Introduction to Operating Systems

M1 MOSIG – Operating System Design

Renaud Lachaize

Acknowledgments

- Many ideas and slides in these lectures were inspired by or even borrowed from the work of others:
  - Arnaud Legrand, Noël De Palma, Sacha Krakowiak
  - David Mazières (Stanford)
    - Many slides directly adapted from those of the CS140 class
  - Remzi and Andrea Arpaci-Dusseau (U. Wisconsin)
  - Textbooks (Silberschatz et al., Tanenbaum)

Administrivia

- Class Web page
  - http://ginf41e0.forge.imag.fr/
  - Assignments and lecture notes available on-line
  - Make sure to check it frequently
- Reference books
  - Main textbook for the class:
    - Remzi Arpaci-Dusseau and Andrea Arpaci-Dusseau. Operating Systems: Three Easy Pieces. (v0.9, 2015)
    - Electronic book, **freely available** on-line from http://www.ostep.org/
    - (Do not try to print the whole book at the university – You will most likely exceed your quotas)
  - See also:
    - Silberschatz, Galvin, Gagne. Operating System Concepts (8^{th} edition). Wiley.
    - Tanenbaum. Modern Operating Systems (3^{rd} edition). Pearson education.

Administrivia

- Teaching staff
  - Lectures:
    - Renaud Lachaize (firstname.lastname AT imag.fr)
    - Thomas Ropars
  - Practical work:
    - Ahmed El-Rheddane
    - Vania Marangozova-Martin
- Contact information
  - Email is the most convenient way
  - Add [M1 Mosig - OS] to the subject of your emails (otherwise, we may not read them)
  - If necessary, we can make appointments via email

Administrivia

- Key dates
  - Lectures
    - 1 slot (3 hours) per week
    - Usually on Tuesday (1:30-4:45 pm)
  - Practical work / lab sessions:
    - 1 slot (3 hours) per week
    - Usually on Wednesday (1:30-4:45 pm)
  - Fall vacation: week 44
  - Midterm exam(s):
    - At least one before the Fall vacation (details to be confirmed)
    - And possibly (likely) another one later in the semester
  - Final exam: week 50 or 51, 3 hours (to be confirmed)
- **Warning**: Some modifications may occur during the semester. Please check regularly both:
  - The web page of the class
  - ADE

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, …

Programming assignments

- For each practical session, you are expected to:
  - Work in groups of two people
  - Turn in your **working** code and a report
  - (Details and deadlines to be discussed during session)

- Among the different practical sessions, some of them (~2 or 3) will be graded
  - You will be notified in advance about these sessions
  - You will usually get a few extra days after the session to polish your work

- The other sessions will not be graded but you are expected to turn in your completed assignment anyway
  - **This will be useful both for you and the instructors (feedback)**

Grading

- No incompletes
  - Contact instructors as soon as possible if you run into real problems
- 20% of grade from practical work projects
  - Project grading will be based on:
    - Score obtained by passing test cases
    - Design and style
    - Quality of report/documentation, comments, answers
- 20% of grade from mid-term exam(s)
- 60% of grade from final exam

Style

- You must turn in a design document along with your code
  - Remember that figures are often very useful to convey/summarize design ideas
- Instructors will manually inspect your code for correctness
  - Does the code respect the specification?
  - Does it actually implement the described design?
  - Does it handle corner cases (e.g., handle malloc failure)?
- Instructors will deduct points for error-prone code without errors
  - Do not use global variables if local ones suffice
  - Do not use obscure/misleading names for variables/functions

Style (continued)

- Your code must be easy to read
  - Indent code, keep lines (and when possible) functions short
  - Use a uniform coding style (try to match existing code)
  - Put comments on structure members, globals, functions
  - Do not leave lots of commented-out garbage code

Assignment requirements

- **Do not look at other people's solutions to projects**
- You can read but must not copy the code of existing operating systems (such as Linux, FreeBSD, etc.)

- **Cite any code that inspired your code**
  - As long as you cite what you used, it is not cheating
  - In the worst case, we will deduct points if this undermines the assignment

- Project deadlines are firm
  - Even for projects that are not graded
- If you run into trouble, contact instructors in advance to ask for an extension

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**

- 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

- 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

Some History
(1) Early operating systems

- In the beginning, the OS did not do much
- Essentially, a set of libraries of commonly-used functions (e.g., 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)
- Assumed no bad users or programs
- Problem: poor utilization
  - ... of hardware (e.g., CPU idle while waiting for I/O completion)
  - ... of 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

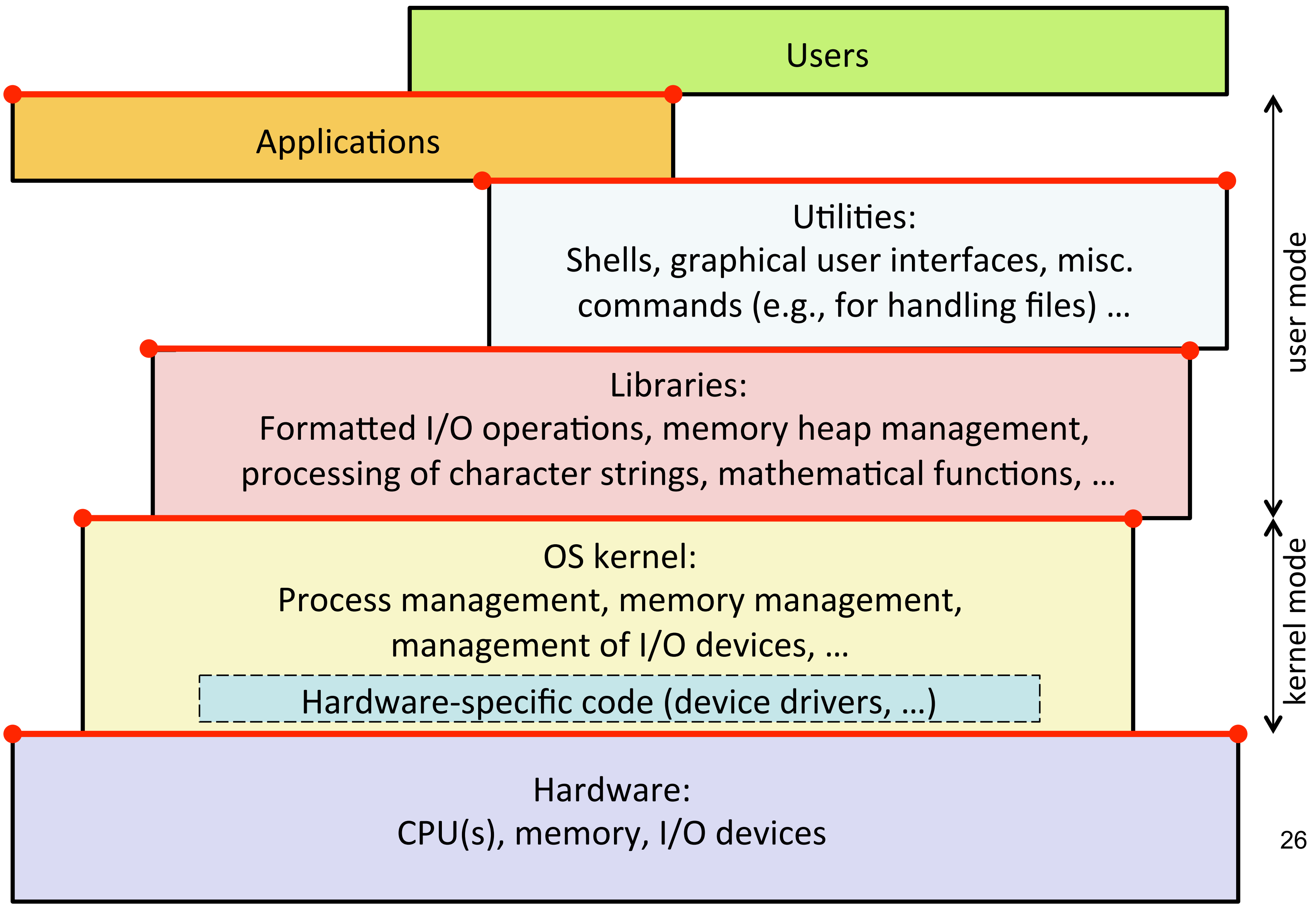
- Idea: Modification of the OS interface
  - Old interface: provide applications with library procedures allowing direct access to critical operations
  - New interface: force application to delegate critical operations, using a hardware mechanism that transfers control to a more privileged execution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

Some History
(3) Multiprogramming / Multitasking

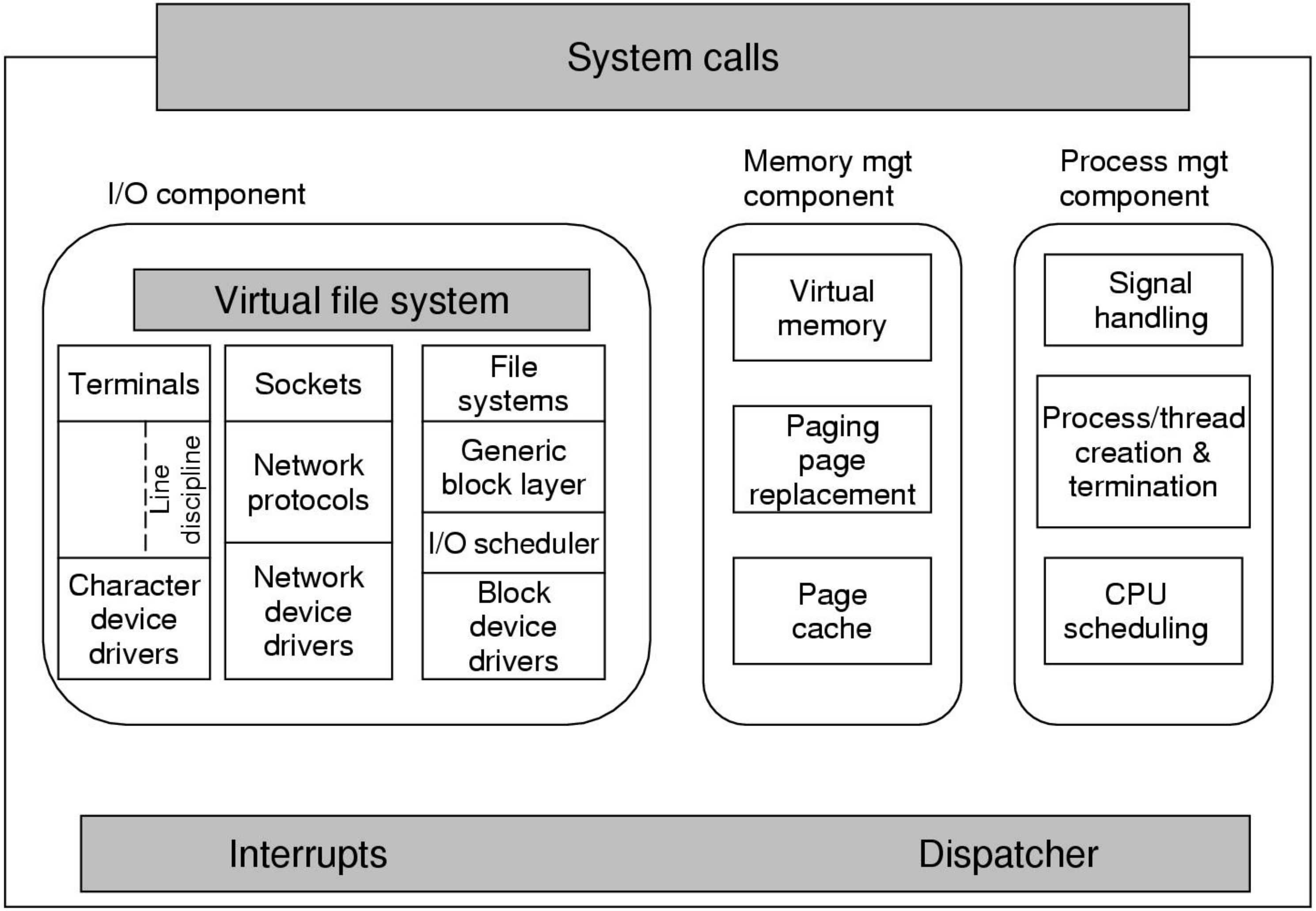
- Idea: improve machine resource utilization by running several programs concurrently
  – When a program blocks (e.g., waiting for input from the disk / the network / the user), run another program

- 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 (e.g., Linux)



Picture from: Tanenbaum, *Modern operating systems* (3rd edition)

Outline

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

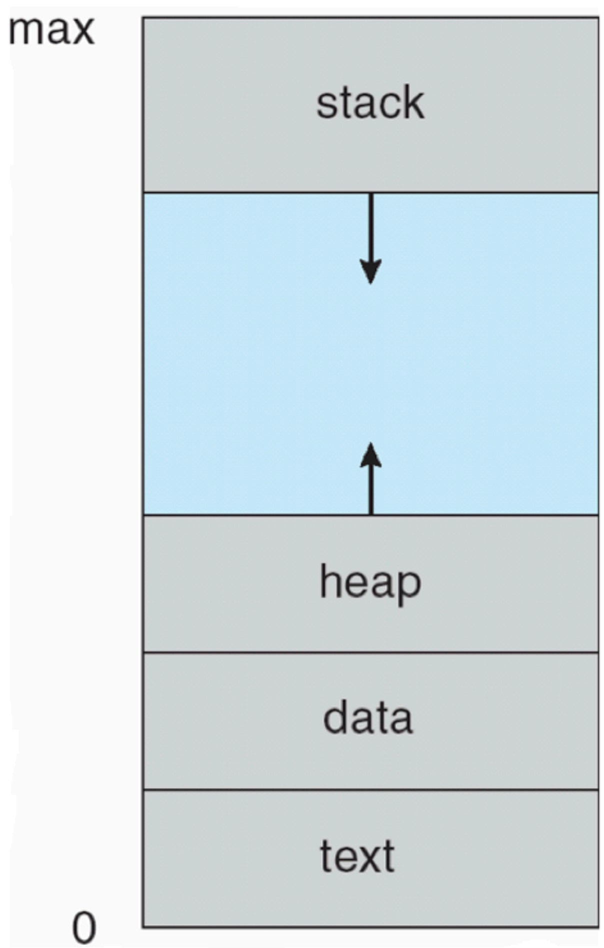
A key OS abstraction: the Process

- 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

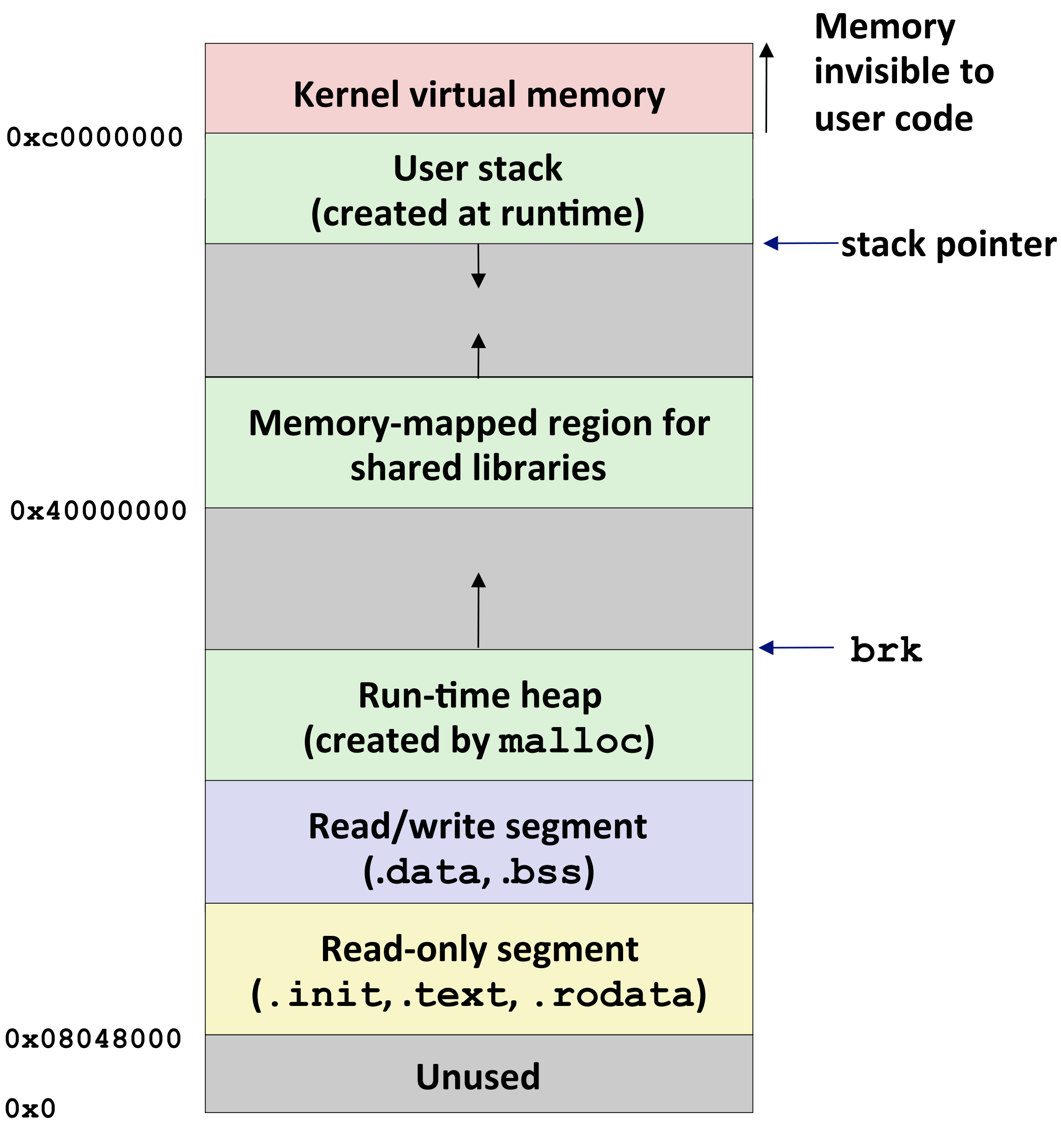
Process address space
A simplified view



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

Process address space
A more detailed view

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)

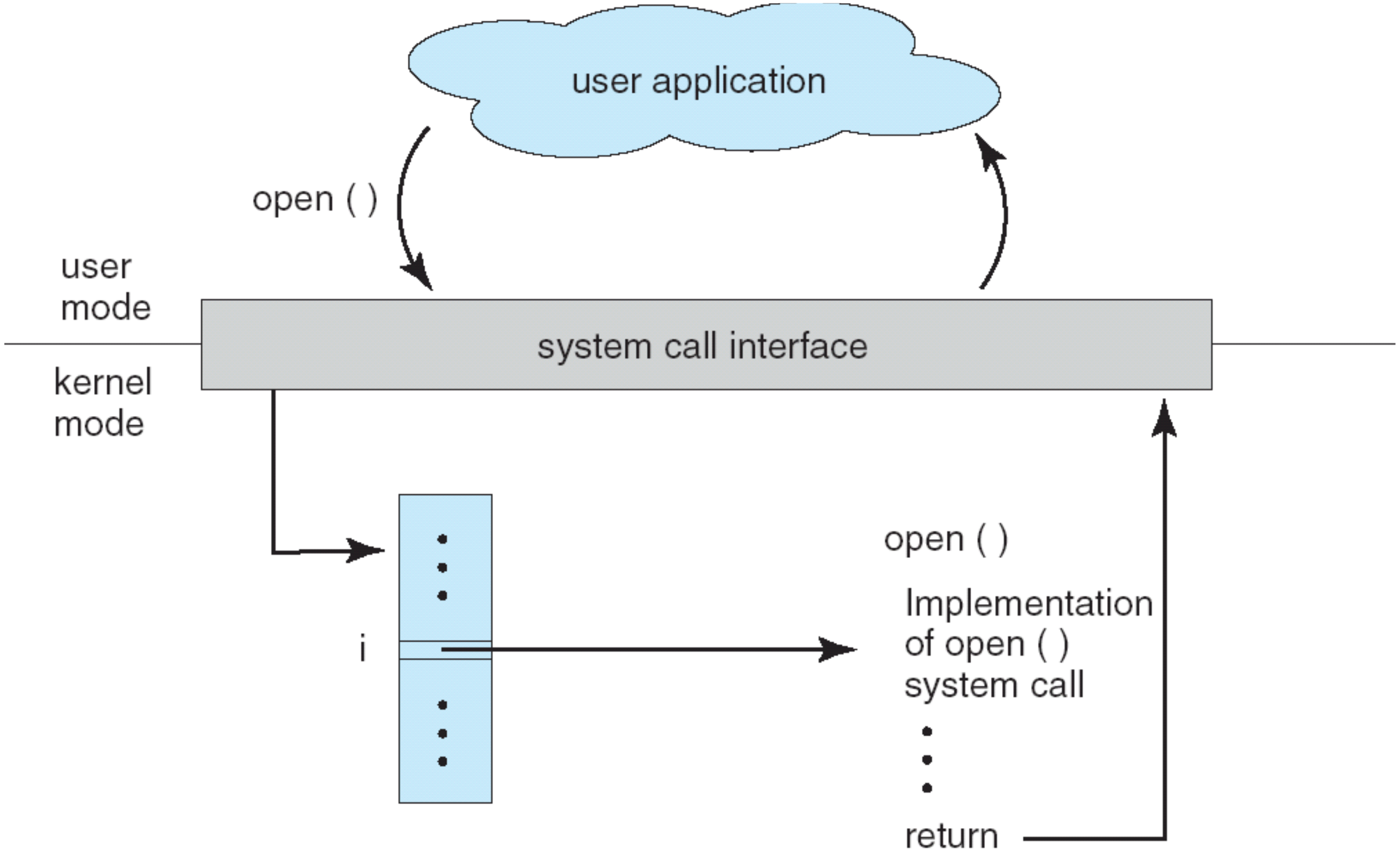
- CPU execution modes
  - CPUs provide 2 execution modes:
    - Privileged (a.k.a. supervisor mode, or kernel-level mode)
    - Unprivileged (a.k.a. user mode, or user-level mode)
  - OS kernel code runs in privileged mode
  - Application code runs in unprivileged mode
  - Protection-related code (resp. 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)



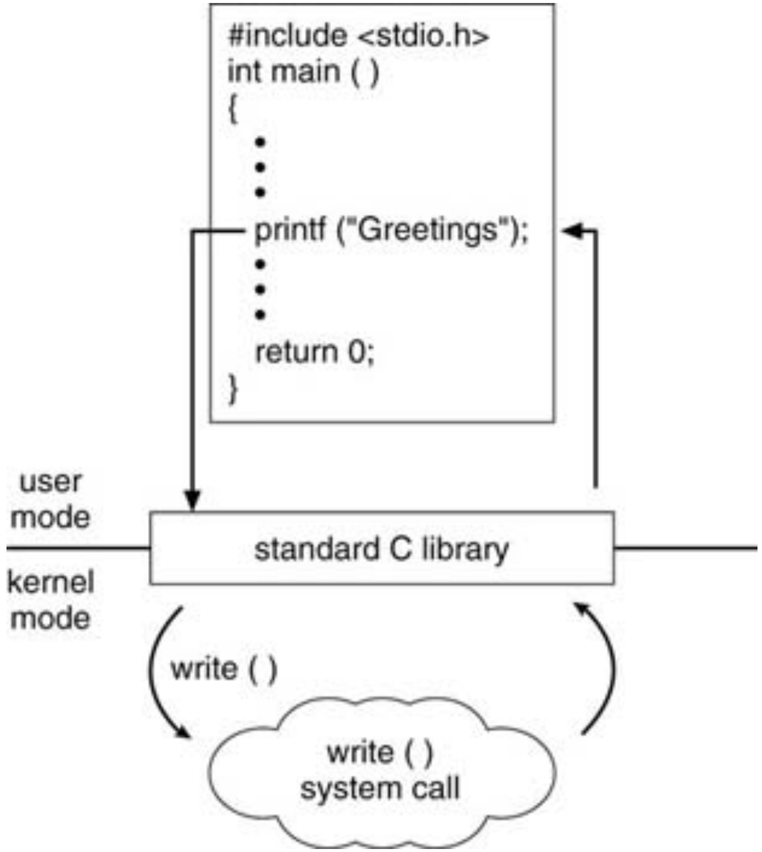
Picture from: Silberschatz et al., *Operating systems concepts* (8th edition)

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 define a timer interrupt handler
  - This handler is run 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 entry points 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

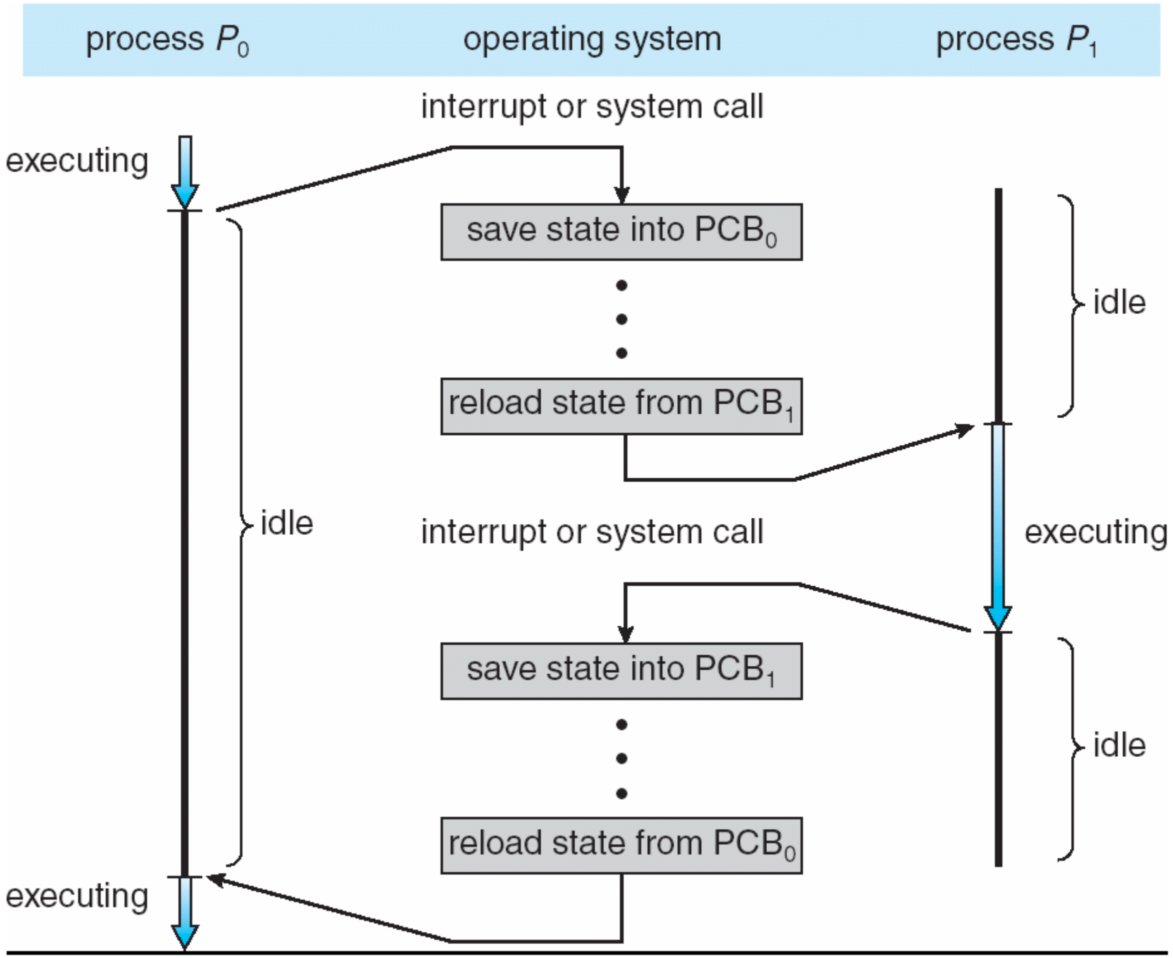
CPU scheduling (continued)

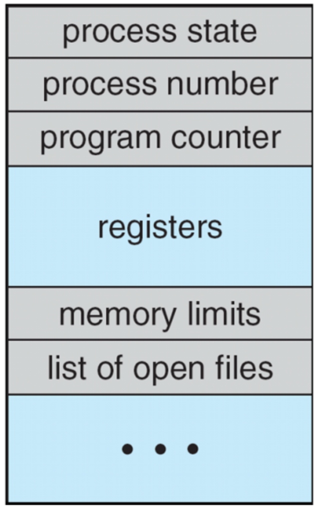
- What does the scheduler do upon invocation?
  - Save execution context of “outgoing” process P1
    - (Except if this process is terminated)
    - This allows resuming the execution of P1 later on
  - Make decision on the process P2 that should obtain the CPU, based on:
    - The list of processes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





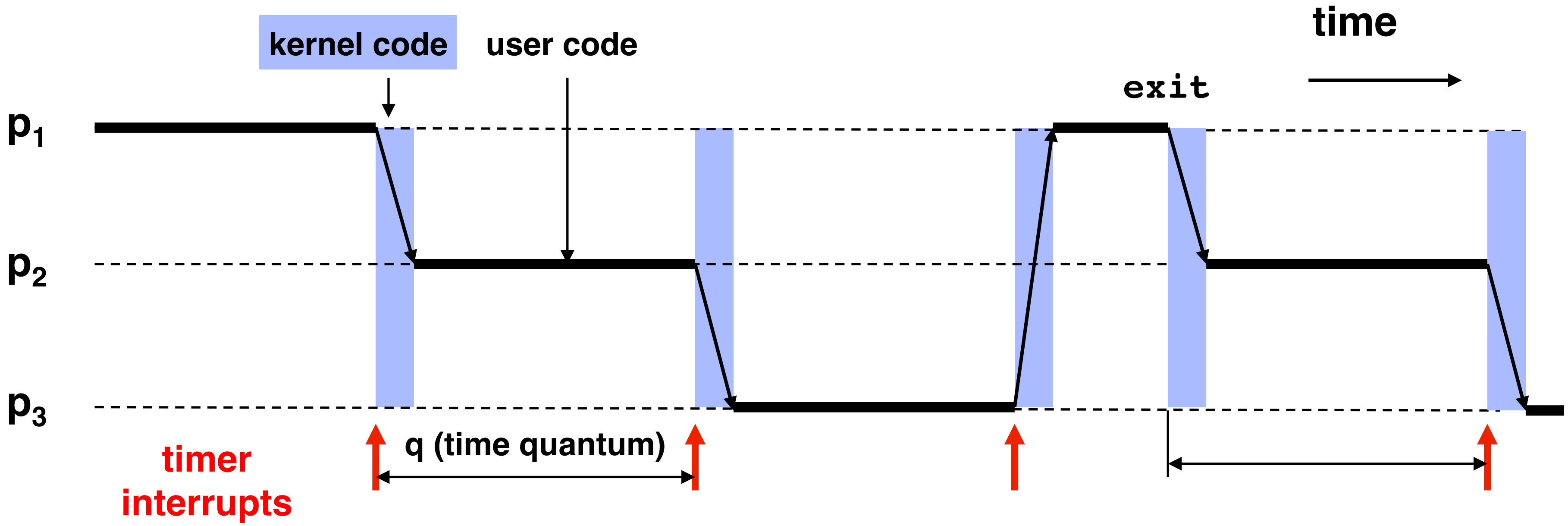
PCB

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

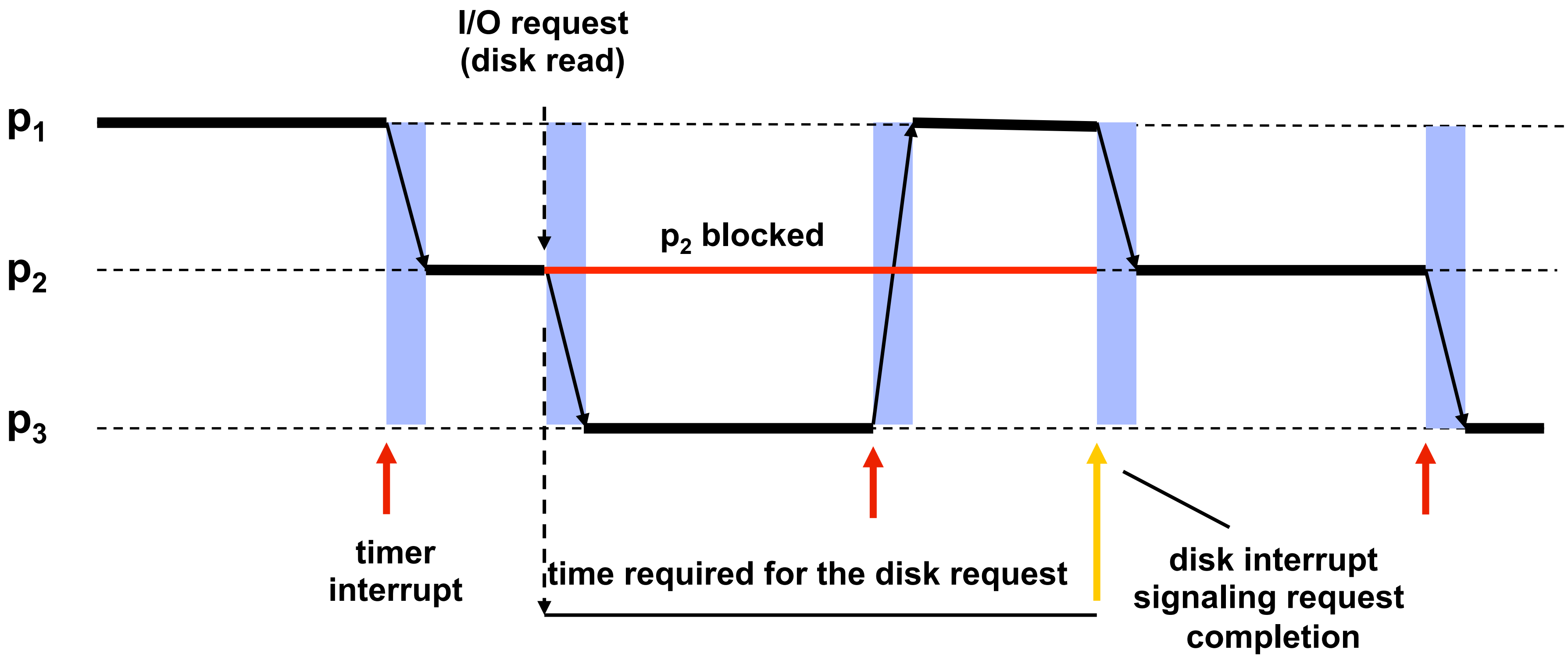
Context switch

- 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



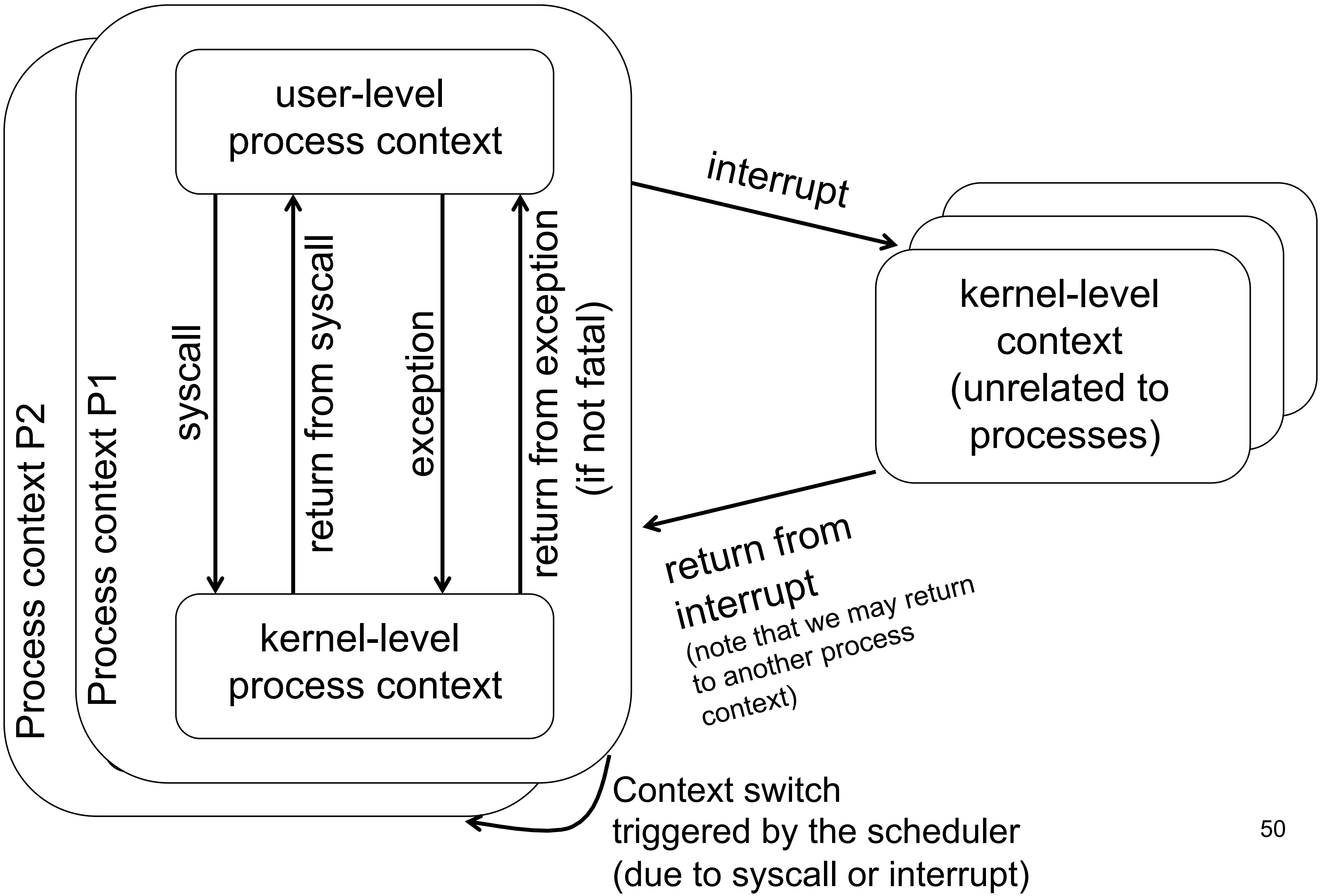
CPU scheduling examples (continued)



Different system “contexts”

- A system can typically be in one of several contexts:
  - User-level process context
    - Running application code or library code called by application
  - Kernel process context
    - Running kernel code on behalf of a particular process
      - Typically, performing a system call
      - Also, exception handling (numeric exceptions, memory faults, ...)
  - Kernel code not associated with a process
    - Timer interrupt handler
    - Device interrupt handlers
    - (Also some handlers for special kinds of interrupts triggered by software)

Different system “contexts” (2)



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
- Translation 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)