs, data, communications, ...
  - Goals: allow the applications to run safely / securely / efficiently / fairly ... despite the fact that they run concurrently
  - Encompasses several dimensions, including: ***allocation***, ***sharing*** and ***protection***
  - Consists in a combination of ***mechanisms*** and ***policies***

# OS Design goals and trade-offs

- Provide **useful abstractions** to improve programmer/administrator/user productivity

- Provide high **performance**
  - Leverage the power/capacity of the hardware
  - Minimize the (time and space) overhead of the OS features

- Provide **protection**
  - Between applications
  - Between applications and OS
  - Between users

- Provide a high degree of **reliability**

- Take care of other aspects such as predictability, energy-efficiency, mobility, ...

# OS Interfaces

- An operating system typically exports **two kinds of interfaces**
  - A command/user interface
  - A programmatic interface

- **Command/user interface**
  - Designed for human users
  - Various forms: textual or graphical
  - Composed of a set of commands
    - Textual example (Unix shell): `rm myfile.txt`
    - Graphical example (most systems): drag the myfile.txt icon into the trash bin.

# OS Interfaces (continued)

- **Programmatic interface**
  - This interface is used/called from application programs running on the system
    - Including the programs implementing command/user interfaces
  - Composed of a set of procedures/functions
    - **Libraries**
    - **System calls** (more details later)
  - Defined both:
    - At the source code level: ***Application Programming Interface*** (**API**)
    - At the machine code level: ***Application Binary Interface*** (**ABI**)

# Some of the topics that we will study during the semester

- **How does the OS virtualize and manage resources?**
  - What are the required mechanisms and policies?
  - What kind of support is required from the hardware?
  - How can these goals be achieved efficiently?
  - We will consider several resources : CPU, main memory, input/output (I/O) devices (e.g., storage devices)

- **How to build concurrent programs?**
  - How to program applications with several “tasks”?
  - How to coordinate these tasks and let them share data?
  - How to make such programs correct and efficient?
  - What kind of support is needed from the OS and the hardware to achieve this goals?

# Outline

- What is an operating system?
- **Some history**
- Abstractions : processes and address spaces
- Protection and resource management

# Early operating systems

## A set of libraries of commonly-used functions

- For example, low-level code for I/O devices
- Running one program at a time
  - Possibly involving a human operator (e.g., for deciding in what order to run the jobs)

## Problems

# Early operating systems

## A set of libraries of commonly-used functions

- For example, low-level code for I/O devices
- Running one program at a time
  - Possibly involving a human operator (e.g., for deciding in what order to run the jobs)

## Problems

- Assumed no bad users or programs
- Poor utilization of resources
  - Hardware (e.g., CPU idle while waiting for I/O completion)
  - Human user (must wait for each program to finish)

# Some History
# (2) Beyond libraries: Protection

- Realization that the code of the OS plays a central role
- **A user/application should not be able to make the whole system fail or to perform unauthorized operations**
  - E.g., issue arbitrary write requests to a storage device

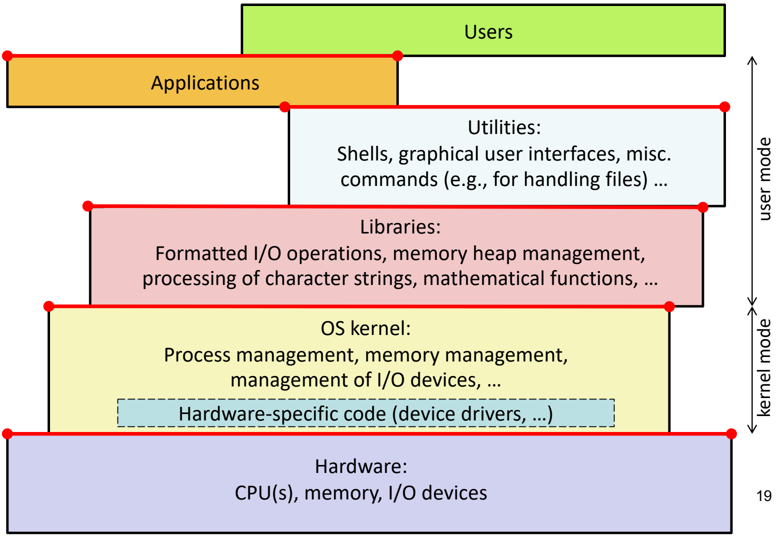
- Idea: Modification of the OS interface
  - Old interface: provide applications with library procedures allowing direct access to critical operations
  - New interface: **force application to delegate critical operations, using a hardware mechanism** that transfers control to a more privileged execution mode
    - Such an interface is called a "system call" or "syscall" (more details later)

# Some History
# (3) Multiprogramming / Multitasking

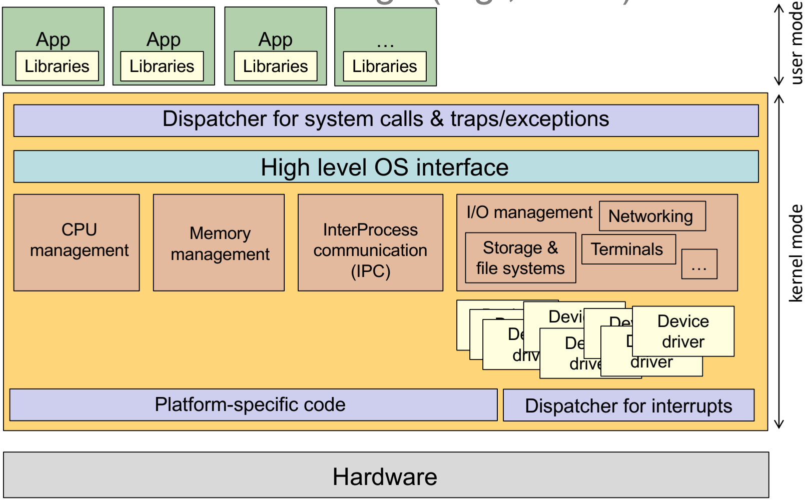
- Idea: **improve machine resource utilization by running several programs concurrently**
  - When a program blocks (e.g., waiting for input from the disk / the network / the user), run another program

- **Problems**: what can an ill-behaved application do ?
  - Never relinquish the CPU (infinite loop)
  - Access the memory of another application
- **The OS provides mechanisms to address these problems**
  - Preemption: take CPU away from a looping application
  - Memory protection: prevent an application from accessing another application's memory

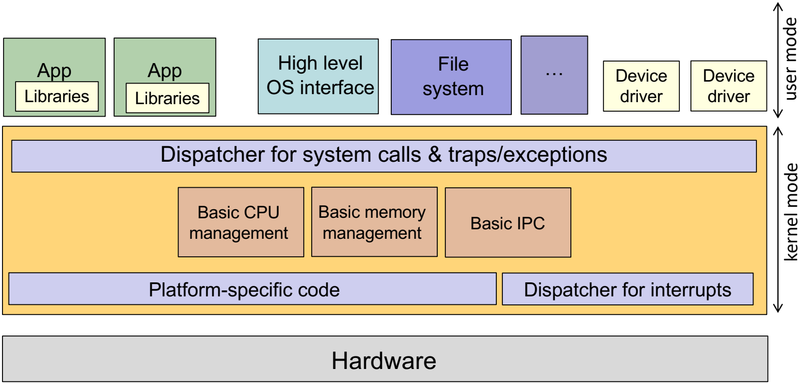
# Typical structure of an operating system



# Monolithic kernel design (e.g., Linux)



# Microkernel design (e.g., L4)



# Outline

- What is an operating system?
- Some history
- **Abstractions: processes and address spaces**
- Protection and resource management

# A key OS abstraction: the Process

- **A *process* is an abstraction corresponding to a running instance of a program**

- Its main role consists in **virtualizing the CPU**

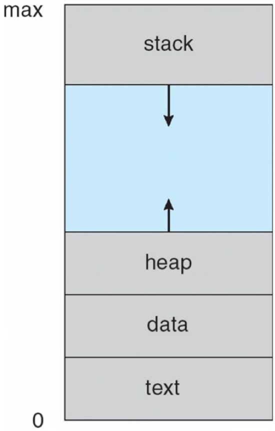
  – Although there are just a few physical CPUs (or even just one), the OS can provide the illusion of a nearly-endless supply of logical CPUs (one per process)

  – Its also allows the OS to capture the state and control the execution of a running program, which are key mechanisms for resource management

# A key OS abstraction: the Process

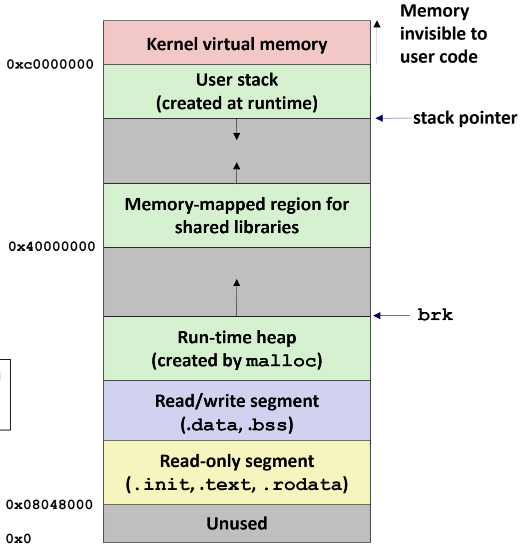
- A process mainly consists in:
  - An ***execution context*** (a.k.a. an *execution flow*, or a *control flow*):
    - A current machine state: a set of current values for the CPU registers, including the program counter (PC) and the stack pointer (SP)
    - An execution stack
  - A ***memory space*** (a.k.a. an *address space*)
  - A **logical state** (is it currently running? If not, why?)
  - Some other information, required by the OS

# Process address space
# A simplified view




Picture from: Silberschatz et al., *Operating systems concepts* (8th edition)

# Process address space
# A more detailed view




Example based on Linux for Intel x86 (32 bits)

Picture from: Bryant & O'Hallaron, *Computer systems: a programmer's perspective*

# Outline

- What is an operating system?
- Some history
- Abstractions : processes and address spaces
- **Protection and resource management**

# Some key techniques for protection

- Overall goal: **prevent bad processes from impacting the OS or other processes**

- **Preemption**
  - **Give a resource to a process and take it away if needed** for something else
  - Example: CPU preemption

- **Interposition**
  - **Place OS between application and resources** (e.g., an I/O device, or a piece of information stored in memory)
  - OS tracks the resources that the application is allowed to use
  - On every access request, check that the access is legal
  - Example: System calls

# Some key techniques for protection (continued)

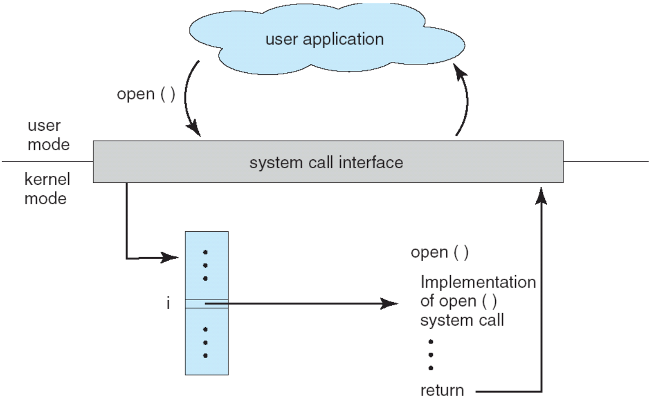
- CPU execution modes
  - CPUs provide **2 execution modes**:
    - Privileged (a.k.a. supervisor mode, or kernel-level mode)
    - Unprivileged (a.k.a. user mode, or user-level mode)
  - **OS kernel code** runs in **privileged mode**
  - **Application code** runs in **unprivileged mode**
  - Protection-related code (resp. data) must only be executed (resp. accessed) in privileged mode
    - Enforced by hardware (details later)
    - A system call is the only way to switch from unprivileged mode to privileged mode

# System calls

- Applications (i.e., user-level code) can **invoke kernel services** through the system call mechanism
  - **Using a special hardware instruction** that triggers a trap into kernel-mode
  - ... and transfers control to a trap handler
  - ... which dispatches to one of a few hundred syscall handlers

# System calls (continued)

- Illustration with the `open` system call (to open a file)




Picture from: Silberschatz et al., *Operating systems concepts* (8th edition)

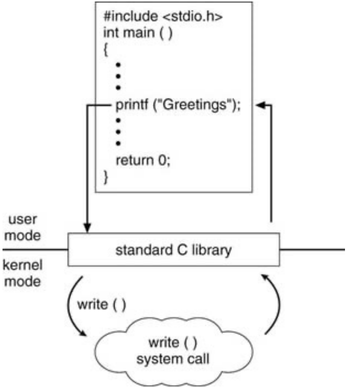
# System calls (continued)

- Goal: **perform things that an application is not allowed to do in unprivileged mode**
  - Like a library call, but into more privileged code

- The kernel supplies a **well-defined system-call interface**
  - Applications set up syscall arguments and trap to kernel
  - Kernel checks if operation is allowed, performs operation and returns results (transfers control back to application)
  - Many higher-level library functions are built on the syscall interface
    - Example (Unix) : functions such as **`printf`** and **`scanf`** are implemented as user-level library code that calls the kernel using system calls such as **`read`** and **`write`**

# System call example

- The standard C library (libc) is implemented in terms of syscalls
  - **`printf`** (in libc) has same privilege as application
  - **`printf`** calls **`write`**, which can access low-level resources such as the console/screen and files






Picture from: Silberschatz et al., *Operating systems concepts* (8th edition)

# CPU preemption

- **Protection mechanism to prevent a process from monopolizing the CPU**
  - Allows the kernel to take back control of the CPU after a maximum time interval
  - Relies on the processor interrupt mechanism and on a timer device

- **The kernel programs the timer to send periodic interrupts** (e.g., every 10 ms)
  - Device configuration is only allowed in privileged mode
  - User code cannot re-program the timer

# CPU preemption (continued)

- The kernel configures the processor to set up a **timer interrupt handler**
  - This handler is a piece of code provided by the kernel, and runs in privileged mode
  - In this way, each periodic timer interrupt will trigger the execution of some kernel-defined code
  - This kernel code can decide to keep the current process running or to give the CPU to another one
  - Note : interrupt handlers cannot be defined/modified by user-level code
    - Thus, there is no way for user code to hijack the interrupt handler

- Result: a process cannot monopolize the CPU with an infinite loop
  - At worst, it may get 1/N of CPU time if there are N CPU-hungry processes

# CPU scheduling

- **The *scheduler* is a component of the OS, in charge of deciding which process should run on the CPU** (1 decision per CPU)

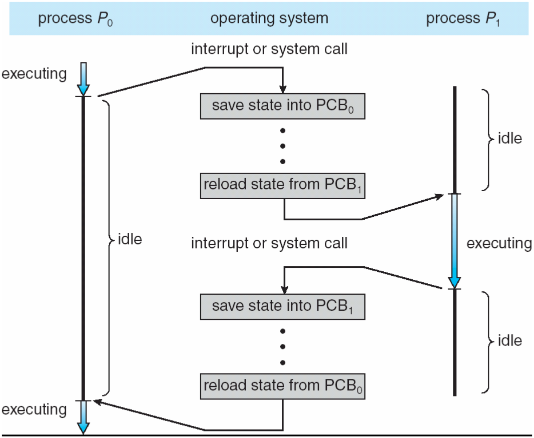
- When is the scheduler invoked?
  - **Periodically, for each timer interrupt**
  - **Punctually, in reaction to some syscalls**:
    - Process termination (exit)
    - Process explicitly releasing the CPU (yield, sleep, ...)
    - Process requesting a blocking action
    - Creation of a new process with a higher priority
    - ...
  - **Punctually, in reaction to some interrupts**
    - E.g., a device notification for available data

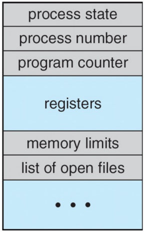
# CPU scheduling (continued)

- **What does the scheduler do upon invocation?**
  - **Make decision on the process P2 that should obtain the CPU**, based on:
    - The list of processes that are ready to run
    - ... and a given scheduling policy
  - **Save execution context of "outgoing" process P1**
    - (Except if this process is terminated)
    - This allows resuming the execution of P1 later on
  - **Inject /restore the execution context of P2 on the CPU**

- This sequence of steps is called a **"context switch"**
  - Note that, just after the switch, P2 runs in kernel mode and must eventually switch back to user mode. This will happen via a return-from-interrupt or a return-from-syscall instruction.

# Context switch




PCB



Pictures from: Silberschatz et al., *Operating systems concepts* (8th edition)

# Context switch (continued)

A simplified code example (taken from “xv6”, a pedagogical mini-OS developed by MIT – this version is for the RISC-V 64-bit processor)

```
struct context {
    uint64 ra;
    uint64 sp;
    // callee-saved
    uint64 s0;
    uint64 s1;
    uint64 s2;
    uint64 s3;
    uint64 s4;
    uint64 s5;
    uint64 s6;
    uint64 s7;
    uint64 s8;
    uint64 s9;
    uint64 s10;
    uint64 s11;
};
```

```
# void swtch(struct context *old, struct context *new);
# Save current register context in old
# and then load register context from new.
.globl swtch
swtch:
  # Save old registers
  sd ra, 0(a0)
  sd sp, 8(a0)
  sd s0, 16(a0)
  sd s1, 24(a0)
  sd s2, 32(a0)
  sd s3, 40(a0)
  sd s4, 48(a0)
  sd s5, 56(a0)
  sd s6, 64(a0)
  sd s7, 72(a0)
  sd s8, 80(a0)
  sd s9, 88(a0)
  sd s10, 96(a0)
  sd s11, 104(a0)
```

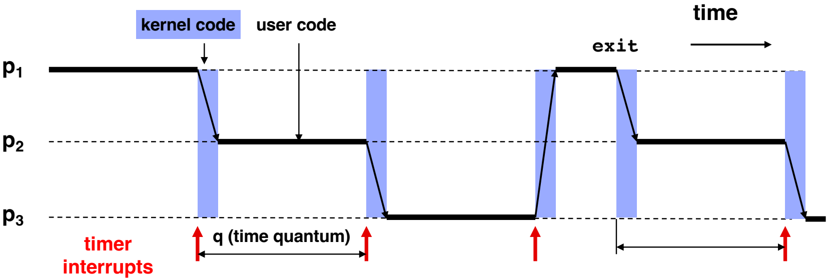
```
  # Load new registers
  ld ra, 0(a1)
  ld sp, 8(a1)
  ld s0, 16(a1)
  ld s1, 24(a1)
  ld s2, 32(a1)
  ld s3, 40(a1)
  ld s4, 48(a1)
  ld s5, 56(a1)
  ld s6, 64(a1)
  ld s7, 72(a1)
  ld s8, 80(a1)
  ld s9, 88(a1)
  ld s10, 96(a1)
  ld s11, 104(a1)

  # Finally return into new ctxt
  ret
```

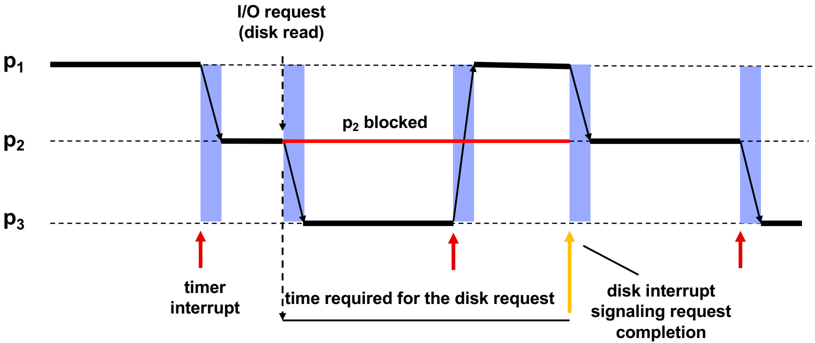
# Context switch (continued)

- Notes:
  - Implementation details are very machine (processor) dependent, but the general principle is the same
  - A context switch has **a non-negligible cost** and should not happen too often
  - **Warning: Do not confuse**
    - **Context-switch** (transition between two execution contexts)
    - **Mode switch** (transition between user and kernel mode, in the same execution context)

# CPU scheduling examples



# CPU scheduling examples (continued)



# Memory virtualization and protection

- **The OS must protect the memory space of a process from the actions of other processes**
- Definitions
  - ***Address space***: all memory locations that a program can name
  - ***Virtual address***: an address in a process address space
  - ***Physical address***: an address in real memory
  - ***Address translation*** : map virtual address to physical address
- **A translation is performed for each executed instruction that issues a memory access**
  - Modern CPUs do this in hardware for speed
- Idea: if you cannot name it, you cannot touch it
  - Ensure that the translations of a process do not include memory areas of other processes

# Memory virtualization and protection (continued)

- **CPU allows kernel-only virtual addresses**
  - The kernel is typically part of all address spaces, e.g., to handle a system call in the same address space
  - But the OS must ensure that applications cannot touch kernel memory
- **CPU allows disabled virtual addresses**
  - Helps catching and halting buggy program that makes wild accesses
  - Makes virtual memory seem bigger than physical (e.g., bring a page in from disk only when accessed)
- **CPU allows read-only virtual addresses**
  - E.g., allows sharing of code pages between processes
- **CPU allows disabling execution of virtual addresses**
  - Makes certain (code injection) security attacks harder

# Summary

- The main roles of an OS are **virtualization** and **resource management**
- Protection is a fundamental concern

- Some **key abstractions**
  - Processes
  - Virtual address spaces

- Some **key mechanisms (hardware-assisted)**
  - Privileged/unprivileged execution modes
  - System calls and traps
  - CPU preemption (relying on processor interrupts)
  - Memory translation (implementation will be studied in next lectures)

# Appendix 1: **[Optional]** **Virtualization**

# Main techniques for virtualization (1/5)

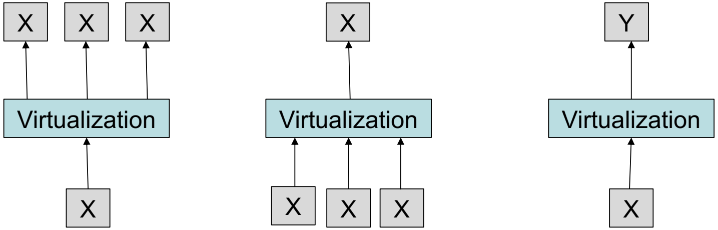
Inspired by: Saltzer & Kaashoek, Bugnion & Nieh & Tsafrir

- In order to virtualize the resources of a machine, operating systems rely on a combination of 3 main techniques:
  - Multiplexing (in space and/or in time)
  - Aggregation
  - Emulation

- Note: these techniques are sometimes also used within some hardware devices.

# Main techniques for virtualization (2/5)

Inspired by: Saltzer & Kaashoek, Bugnion & Nieh & Tsafrir




Multiplexing

Aggregation

Emulation

# Main techniques for virtualization (3/5)

Inspired by: Saltzer & Kaashoek, Bugnion & Nieh & Tsafrir

- Multiplexing:
  - Exposes a resource among multiple virtual entities
  - Two types of multiplexing: in space and in time
  - Examples:
    - CPUs (in time)
    - Memory (in space and possibly also in time when using swapping)
    - I/O devices (in time, and also in space for storage devices)

# Main techniques for virtualization (4/5)

Inspired by: Saltzer & Kaashoek, Bugnion & Nieh & Tsafrir

- Aggregation:
  - The opposite of multiplexing
  - Takes multiple resources and makes them appear as a single abstraction
  - Examples:
    - Memory controller with several DIMMS (hardware)
    - RAID (hardware or software)

# Main techniques for virtualization (5/5)

- Emulation
  - Expose (using a level of indirection in software ) a virtual resource that is not provided by the underlying machine
  - Examples
    - Sockets and files provide higher-level abstractions above hardware devices
    - Binary translation (compatibility layer)
      - A CPU emulator can run programs compiled for a given processor family X (e.g., Intel) on another processor family Y (e.g., ARM)

Inspired by: Saltzer & Kaashoek, Bugnion & Nieh & Tsafrir

# Appendix 2: **[Optional]**
# **Observing system & library calls**

# Tracing library & system calls

- It is possible to obtain a trace the calls performed by a process via specific tools.

- This is useful for many different purposes: debugging, performance troubleshooting, reverse engineering, understanding complex applications …

- In Unix/Linux systems:
  - The **`strace`** utility allows tracing **system calls**
  - The **`ltrace`** utility allows tracing **library calls**

# A simple tracing example

```c
#include <stdio.h>
#include <unistd.h>

int main(){
    pid_t mypid;
    printf("Hello\n");
    mypid = getpid();
    printf("My pid is: %ld\n",
           (long)mypid);
}
```

```
$ gcc -Wall -o test.run test.c
$ ltrace ./test.run

__libc_start_main(0xaaaabec50814, 1, 0xffffe4670ff8, 0
<unfinished ...>
puts("Hello"Hello) = 6
getpid() = 21198
printf("My pid is: %ld\n", 21198My pid is: 21198) = 17
__cxa_finalize(0xaaaabec61008, 0xaaaabec507c0, 0x10d88, 1) = 1
+++ exited (status 0) +++
```

# A simple tracing example (continued)

```
$ strace ./test.run

execve("./test.run", ["./test.run"], 0xffffd9332c50 /* 56 vars
*/) = 0
[ … Many initialization system calls omitted for simplification]
write(1, "Hello\n", 6Hello)                          = 6
getpid()                                        = 21391
write(1, "My pid is: 21391\n", 17My pid is: 21391)      = 17

exit_group(0)                                   = ?
+++ exited with 0 +++
```

# A simple tracing example (continued)

```
$ strace -c ./test.run
Hello
My pid is: 21506
% time     seconds  usecs/call     calls    errors syscall
------ ----------- ----------- --------- --------- ----------------
 23,50    0,000329         329         1           execve
 15,71    0,000220          36         6           mmap
  9,71    0,000136          34         4           mprotect
  8,14    0,000114          38         3           newfstatat
  7,14    0,000100          33         3           munmap
  6,57    0,000092          30         3           brk
  5,29    0,000074          37         2           openat
  4,71    0,000066          33         2           write
  3,07    0,000043          43         1         1 faccessat
  2,93    0,000041          20         2           close
  2,29    0,000032          32         1           set_tid_address
  2,07    0,000029          29         1           read
  1,93    0,000027          27         1           rseq
  1,86    0,000026          26         1           getrandom
  1,71    0,000024          24         1           set_robust_list
  1,71    0,000024          24         1           prlimit64
  1,64    0,000023          23         1           getpid
------ ----------- ----------- --------- --------- ----------------
100,00    0,001400          41        34         1 total
```