CS 370: OPERATING SYSTEMS

[COMPREHENSIVE REVIEW]

Computer Science
Colorado State University

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Spring 2024

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Topics covered in this lecture

- Introduction on Operating Systems
- Processes
- Inter-Process Communications
- Threads
- Process Synchronization and Atomic Transactions
- CPU scheduling algorithms
- Deadlocks
- Memory management
- Virtual memory
- Virtualization
- File systems

Disclaimer and preparation for the final

- This slide set is meant to guide you in your preparation, but it does not mean other lecture slides omitted here are useless! Return to each lecture as needed to polish your understanding of concepts
- Your final will be 2h duration, taken online via Canvas+respondus, and will close Monday May 6th at 11:59pm (end time to complete the exam). It will open Sunday May 5th at 00:01am. Official final date is Monday morning, but I open for a longer period of time to accommodate people with jobs, etc.
- All objectives listed for each module will be evaluated with at least one question, with a majority of points on checking you have achieved the learning objectives, and a minority of points on more advanced questions checking your full understanding of some specific concepts. These advanced questions will only cover lectures/content taught after the spring break

Introduction on Operating Systems

Objectives:

- Summarize basic operating systems concepts
- Highlight key developments in the history of operating systems

A modern computer is a complex system

- Multiple processors
- Main memory and Disks
- Keyboard, Mouse and Displays
- Network interfaces
- I/O devices

Why do we need Operating Systems?

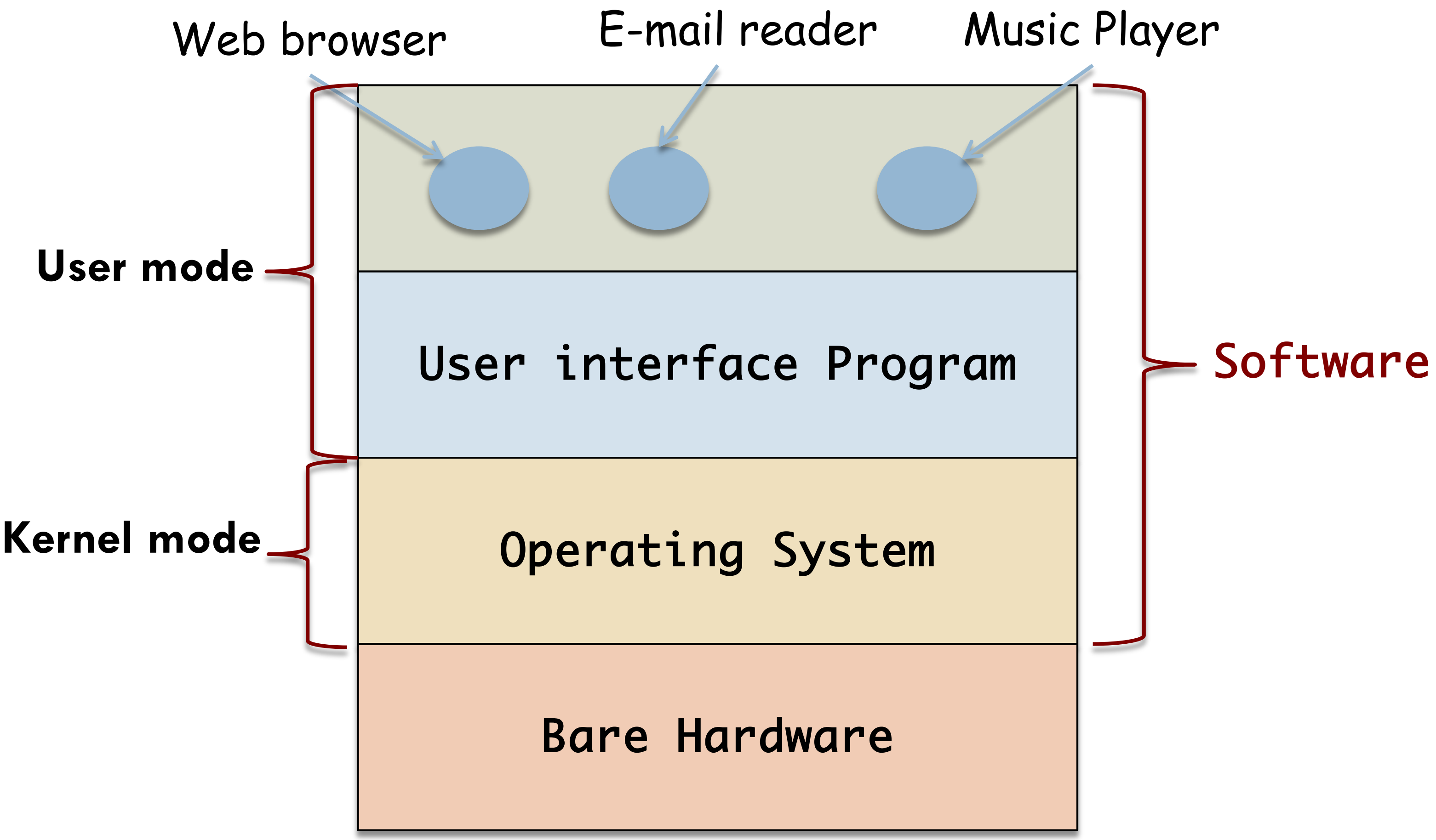
- If every programmer had to understand how *all* these components work?
  - Software development would be arduous

- Managing all components and using them optimally is a challenge

Computers are equipped with a layer of software

- Called the **Operating System**
- Functionality:
  - Provide user programs with a better, simpler, cleaner model of the computer
  - Manage resources efficiently

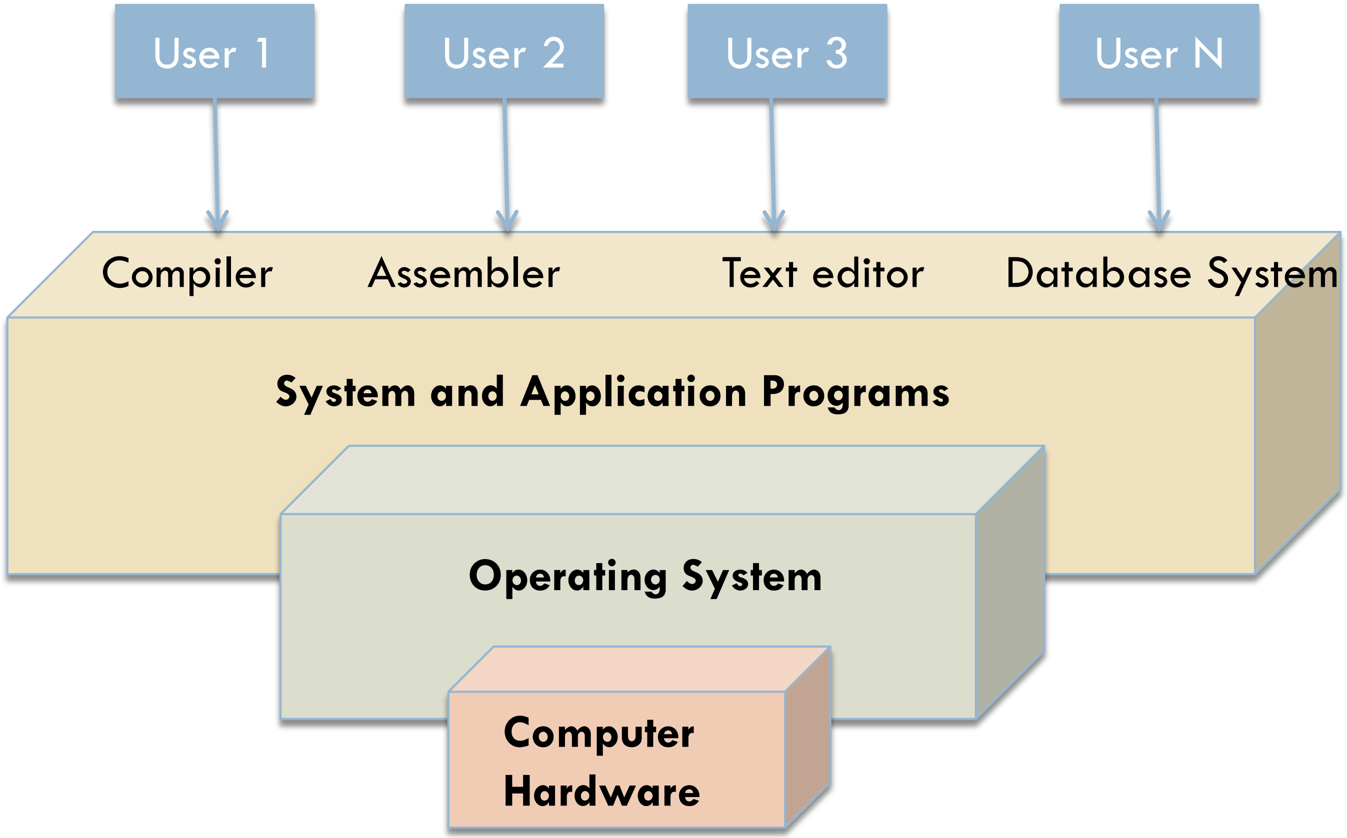
Where the operating system fits in



Where the operating system fits in

- The OS runs on bare hardware in **kernel mode**
  - *Complete access* to all hardware
  - Can execute *any* instruction that the machine is capable of executing
- Provides the base for all software
  - Rest of the software runs in **user-mode**
    - Only a **subset** of machine instructions is available

The OS controls hardware and coordinates its use among various programs



Kernel and user modes

- Everything running in kernel mode is part of the OS
- But some programs running outside it are part of it or at least closely associated with it

Operating systems tend to be huge, complex and long-lived

- Source code of an OS like Linux or Windows?
  - Order of 5 million lines of code (for kernel)
    - 50 lines page, 1000 pages/volume = 100 volumes
- Application programs such as GUI, libraries and application software?
  - 10-20 times that

Why do operating systems live for a long time?

- Hard to write and folks are loath to throw it out

- Typically **evolve** over long periods of time
  - Windows 95/98/Me is one OS
  - Windows NT/2000/XP/Vista/7/8 is another
  - System V, Solaris, BSD derived from original UNIX
  - Linux is a fresh code base
    - Closely modeled on UNIX and highly compatible with it
  - Apple OS X based on XNU (X is not Unix) which is based on the Mach microkernel and BSD's POSIX API

An operating system performs two unrelated functions

- Providing application programmers a clean **abstract** set of resources
  - Instead of messy hardware ones
- **Managing** hardware resources

The OS as an extended machine

- The **architecture** of a computer includes
  - Instruction set, memory organization, I/O, and bus structure

- The architecture of most computers at the machine language level
  - Primitive and awkward to program especially for I/O

Main memory is generally the only large storage device the CPU deals with

- To execute a program, it must be **mapped** to absolute addresses and loaded into memory
- Execution involves accesses to instructions and data from memory
  - By generating absolute addresses
- When program terminates, memory space is **reclaimed**

Virtual memory allows processes not completely memory resident to execute

- Enables us to run programs that are **larger** than the actual physical memory
- Separates **logical memory** as viewed by user from *physical memory*
- Frees programmers from memory storage limitations

Program Construct: Asynchronous operation

- Events happen at unpredictable times AND in unpredictable order.
  - Interrupts from peripheral devices
  - For e.g. keystrokes and printer data
- To be *correct*, a program must work will ***all*** possible timings
- Timing errors are very hard to repeat

Program Construct: Concurrency

- Sharing resources in the same ***time frame***
- Interleaved execution
- Major task of modern OS is **concurrency control**
- Bugs are hard to reproduce, and produce unexpected side effects

Concurrency occurs at the hardware level because devices operate at the same time

- Interrupt: **Electrical signal** generated by a peripheral device to set hardware flag on CPU
- Interrupt detection is part of instruction cycle
- If interrupt detected
  - **Save current** value of program counter
  - **Load new** value that is address of interrupt service routine or interrupt handler: device drivers
    - Drivers use signals (software) to notify processes

Signal is the software notification of an event

- Often a *response* of the OS to an interrupt
  - OS uses signals to notify processes of completed I/O operations or errors
- Signal generated when event that causes signal occurs
  - For example: keystroke and Ctrl-C
- A process catches a signal by executing handlers for the signal

Concurrency constructs: I/O operations

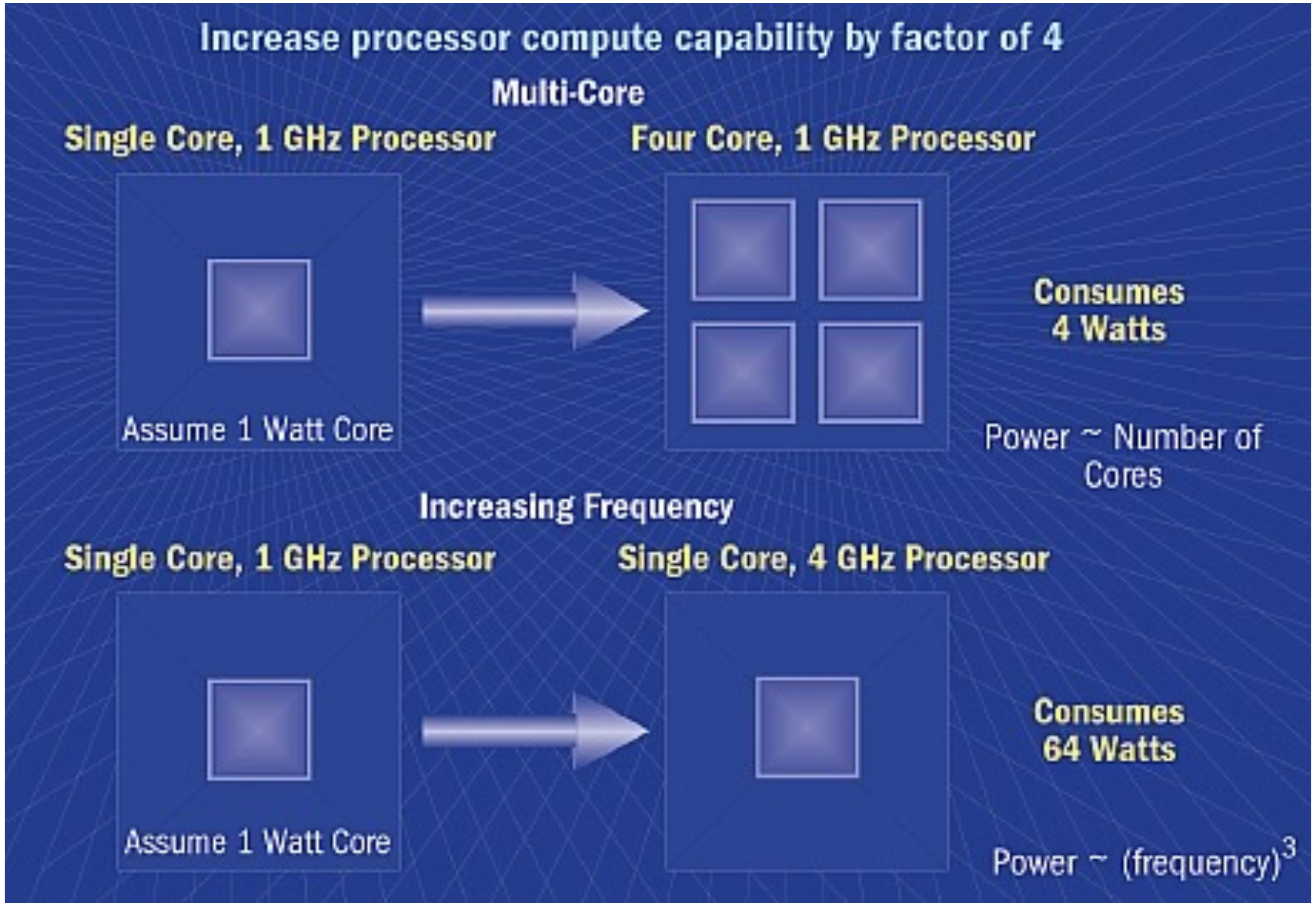
- Coordinate resources so that CPU is not idle
- Blocking I/O blocks the progress of a process
- Asynchronous I/O (dedicated) threads circumvent this problem
- Ex: Application monitors 2 network channels
  - If application is blocked waiting for input from one source, it *cannot respond* to input on 2nd channel

Concurrency constructs: Processes & threads

- User can create multiple processes; `fork()` in UNIX
- Inter process communications
  - Common ancestor: pipes
  - No common ancestor: signals, semaphores, shared address spaces, or messages
- Multiple threads within process = concurrency

Trend: going multi-core for CPUs

- Driven by power / physics
- Problem: parallelism in the application?
- We merely see 16-core CPUs as HEDT in 2024



Grabbed from DoE Scidac

Multiprogramming organizes jobs so that the CPU always has one to execute

- A single program (generally) cannot keep CPU & I/O devices busy at all times
- A user frequently runs multiple programs
- When a job needs to **wait**, the CPU **switches** to another job.
- Utilizes resources (cpu, memory, peripheral devices) effectively.

Time sharing is a logical *extension* of the multiprogramming model

- CPU switches between jobs **frequently**, users can interact with programs
- Time shared OS allows many users to use computer simultaneously
- Each action in a time shared OS tends to be **short**
  - CPU time needed for each user is small

Processes

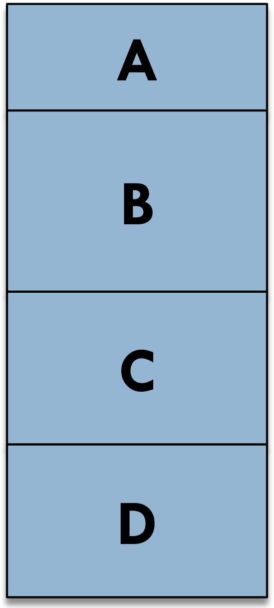
Objectives:

- Contrast programs and processes
- Explain the memory layout of processes
- Describe Process Control Blocks
- Explain the notion of Interrupts and Context Switches
- Describe process groups

A process is just an instance of an executing program

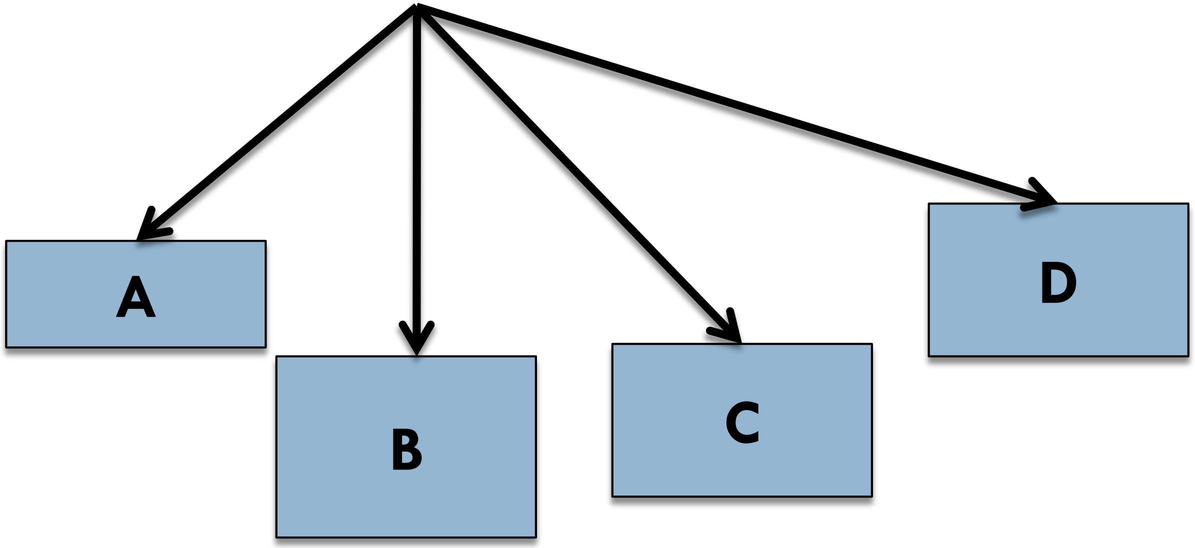
- Conceptually each process has its own **virtual CPU**
- In reality, the CPU switches back-and-forth from process to process
- Processes are <u>not affected</u> by the multiprogramming
  - Or *relative speeds* of different processes

An example scenario: 4 processes



4 processes in memory

Four Program Counters



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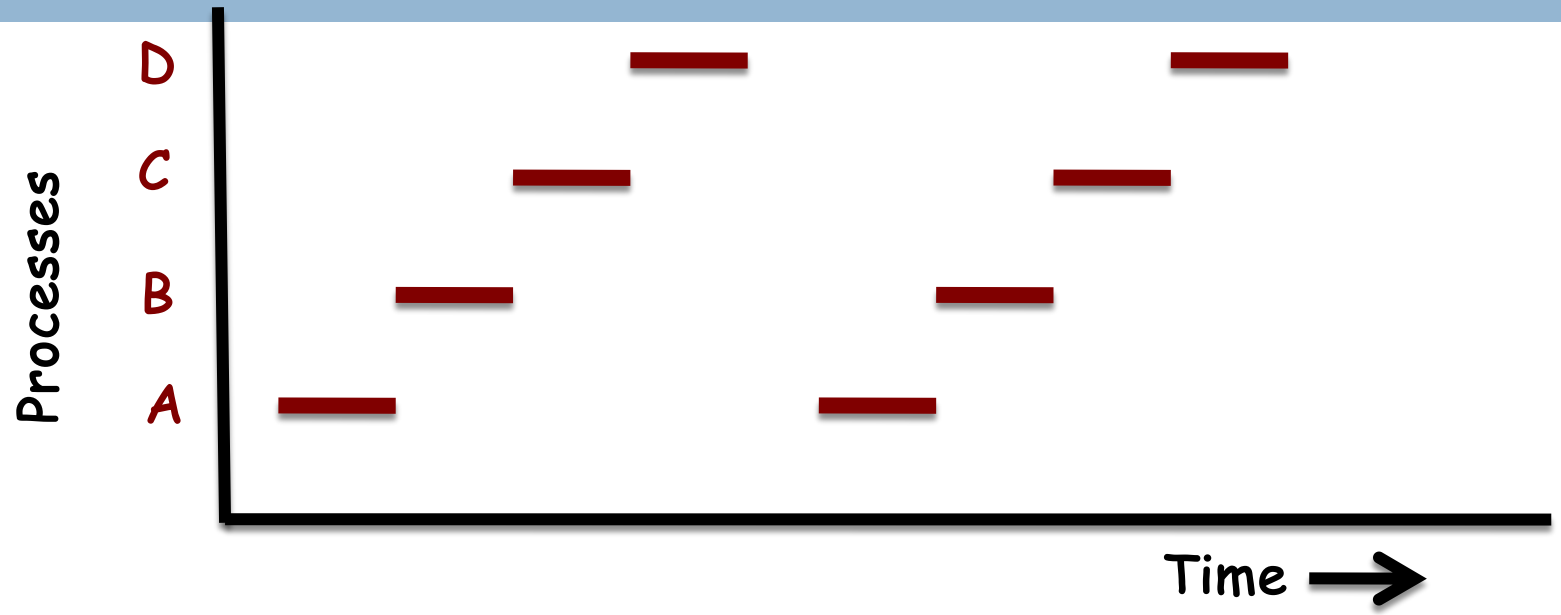

- At any instant <u>only one</u> process executes
- *Viewed over a long time*, all processes have made **progress**

Programs and processes

- Programs are **passive**, processes are **active**
- The difference between a program and a process is subtle, but crucial

Key concepts

- Process is an **activity** of some kind; it has a
  - Program
  - Input and Output
  - State
- Single processor may be shared among several processes
  - **Scheduling algorithm** decides when to stop work on one, and start work on another

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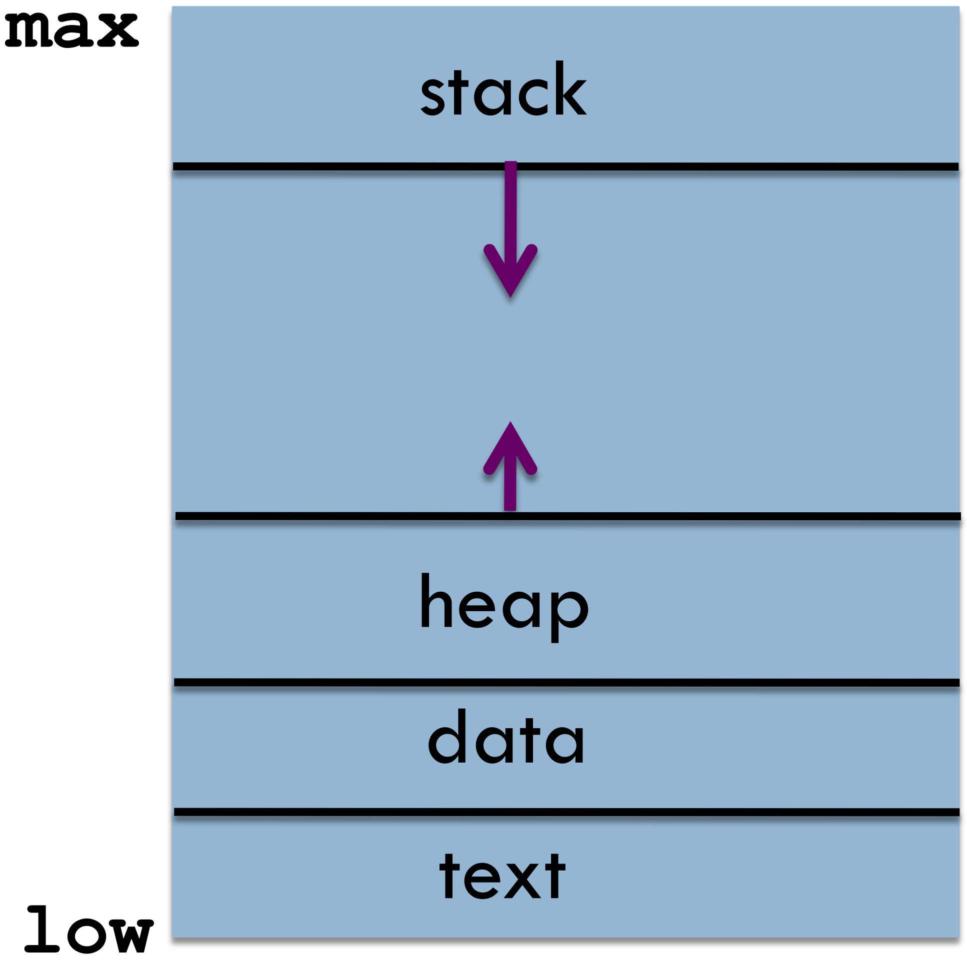
How a program becomes a process

- When a program is executed, the OS *copies* the program image into main memory
- Allocation of memory is *not enough* to make a program into a process
- Must have a process ID
- OS tracks IDs and process **state**s to orchestrate system resources

A process in memory



{Function parameters, return addresses, and local variables}

{Memory allocated dynamically during runtime}

{Global variables}

{Program code}

Program in memory (I)

- Program image *appears* to occupy **contiguous** blocks of memory
- OS **maps** programs into non-contiguous blocks

Program in memory (II)

- Mapping divides the program into equal-sized pieces: **pages**
- OS loads pages into memory
- When processor references memory on page
  - OS looks up page in table, and loads into memory

Advantages of the mapping process

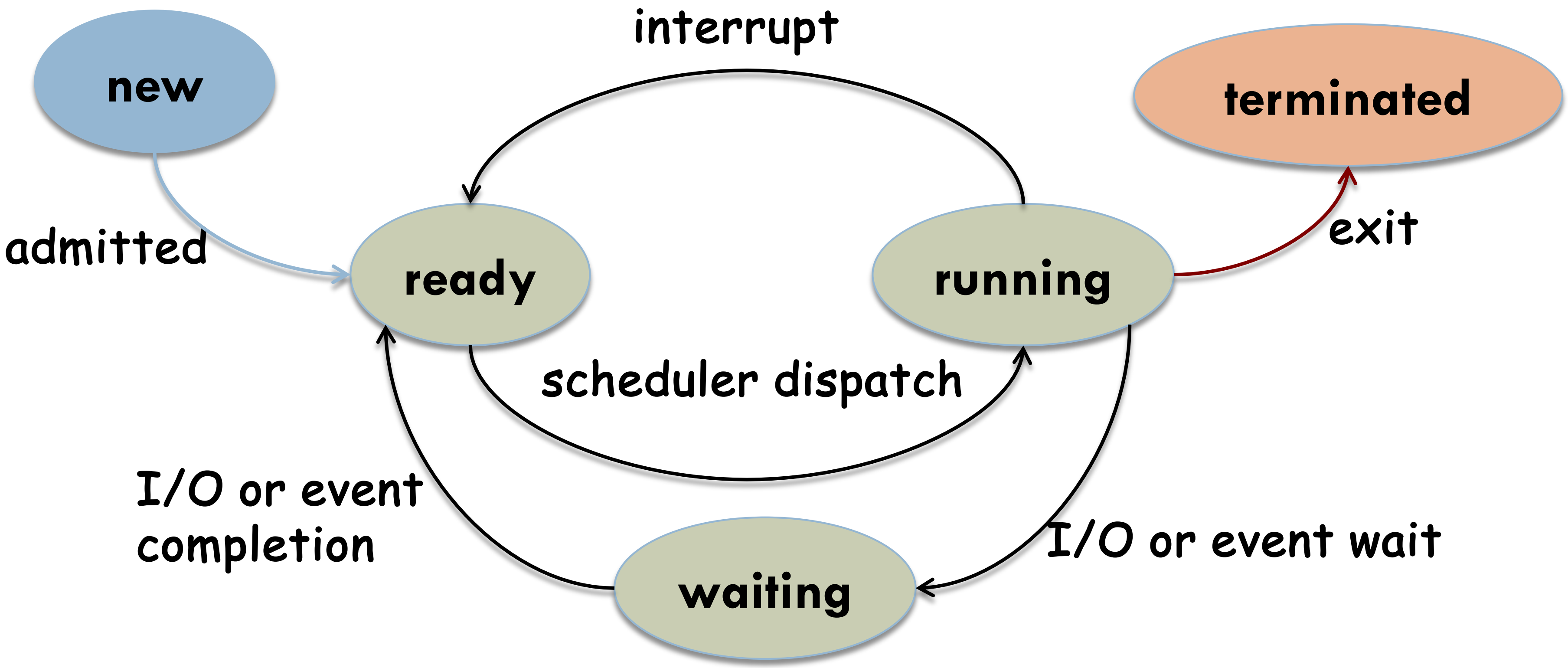
- Allows **large** logical address space for stack and heap
  - **No physical memory used** <u>unless</u> actually needed

- OS hides the mapping process
  - Programmer views program image as **logically contiguous**
  - Some pages may not reside in memory

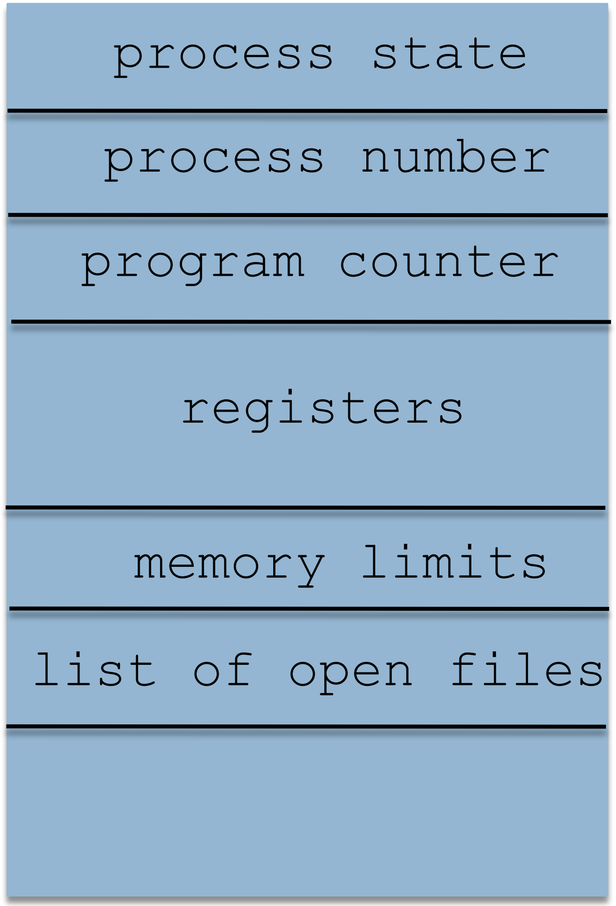
Finite State Machine

- An initial **state**
- A set of possible **input** events
- A finite number of states
- **Transitions** between these states
- Actions

Process state transition diagram: When a process executes it changes state

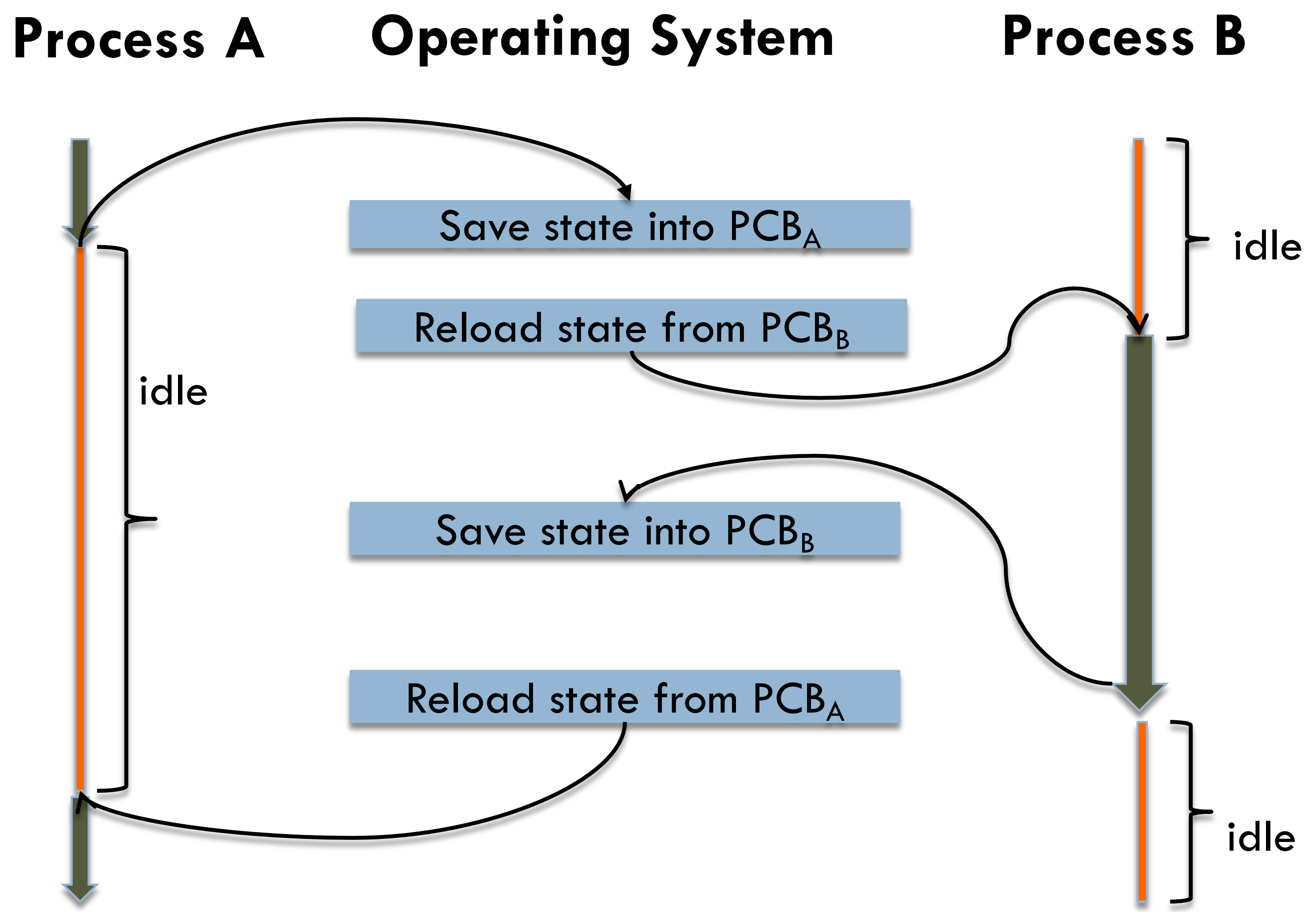


Each process is represented by a process control block (PCB)



PCB is a **repository** for *any* information that *varies* from process to process.

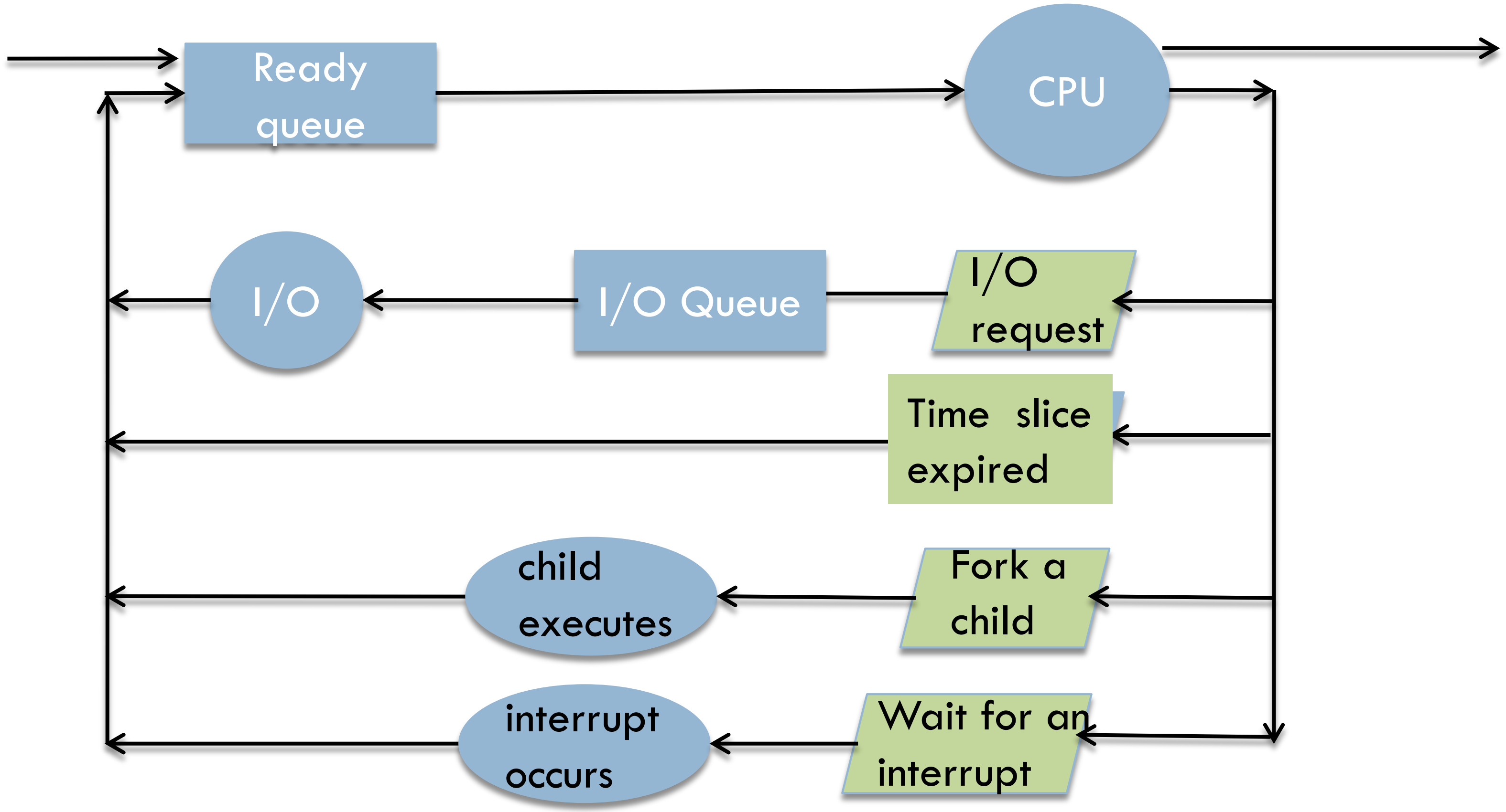
An example of CPU switching between processes



Scheduling Queues

- Job Queue: Contains <u>all</u> processes
  - A newly created process enters here first
- Ready Queue
  - Processes residing in main memory
  - Ready *and* waiting to execute
  - Typically a linked list
- Device Queue
  - Processes waiting for a particular I/O device

Process scheduling



Interrupts and Contexts

- Interrupt causes the OS to **change** CPU from its current task to run a kernel routine
- Save current context so that ***suspend*** and ***resume*** are possible
- Context is represented in the **PCB**
  - Value of CPU registers
  - Process state
  - Memory management information

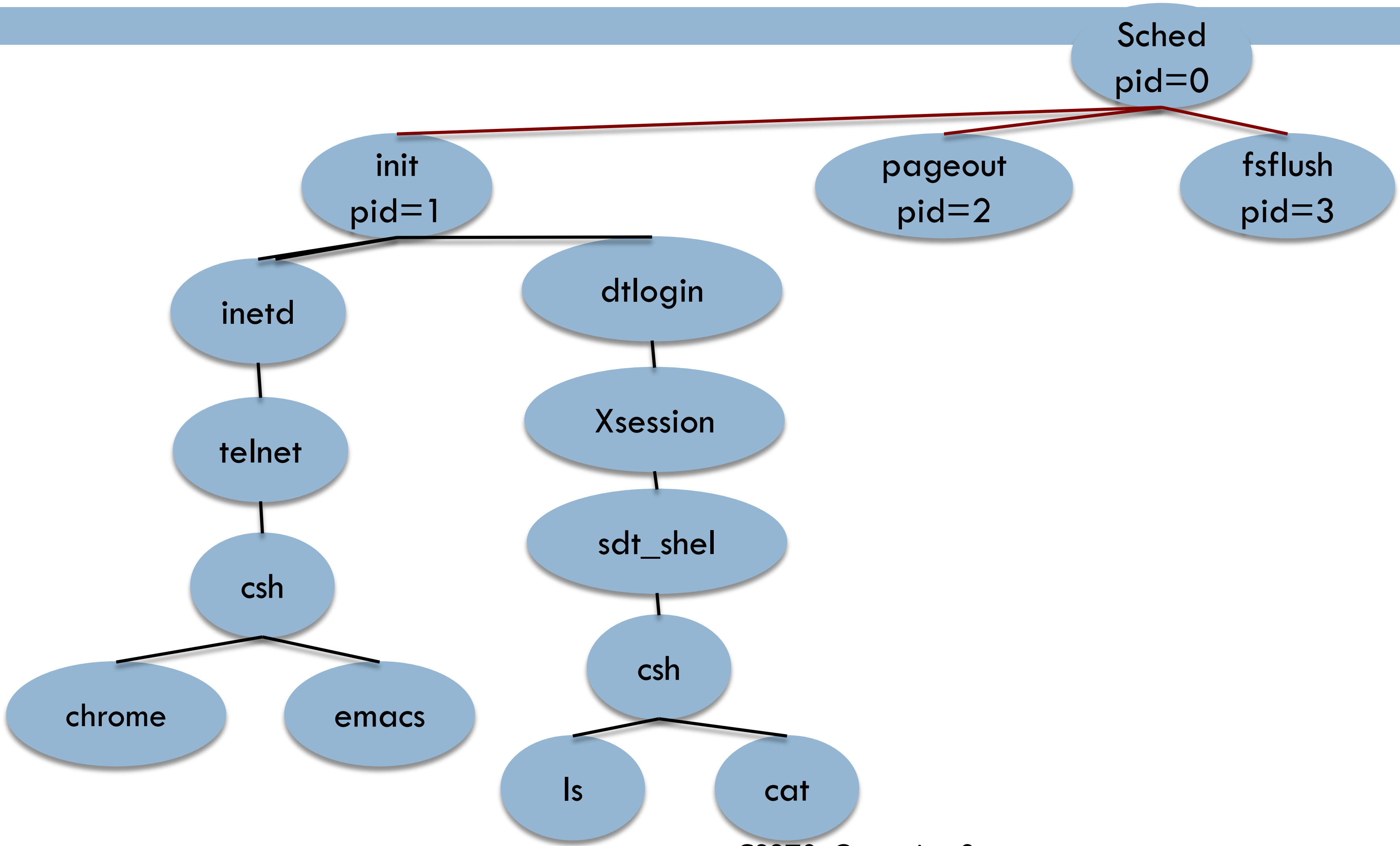
Context switch refers to switching from one process to another

① **Save** state of current process

② **Restore** state of a different process

- Context switch time is pure **overhead**
  - No useful work done while switching

Example: Process tree in Solaris



Processes in UNIX

- `init` : Root parent process for all user processes
- Get a listing of processes with **`ps`** command
  - `ps`: List of all processes associated with user
  - `ps -a` : List of all processes associated with terminals
  - `ps -A` : List of all active processes

Resource sharing between a process and its subprocess

- Child process may obtain resources **directly from OS**
- Child may be **constrained** to a subset of parent's resources
  - Prevents any process from overloading system
- Parent process also passes along initialization data to the child
  - Physical and logical resources

Parent/Child processes: Execution possibilities

- Parent executes **concurrently** with children
- Parent **wait**s until some or all of its children terminate

Parent/Child processes: Address space possibilities

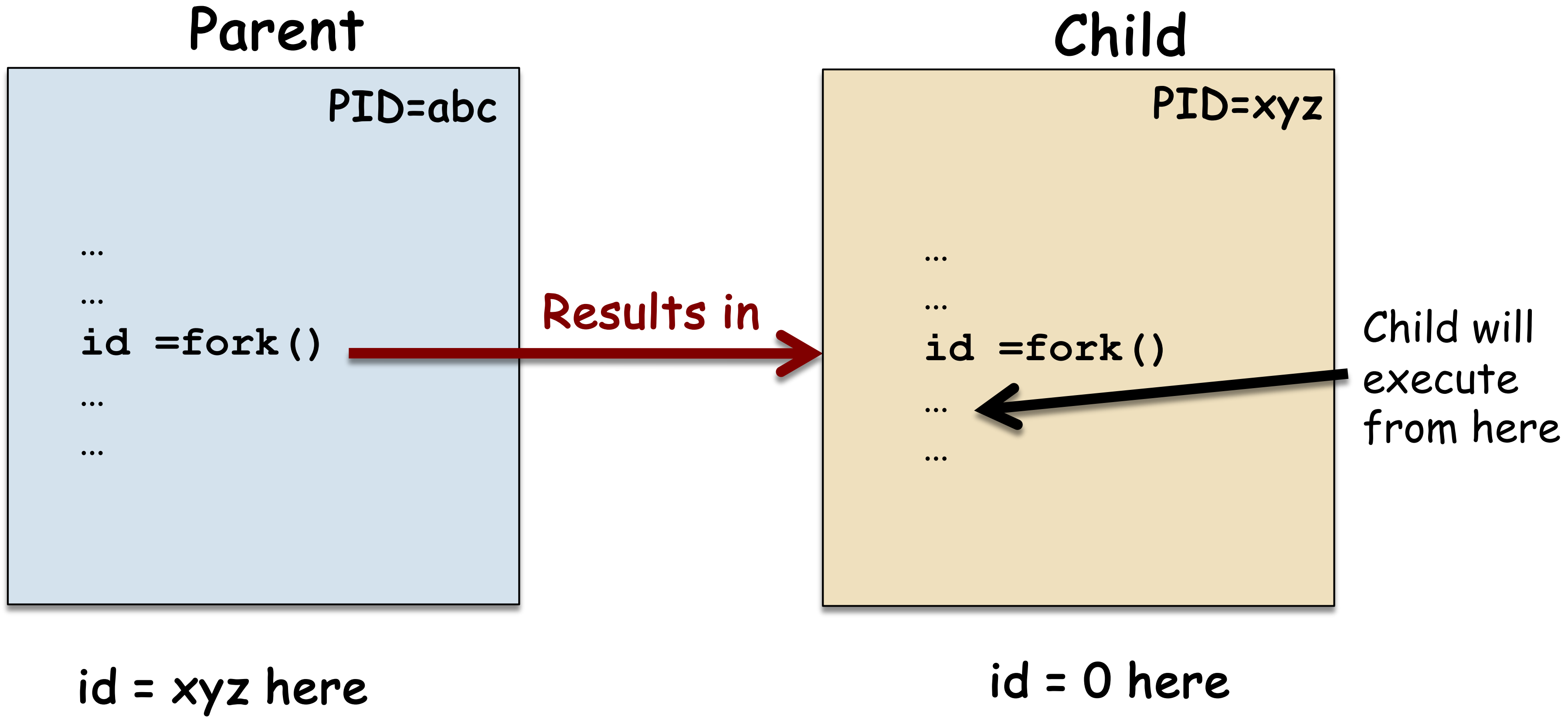
- Child is a **duplicate** of the parent
  - Same program and data as parent

- Child has a **new program** loaded into it

Process creation in UNIX

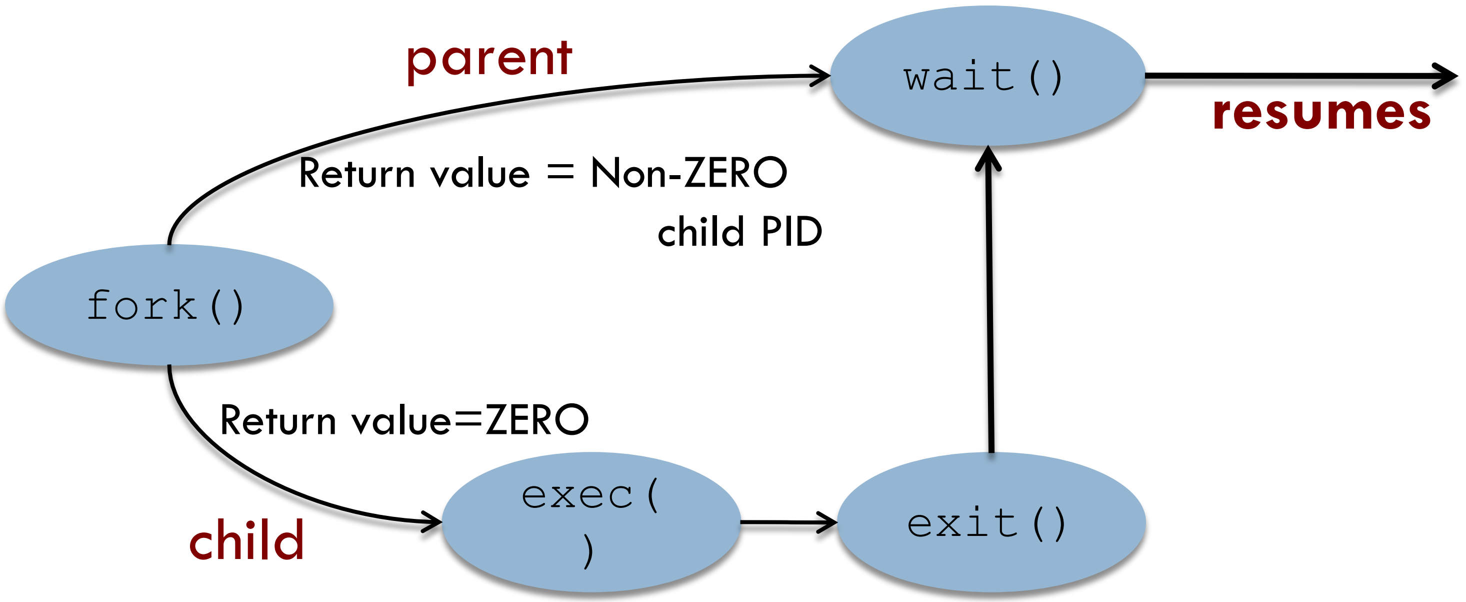
- Process created using **`fork()`**
  - `fork()` copies parent's memory image
  - Includes copy of parent's address space
- Parent and child continue execution **at instruction after** `fork()`
  - Child: Return code for `fork()` is **`0`**
  - Parent: Return code for `fork()` is the non-ZERO *process-ID* of new child

`fork()` results in the creation of 2 distinct programs



A parent can move itself from off the ready queue and await child's termination

- Done using the `wait()` system call.
- When child process completes, parent process resumes



`wait/waitpid` allows caller to suspend execution till a child's status is available

- Process status availability
  - Most commonly after termination
  - Also available if process is stopped
- `waitpid(pid, *stat_loc, options)`
  - `pid== -1` : any child
  - `pid > 0` : specific child
  - `pid == 0` : any child in the same **process group**
  - `pid < -1` :any child in process group abs(`pid`)

Process groups

- Process group is a *collection* of processes
- Each process has a **process group ID**
- Process group leader?
  - Process with `pid==pgid`
- **`kill`** treats negative `pid` as `pgid`
  - Sends signal to all constituent processes

Process Group IDs: When a child is created with `fork()`

① **Inherits** parent's process group ID

② **Parent can change** group ID of child by using `setpgid`

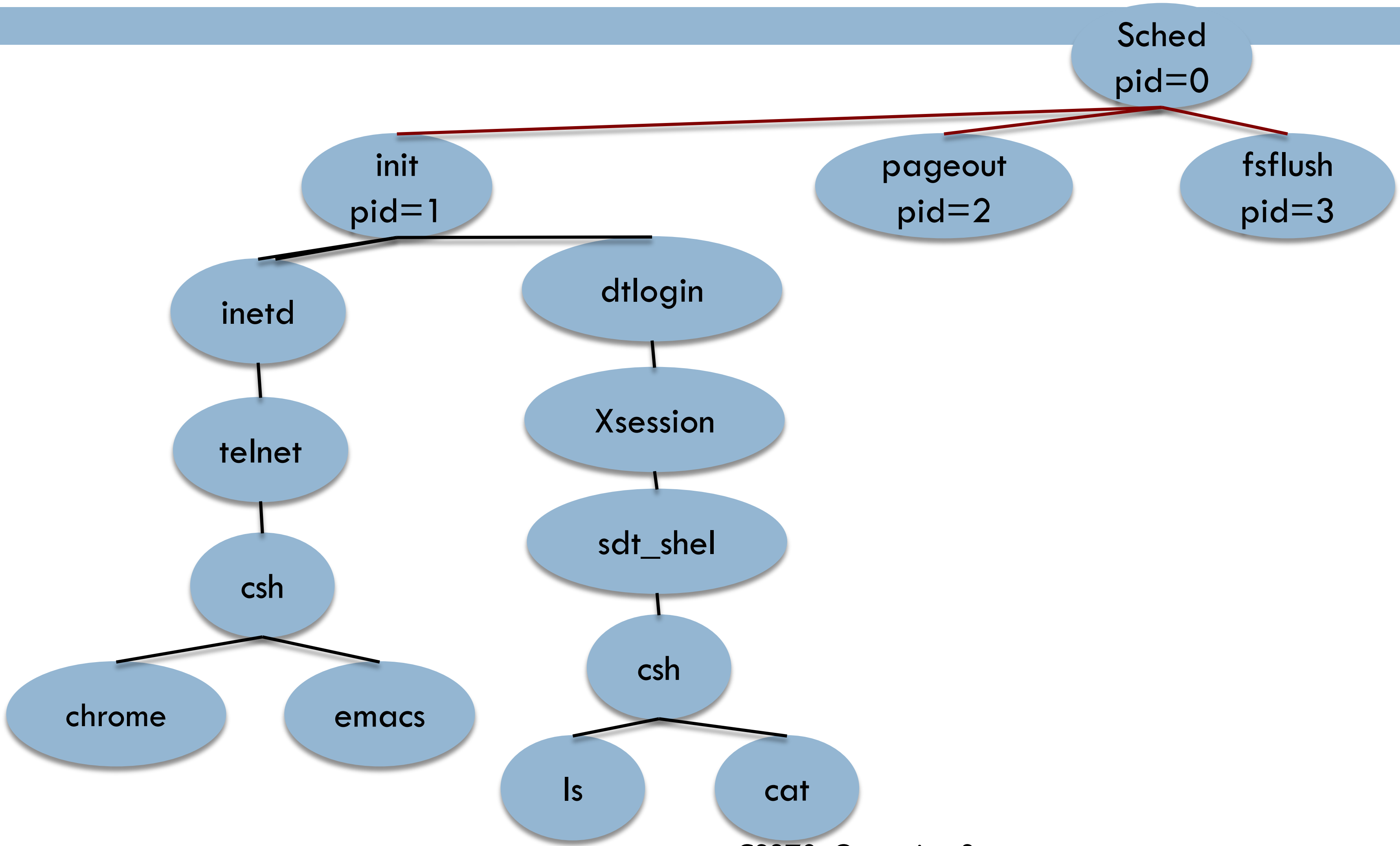
③ Child can **give itself** new process group ID

- Set process group ID = its process ID

Process groups

- It can contain processes which are:
  1. Parent (and further ancestors)
  2. Siblings
  3. Children (and further descendants)
- A process can only send **signals** to members of its process group

Example: Process tree in Solaris



Windows has no concept of a process hierarchy

- The only hint of a hierarchy?
  - When a process is created, parent is given a special *token* (called **handle**)
    - Use this to control the child

- However, parent is free to **pass** this token to some other process
  - **Invalidates** hierarchy

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Process terminations

- Normal exit (voluntary)
  - E.g. successful compilation of a program
- Error exit (voluntary)
  - E.g. trying to compile a file that does not exist

Process terminations

- Fatal error (involuntary)
  - Program bug
    - Referencing non-existing memory, dividing by zero, etc

- Killed by another process (involuntary)
  - Execute system call telling OS to <u>kill some other</u> process
  - *Killer* must be authorized to do the *killing of the killee*
  - Unix: **`kill`** Win32: **`TerminateProcess`**

Process terminations: This can be either normal or abnormal

- OS **deallocates** the process resources
  - Cancel pending timers and signals
  - Release virtual memory resources and locks
  - Close any open files
- Updates statistics
  - Process status and resource usage
- Notifies parent in response to a `wait()`

On termination a UNIX process DOES NOT fully release resources until a parent execute a wait() for it

- When the parent is not waiting when the child terminates?
  - The process becomes a **zombie**

- Zombie is an *inactive* process
  - Still has an entry in the process table
  - But is already dead, so cannot be killed easily!! ☺

- Zombie processes often come from error in programming: not properly waiting on all children created, changing the parent while children still active, etc.

Zombies and termination

- When a process terminates, its *orphaned* children and are *adopted* by a special process
  - This special system process is **`init`**
- Some more about the special process **`init`**
  1. Has a `pid` of 1
  2. Periodically executes wait() for children
  3. Children without a parent are adopted by init
     - Zombie processes are adopted by init after killing their parent, then cleaned by the periodic wait()

Normal termination of processes

- Return from `main`
- Implicit return from `main`
  - Function **falls off the end**
- Call to `exit`, `_Exit` or `_exit`

Protection and Security

- Control access to system resources
  - Improve reliability
- Defend against use (misuse) by unauthorized or incompetent users
- Examples
  - Ensure process executes within its own space
  - Force processes to relinquish control of CPU
  - Device-control registers accessible only to the OS

Inter-Process Communications

Objectives:

- Explain inter-process communications based on Shared Memory
- Explain inter-process communications based on Pipes
- Explain inter-process communications based on message passing
- Contrast inter-process communications based on shared memory, pipes, and message passing
- Design programs that implement inter-process communications

Independent and Cooperating processes

- Independent: **CANNOT** *affect* or *be affected* by other processes
- Cooperating: **CAN** *affect* or *be affected* by other processes

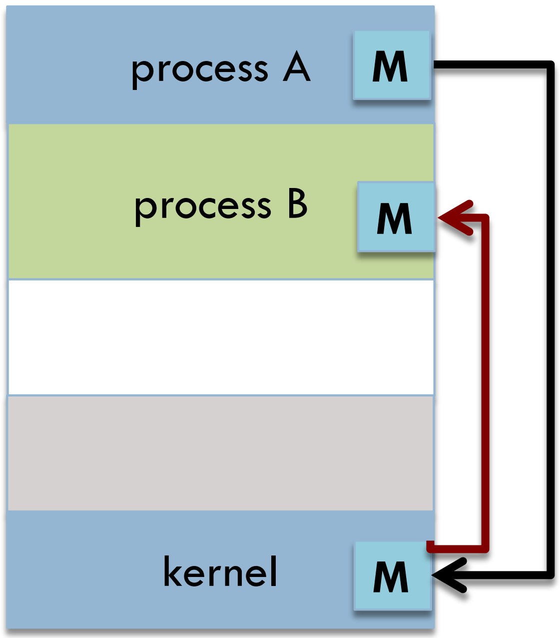
Why have cooperating processes?

- Information sharing: shared files
- Computational speedup
  - Sub tasks for concurrency
- Modularity
- Convenience: Do multiple things in parallel
- Privilege separation
- Etc.

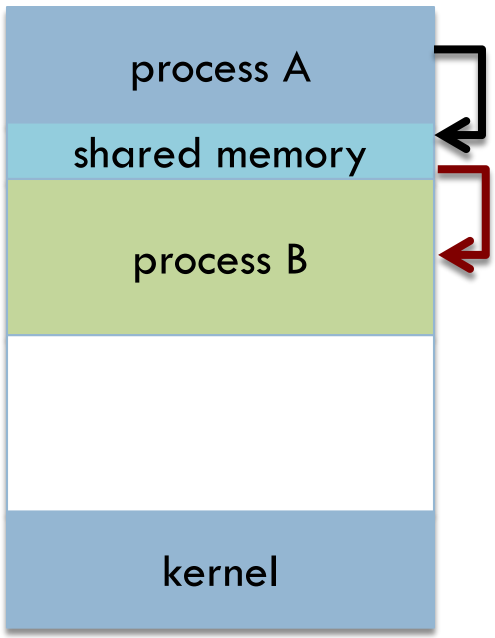
Cooperating processes need IPC to exchange data and information

- **Shared memory**
  - Establish memory region to be shared
  - Read and write to the shared region
- **Message passing**
  - Communications through message exchange

Contrasting the two IPC approaches



Easier to implement
Best for **small** amounts of data
Kernel intervention for communications



Maximum **speed**
System calls to **establish** shared memory

Shared memory systems

- Shared memory resides **in** the address space of process creating it
- Other processes must **attach** segment to their address space

IPC: Use of the created shared memory

- Once shared memory is attached to the process's address space
  - Routine memory accesses using * from `shmat()`
    - Write to it
      - `sprintf(`**`shared_memory`**`, "Hello");`
    - Print string from memory
      - `printf("*%\n", `**`shared_memory`**`);`

- **RULE:** First attach, and then access

IPC Shared Memory: What to do when you are done

① **Detach** from the address space.

- `shmdt()` :SHared Memory DeTtach
- `shmdt(shared_memory)`

② To **remove** a shared memory segment

- `shmctl()` : SHared Memory ConTroL operation
  - Specify the segment ID to be removed
  - Specify operation to be performed: `IPC_RMID`
  - Pointer to the shared memory region

Message Passing: Communicate and synchronize actions without sharing the same address space

- Useful in distributed environments (e.g., Message Passing Interface)
- Two main operations
  - `send(message)`
  - `receive(message)`
- Message sizes can be:
  - Fixed: Easy
  - Variable: Little more effort

Communications between processes

- There needs to be a communication link
- Underlying physical implementation
  - Shared memory
  - Hardware bus
  - Network

Aspects to consider for IPC

① Communications

- Direct or indirect

② Synchronization

- Synchronous or asynchronous

③ Buffering

- Automatic or explicit buffering

Naming allows processes to refer to each other

- Processes use each other's identity to communicate
- Communications can be
  - Direct
  - Indirect

Direct Communications: Addressing

- Symmetric addressing
  - `send(P, message)`
  - `receive(Q, message)`

Explicitly name recipient and sender of message

- Asymmetric addressing
  - `send(P, message)`
  - `receive(id, message)`
    - Variable `id` set to name of the sending process

Only sender names recipient
Recipient does not

Direct Communications: Disadvantages

- **Limited modularity** of process definitions
- **Cascading effects** of changing the identifier of process
  - Examine *all* other process definitions

Indirect communications: Message sent and received from mailboxes (ports)

- Each **mailbox** has a unique identification & owner
  - POSIX message queues use `integers` to identify mailboxes
- Processes communicate *only* if they have **shared mailbox**
  - `send(A, message)`
  - `receive(A, message)`

Indirect communications

- Processes `P1`, `P2` and `P3` share mailbox `A`
  - `P1` sends a message to `A`
  - `P2`, `P3` execute a `receive()` from `A`

- Possibilities? Allow …
  1. Link to be associated with at most 2 processes
  2. At most 1 process to execute `receive()` at a time
  3. System to arbitrarily select who gets message

Mailbox ownership: Owned by OS

- Mailbox has its own existence
- Mailbox is **independent**
  - Not attached to any process
- OS must allow processes to
  - Create mailbox
  - Send and receive *through* the mailbox
  - Delete mailbox

Message passing: Synchronization issues Options for implementing primitives

- Blocking send
  - Block *until* received by process or mailbox
- Nonblocking send
  - Send and *promptly resume* other operations
- Blocking receive
  - Block *until* message available
- Nonblocking receive
  - Retrieve *valid* message or *null*
- Producer-Consumer problem: Easy with blocking

Communicate and synchronize actions without sharing the same address space

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Direct communications

- Explicitly name recipient or sender
- Link is established automatically
  - Exactly one link between the 2 processes
- Addressing
  - Symmetric
  - Asymmetric

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Indirect communications: Link properties

- Link established only if both members share mailbox
- Link may be associated with more than two processes

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  - Send and receive *through* the mailbox
  - Delete mailbox

Message passing: Synchronization issues Options for implementing primitives

- Blocking send
  - Block *until* received by process or mailbox
- Nonblocking send
  - Send and *promptly resume* other operations
- Blocking receive
  - Block *until* message available
- Nonblocking receive
  - Retrieve *valid* message or *null*
- Producer-Consumer problem: Easy with blocking

Threads

Objectives:

- Explain differences between processes and threads
- Compare multithreading models
- Contrast differences between user and kernel threads
- Relate dominant threading libraries: POSIX, Win32, and Java
- Design threaded programs that can synchronize their actions

What are threads?

- Miniprocesses or lightweight processes
- Why would anyone want to have a *kind of process* **within** a process?

The main reason for using threads

- In many applications *multiple activities* are going on at once
  - Some of these may block from time to time

- Decompose application into multiple sequential threads
  - Running in **quasi-parallel**

Isn’t this precisely the argument for processes?

- Yes, *but* there is a new dimension …
- Threads have the ability to **share the address space** (and all of its data) among themselves
- For several applications
  - Processes (with their *separate* address spaces) don’t work

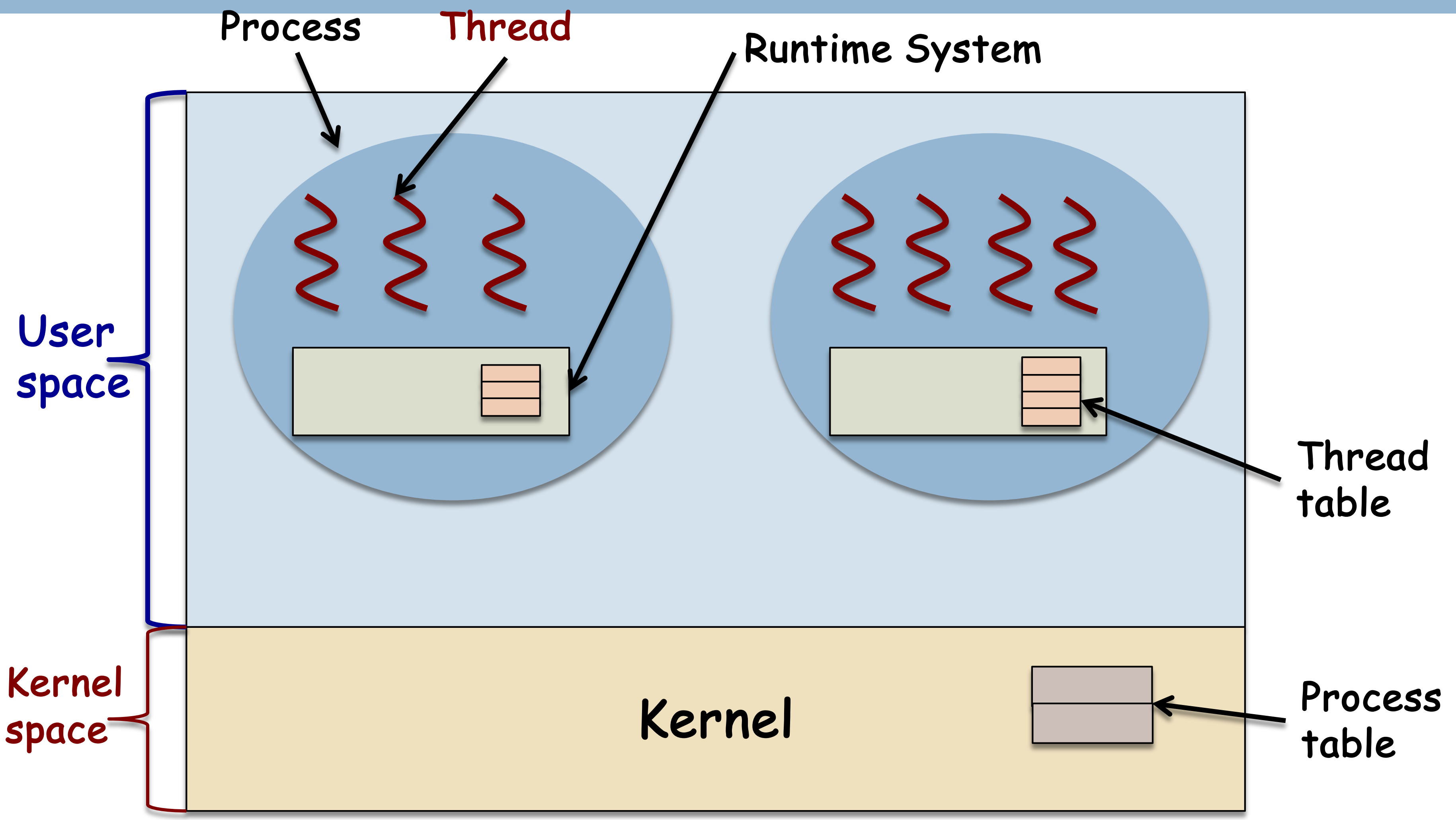
Threads are also lighter weight than processes

- **Faster** to create and destroy than processes
- In many systems thread creation is 10-100 times faster
- When number of threads needed changes dynamically and rapidly?
  - Lightweight property is very useful

Threads: The performance argument

- When all threads are CPU bound all the time?
  - Additional threads would likely yield **no** performance gain
- But when there is substantial computing ***and substantial I/O***
  - Having threads allows activities to **overlap**
  - Speeds up the application possibly

User-level threads: Overview



User threads are invisible to the kernel and have low overhead

- **Compete among themselves** for resources allocated to their encapsulating process
- Scheduled by a *thread runtime* system that is **part** of the process code
- Programs link to a special library
  - Each library function is enclosed by a **jacket**
  - Jacket function calls thread runtime to do thread management
    - Before (and possibly after) calling jacketed library function.

User level thread libraries: Managing blocking calls

- **Replace** potentially blocking calls with non-blocking ones
- If a call does not block, the runtime invokes it
- If the call *may block*
  1. Place thread on a list of *waiting* threads
  2. Add call to list of actions to *try later*
  3. Pick another thread to run
- ALL control is **invisible** to user and OS

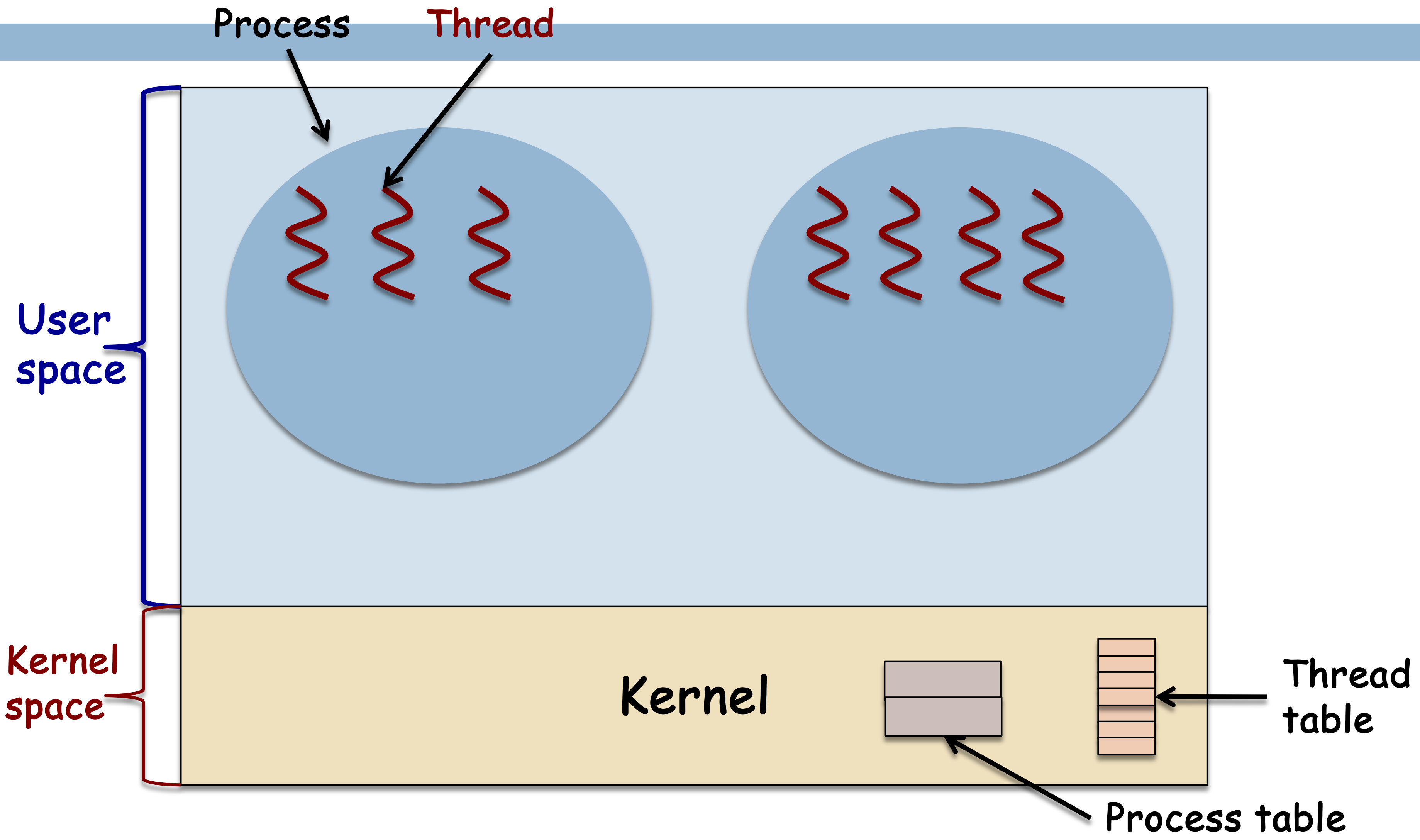
Disadvantages of the user level threads model (1)

- Assumes that the runtime will **eventually regain** control, this is thwarted by:
  - CPU bound threads
  - Thread that *rarely* perform library calls …
    - Runtime can’t regain control to schedule other threads
- Programmer must avoid **lockout** situations
  - Force CPU-bound thread to *yield* control

Disadvantages of the user level threads model (2)

- Can only share processor resources allocated to encapsulating process
  - **Limits** available parallelism

Kernel-level threads: Overview



Kernel threads

- Kernel is aware of kernel-level threads as **schedulable entities**
  - Kernel maintains a thread table to keep track of all threads in the system
- **Compete systemwide** for processor resources
  - Can take advantage of multiple processors

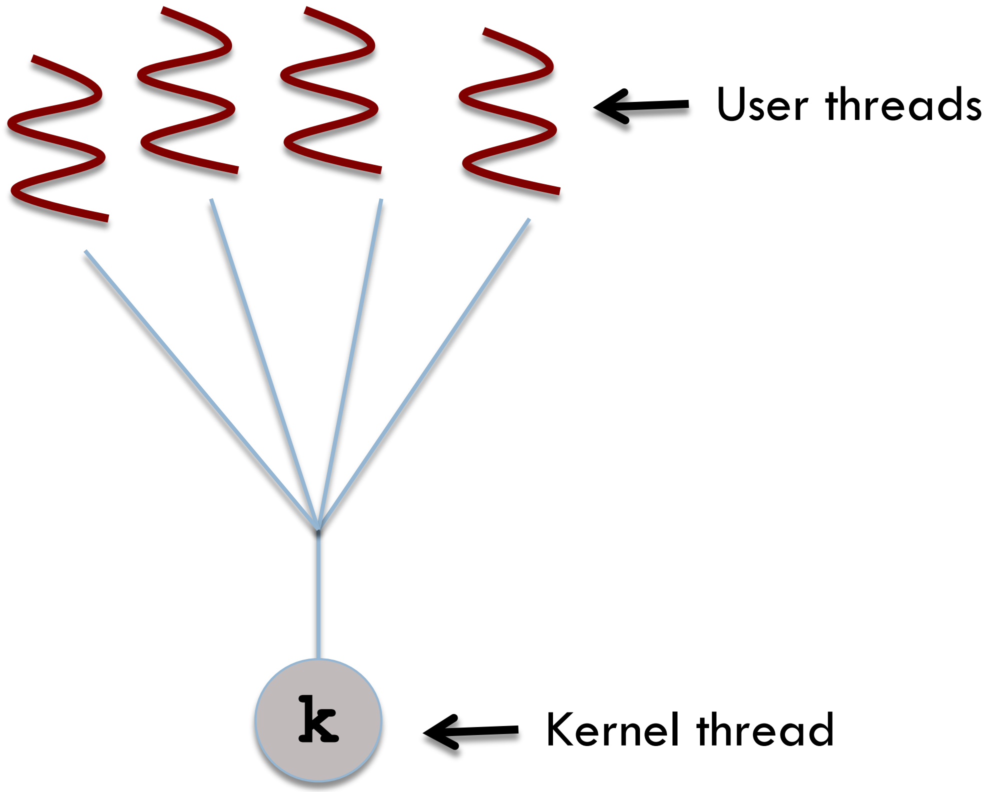
Kernel threads: Management costs

- Scheduling is **almost as expensive** as processes
  - Synchronization and data sharing *less expensive* than processes
- More expensive to manage than user-level threads

Hybrid thread models

- Write programs in terms of user-level threads
- Specify number of schedulable entities associated with process
  - **Mapping at runtime** to achieve parallelism
- Level of user-control over mapping
  - Implementation dependent

The Many-to-One threading model



Many-to-One Model maps many user level threads to 1 kernel thread

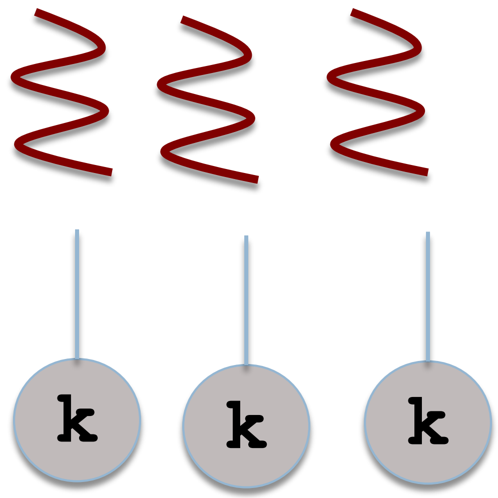
- Thread management done by thread library in **user-space**
- What happens when one thread makes a *blocking system call?*
  - The entire process blocks!

Many-to-One Model maps many user level threads to 1 kernel thread

- Only 1 thread can access kernel at a time
  - Multiple threads **unable** to run in parallel on multi-processor/core system

- E.g.: Solaris Green threads, GNU Portable threads

The One-to-One threading model



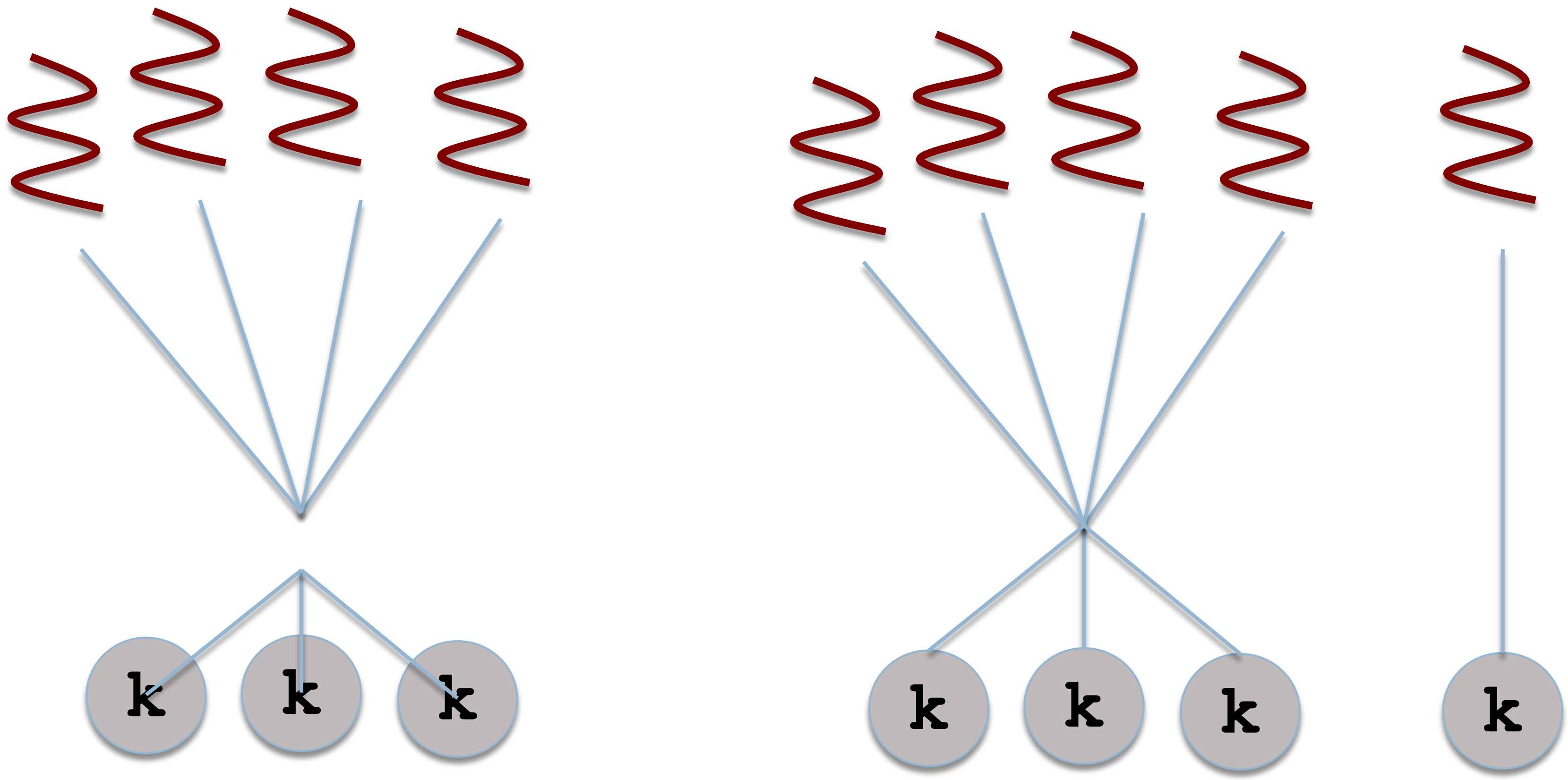
One-to-One Model: Maps each user thread to a kernel thread

- More **concurrency**
  - Another thread can continue to run, when a thread invokes a blocking system call
- Threads run in **parallel** on multiprocessors

One-to-One Model:
Maps each user thread to a kernel thread

- Disadvantages:
  - There is an **overhead** for kernel thread creation
    - Multiple user threads can degrade application performance
  - Uses more kernel threads so uses more resources
- Supported by:
  - Linux
  - Windows family: NT/XP/2000
  - Solaris 9 and up

Many-to-Many threading Model: 2-level is a variant of this



Many-to-Many **Two-level**

Many-to-Many model

- **Multiplex** many user-level threads on a smaller number of kernel threads
- Number of kernel threads may be specific to
  - Particular application
  - Particular machine
- Supported in
  - IRIX, HP-US, and Solaris (prior to version 9)

A comparison of the three models

	Many-to-one	One-to-One	Many-to-Many
Kernel Concurrency	NO	YES if many threads	YES
During blocking system call?	Process Blocks	Process DOES NOT block if other threads	Process DOES NOT block
Kernel thread creation	Kernel thread already exists	Kernel thread creation overhead	Kernel threads available
Caveat	Use system calls (blocking) with care	Don't create too many threads to not use too much resources	

Thread libraries provide an API for creating and managing threads

	User level library	Kernel level library
Library code and data structures	Reside in user space	Reside in kernel space
Thread creation requires a system call?	NO	YES
OS/Kernel support	NO	YES

Dominant thread libraries (1)

- POSIX pthreads
  - Extends POSIX standard (IEEE 1003.1c)
  - Provided as user- or kernel-level library
  - Solaris, Mac OS X, Linux, …
- Win32 thread library
  - Kernel-level library

Dominant thread libraries (2)

- Java threading API
  - Implemented using **thread library on host system**
    - On Windows: Threads use Win32 API
    - UNIX/Linux: Uses pthreads

Process Synchronizations and Atomic Transactions

Objectives:

- Formulate the critical section problem
- Dissect a software solution to the critical section problem (case study: Peterson's solution)
- Explain Synchronization hardware and Instruction Set Architecture support for concurrency primitives.
- Assess classic problems in synchronization: bounded buffers, readers-writers, dining philosophers.
- Explain serializability of transactions
- Assess locking protocols
- Explain checkpointing and rollback recovery in transactional systems

A look at the producer consumer problem

```
while (true) {
  while (counter == BUFFER_SIZE) {
      ; /*do nothing */
    }
    buffer[in] = nextProduced
    in = (in +1)%BUFFER_SIZE;
    counter++;
}
```

Producer

```
while (true) {
  while (counter == 0) {
      ; /*do nothing */
    }
    nextConsumed = buffer[out]
    out = (out +1)% BUFFER_SIZE;
    counter--;
}
```

Consumer

Implementation of ++/-- in machine language

```
counter++
  register1 = counter
  register1 = register1 + 1
  counter   = register1
```

```
counter--
  register2 = counter
  register2 = register2 - 1
  counter   = register2
```

Lower-level statements may be interleaved in any order

```
Producer execute:  register1 = counter
Producer execute:  register1 = register1 + 1
Producer execute:  counter = register1

Consumer execute:  register2 = counter
Consumer execute:  register2 = register2 - 1
Consumer execute:  counter = register2
```

Lower-level statements may be interleaved in any order

```
Producer execute:   register1 = counter
Consumer execute:   register2 = counter
Producer execute:   register1 = register1 + 1
Consumer execute:   register2 = register2 - 1
Producer execute:   counter = register1
Consumer execute:   counter = register2
```

The **order** of statements *within* each high-level statement is **preserved**

Lower-level statements may be interleaved in any order (counter = 5)

`Producer execute: register1 = counter`	{register1 = 5}
`Producer execute: register1 = register1 + 1`	{register1 = 6}
`Consumer execute: register2 = counter`	{register2 = 5}
`Consumer execute: register2 = register2 - 1`	{register2 = 4}
`Producer execute: counter = register1`	{counter = 6}
`Consumer execute: counter = register2`	{counter = 4}

Counter has ***incorrect*** state of 4

Lower-level statements may be interleaved in any order (counter = 5)

`Producer execute:  register1 = counter`	{register1 = 5}
`Producer execute:  register1 = register1 + 1`	{register1 = 6}
`Consumer execute:  register2 = counter`	{register2 = 5}
`Consumer execute:  register2 = register2 - 1`	{register2 = 4}
`Consumer execute:  counter = register2`	{counter = 4}
`Producer execute:  counter = register1`	{counter = 6}

Counter has ***incorrect*** state of 6

Race condition

- Several processes access and manipulate data **concurrently**
- **Outcome** of execution *depends* on
  - Particular **order** in which accesses takes place
- Debugging programs with race conditions?
  - Painful!
  - Program runs fine most of the time, but once in a rare while something weird and unexpected happens

The kernel is subject to several possible race conditions

- E.g.: Kernel maintains list of all open files
  - 2 processes open files simultaneously
  - Separate updates to kernel list may result in a race condition
- Other kernel data structures
  - Memory allocation
  - Process lists
  - Interrupt handling

Critical-Section

- System of n processes $\{P_0, P_1, \ldots, P_{n-1}\}$
- Each process has a segment of code (**critical section**) where it:
  - **Changes common variables**, updates a table, etc
- No two processes can execute in their critical sections at the same time

The Critical-Section problem

- Design a **protocol** that processes can use to cooperate

- Each process must **request permission** to enter its critical section
  - The **entry** section

General structure of a participating process

```
do {

        entry section

        critical section

        exit section

        remainder section

} while (TRUE);
```

Request permission to enter

Housekeeping to let other processes enter

Requirements for a solution to the critical section problem

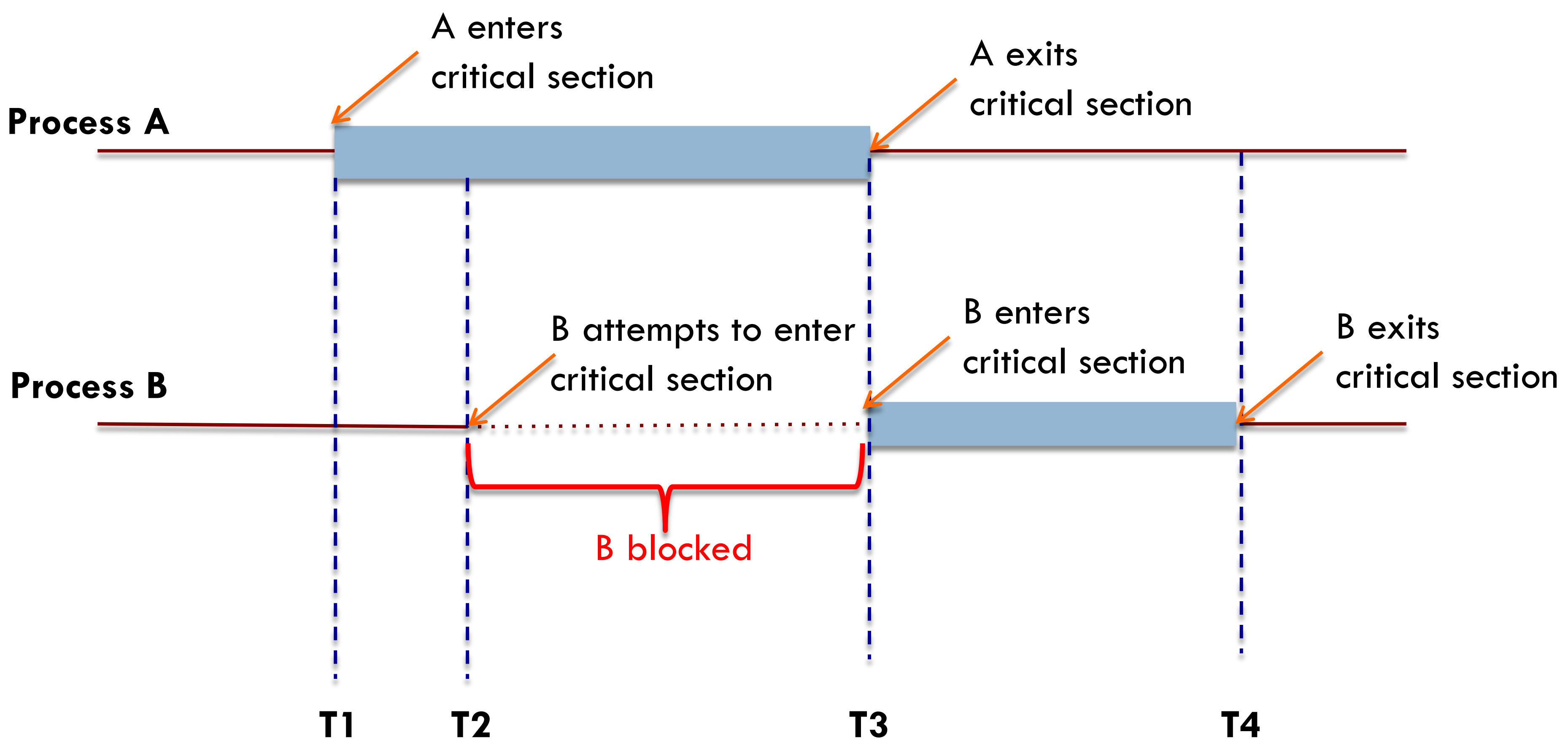
1. Mutual exclusion
2. Progress
3. Bounded wait

- PROCESS SPEED
  - Each process operates at *non-zero* speed
  - Make <u>no assumption</u> about the ***relative speed*** of the *n* processes

Mutual Exclusion

- Only **one** process can execute in its critical section
- When a process executes in its critical section
  - **No other process** is allowed to execute in *its* critical section

Mutual Exclusion: Depiction



Progress

- **{C1}** If *No* process is executing in its critical section, and …
- **{C2}** *Some* processes wish to enter their critical sections

- **Decision** on who gets to enter the critical section
  - Is made by processes that are NOT executing in their remainder section
  - Selection **cannot be postponed indefinitely**

Bounded waiting

- *After* a process has made a **request** to enter its critical section
  - AND *before* this request is granted
- **Limit number** of times other processes are allowed to enter their critical sections

Approaches to handling critical sections in the OS

- Nonpreemptive kernel
  - If a process runs in kernel mode: no preemption
  - **Free** from race conditions on kernel data structures

- Preemptive kernels
  - Must ensure shared kernel data is free from race conditions
  - <u>Difficult</u> on SMP (Symmetric Multi Processor) architectures
    - 2 processes may run simultaneously on different processors

Kernels: Why preempt?

- Suitable for real-time
  - A real-time process may preempt a kernel process

- More **responsive**
  - *Less risk* that kernel mode process will run arbitrarily long

Peterson's Solution

- **Software solution** to the critical section problem
  - Restricted to two processes

- No guarantees on modern architectures
  - Machine language instructions such as `load` and `store` implemented differently

- Good algorithmic description
  - Shows how to address the 3 requirements

Peterson's Solution: The components

- Restricted to two processes in this example (but generalizable to n)
  - P_i and P_j

- **Share** two data items
  - `int turn`
    - Indicates whose *turn* it is to enter the critical section
  - `boolean flag[2]`
    - Whether process *is ready* to enter the critical section

Peterson's solution: Structure of process P_i

```
do {
        flag[0] = TRUE;
        turn = 1;
        while (flag[0] && turn==1) {;}

        critical section

        flag[0] = FALSE;

        remainder section

} while (TRUE);
```

Peterson's solution: Structure of process P_j

```
do {
        flag[1] = TRUE;
        turn = 0;
        while (flag[0] && turn==0) {;}

        critical section

        flag[0] = FALSE;

        remainder section

} while (TRUE);
```

Peterson's solution: Mutual exclusion

```
while (flag[j] == true && turn==j) {;}
```

- P_i enters critical section only if
  `flag[j] == false OR turn == i`

- If both processes try to execute in critical section at the same time
  - `flag[0] == flag[1] == true`
  - **But** `turn` can be `0` or `1`, not BOTH

- If P_j entered critical section
  - `flag[j] == true AND turn == j`
  - Will persist as long as P_j is in the critical section

Peterson's Solution: Progress and Bounded wait

- P_i can be stuck only if `flag[j]==true AND turn==j`
  - If P_j is *not ready*: `flag[j]== false`, and P_i can enter
  - Once P_j *exits*: it resets `flag[j]` to `false`

- If P_j resets `flag[j]` to `true`
  - Must set `turn = i;`

- P_i **will enter** critical section (*progress*) after <u>at most one</u> entry by P_j (*bounded wait*)

Solving the critical section problem using locks

```
do {

        acquire lock
        critical section

        release lock

        remainder section


} while (TRUE);
```

Possible assists for solving critical section problem (1/2)

- Uniprocessor environment
  - **Prevent interrupts** from occurring when shared variable is being modified
    - *No unexpected modifications*!
- Multiprocessor environment
  - Disabling interrupts is *time consuming*
    - Message passed to ALL processors

Possible assists for solving critical section problem (2/2)

- Special **atomic** hardware instructions
  - Swap content of two words
  - Modify word

Swap()

```
void Swap(boolean *a, boolean *b ) {

      boolean temp = *a;
      *a = *b;
      *b = temp;
}
```

Swap: Shared variable LOCK is initialized to false

```
do {
        key = TRUE;
        while (key == TRUE) {
            Swap(&lock, &key)
        }

        critical section

        lock = FALSE;


        remainder section


} while (TRUE);
```

Cannot enter critical section UNLESS `lock == FALSE`

`lock` is a SHARED variable
`key` is a LOCAL variable

TestAndSet()

```
boolean TestAndSet(boolean *target ) {

     boolean rv = *target;
     *target = TRUE;
     return rv;
}
```

Sets `target` to `true` and returns old value of `target`

`TestAndSet`: Shared boolean variable `lock` initialized to `false`

```
do {

        while (TestAndSet(&lock)) {;}

        critical section

        lock = FALSE;

        remainder section

} while (TRUE);
```

To break out:
Return value of `TestAndSet` should be `FALSE`

If two `TestAndSet()` are executed *simultaneously*, they will be executed *sequentially* in some arbitrary order

Entering and leaving critical regions using TestAndSet and Swap (Exchange)

```
enter_region:
    TSL REGISTER, LOCK
    CMP REGISTER, #0
    JNE enter_region
    RET

leave_region:
    MOVE LOCK, #0
    RET
```

```
enter_region:
    MOVE REGISTER, #1
    XCHNG REGISTER,LOCK
    CMP REGISTER, #0
    JNE enter_region
    RET

leave_region:
    MOVE LOCK, #0
    RET
```

All Intel x86 CPUs have the `XCHG` instruction for low-level synchronization

Semaphores

- Semaphore **S** is an integer variable
- Once *initialized*, accessed through **atomic** operations
  - `wait()`
  - `signal()`

Defining the semaphore

```
typedef struct {
   int value;
   struct process *sleeping_list;
} semaphore;
```

list of processes

The `wait()` operation to eliminate busy waiting

```
wait(semaphore *S){
    S->value--;

    if (S->value <0) {
      add process to S->sleeping_list;
      block();
    }

}
```

If value < 0
abs(value) is the number of waiting processes

`block()` suspends the process that invokes it

The `signal()` operation to eliminate busy waiting

```
signal(semaphore *S) {
    S->value++;

    if (S->value <= 0) {
      remove a process P from S->sleeping_list;
      wakeup(P);
    }

}
```

`wakeup(P)` resumes the execution of process `P`

Deadlocks and Starvation: Implementation of semaphore with a waiting queue

Process P0	Process P1
`wait(S);`	`wait(Q);`
`wait(Q);`	`wait(S);`
`signal(S);`	`signal(Q);`
`signal(Q);`	`signal(S);`

Say: P0 executes `wait(S)` and *then* **P1** executes `wait(Q)`

P0 must wait till **P1** executes `signal(Q)`
P1 must wait till **P0** executes `signal(S)`

Cannot be executed so deadlock

Semaphores and atomic operations

- Once a semaphore action has started
  - **No other process** can access the semaphore UNTIL
    - Operation has *completed* or *process has blocked*
- Atomic operations
  - Group of related operations
  - Performed without interruptions
    - Or not at all

The bounded buffer problem

- Binary semaphore (`mutex`)
  - Provides mutual exclusion for accesses to buffer pool
  - Initialized to 1
- Counting semaphores
  - `empty`: Number of empty slots available to produce
    - Initialized to ***n***
  - `full`: Number of filled slots available to consume
    - Initialized to **0**

Some other things to bear in mind

- Producer and consumer must be **ready** before they **attempt to enter** critical section
- Producer readiness?
  - When a slot is available **to add** produced item
    - `wait(empty)`: `empty` is initialized to **n**
- Consumer readiness?
  - When a **producer has added** new item to the buffer
    - `wait(full)` : `full` initialized to **0**

The Producer

```
do {
        produce item nextp
        wait(empty);
        wait(mutex);

        add nextp to buffer

        signal(mutex);
        signal(full);

        remainder section

} while (TRUE);
```

`wait` till slot available

Only producer OR consumer can be in critical section

Allow producer OR consumer to (re)enter critical section

`signal` consumer that a slot is available

The Consumer

```
do {

        wait(full);
        wait(mutex);

     remove item from buffer
          (nextc)

        signal(mutex);
        signal(empty);

        consume nextc

} while (TRUE);
```

`wait` till slot available for consumption

Only producer OR consumer can be in critical section

Allow producer OR consumer to (re)enter critical section

`signal` producer that a slot is available to add

The Readers-Writers problem

- A database is **shared** among several concurrent processes

- Two types of processes
  - Readers
  - Writers

Readers-Writers: Potential for adverse effects

- If *two readers* access shared data simultaneously?
  - No problems
- If a *writer and some other reader* (or writer) access shared data simultaneously?
  - Chaos

Writers must have exclusive access to shared database while writing

- FIRST readers-writers problem:
  - No reader should wait for other readers to finish; simply because a writer is waiting
    - Writers may starve

- SECOND readers-writers problem:
  - If a writer is ready it performs its write ASAP
    - Readers may starve

Solution to the FIRST readers-writers problem

- Variable `int readcount`
  - Tracks how many readers are reading object
- Semaphore **`mutex`** **{1}**
  - Ensure mutual exclusion when `readcount` is accessed
- Semaphore **`wrt`** **{1}**
  1. Mutual exclusion for the writers
  2. First (last) reader that enters (exits) critical section
     - Not used by readers, when **other** readers **are in** their critical section

The Writer: When a writer signals either a waiting writer or the readers resume

```
do {

    wait(wrt);


    writing is performed


    signal(wrt);



} while (TRUE);
```

When:
writer in critical section
and if n readers waiting

1 reader is queued on **wrt**
(n-1) readers queued on **mutex**

The Reader process

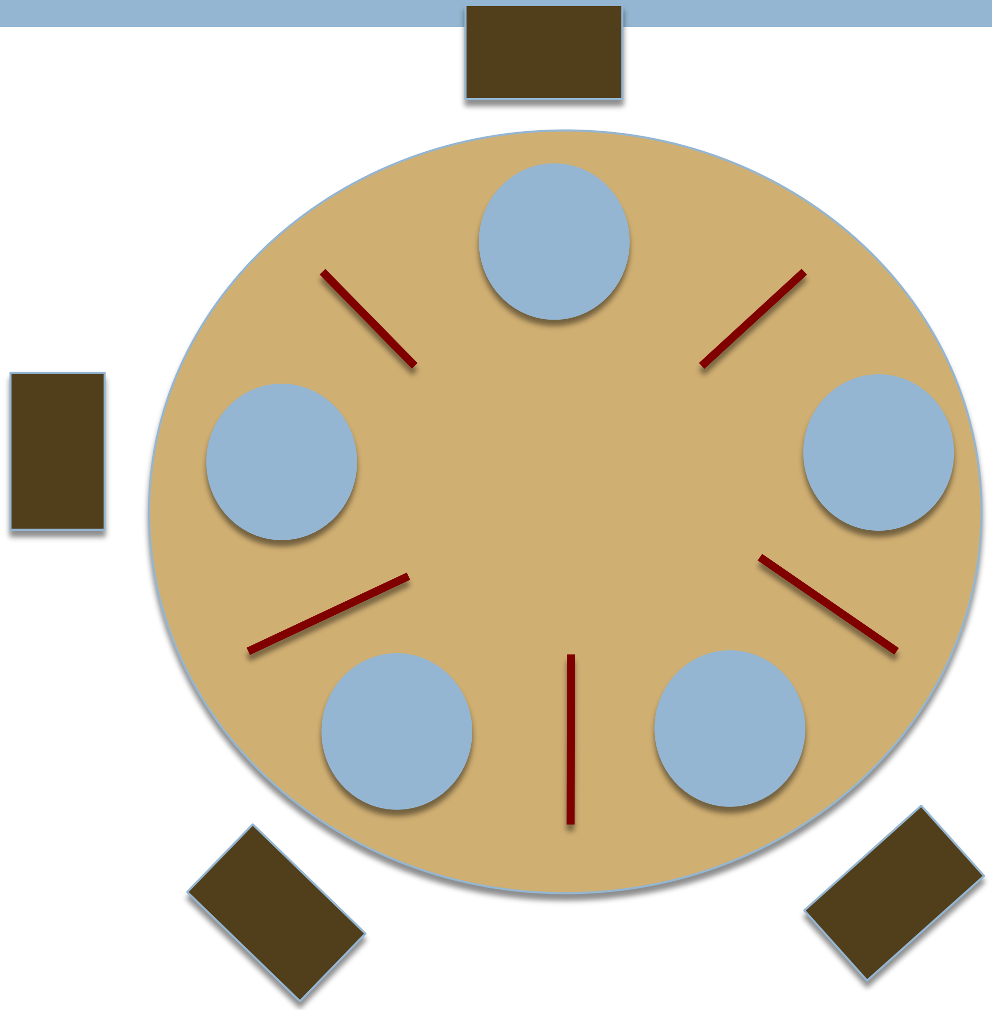
```
do {
      wait(mutex);
      readcount++;
      if (readcount ==1) {
         wait(wrt);
      }
      signal(mutex);

      reading is performed

      wait(mutex);
      readcount--;
      if (readcount ==0) {
         signal(wrt);
      }
      signal(mutex);
} while (TRUE);
```

mutex for mutual exclusion to `readcount`

When:
writer in critical section
and if n readers waiting

1 is queued on **wrt**
(n-1) queued on **mutex**

Dining Philosopher's Problem: the situation



The Problem

① Philosopher tries to *pick up two closest* **{LR}** chopsticks

② Pick up only **1 chopstick at a time**

- Cannot pick up a chopstick being used

③ Eat only when you have *both* chopsticks

④ When done; *put down both* the chopsticks

Why is the problem important?

- Represents allocation of **several resources**
  - AMONG **several processes**

- Can this be done so that it is:
  - Deadlock free
  - Starvation free

Dining philosophers: Simple solution

- Each chopstick is a semaphore
  - Grab by executing `wait()`
  - Release by executing `signal()`

- Shared data
  - `semaphore chopstick[5];`
  - All elements are initialized to 1

What if all philosophers get hungry and grab the same {L/R} chopstick?

```
do {

        wait(chopstick[i]);
        wait(chopstick[(i+1)%5]);

           //eat

        signal(chopstick[i]);
        signal(chopstick[(i+1)%5]);

            //think

} while (TRUE);
```

Deadlock:
If all processes access chopstick with same hand

We will look at solution with monitors

Dining-Philosophers Using Monitors Deadlock-free

```
enum {THINKING,HUNGRY,EATING} state[5];
```

- `state[i] = EATING` **only if**
  - `state[(i+4)%5] != EATING && state[(i+1)%5] != EATING`
- `condition self[5]`
  - **Delay** self when *HUNGRY but unable* to get chopsticks

The `pickup()` and `putdown()` operations

```
pickup(int i) {
   state[i] = HUNGRY;
   test(i);
   if (state[i] != EATING) {
      self[i].wait();
   }
}
```

Suspend self if unable to acquire chopstick

```
putdown(int i) {
   state[i] = THINKING;
   test( (i+4)%5 );
   test( (i+1)%5 );
}
```

Check to see if person on left or right can use the chopstick

`test()` to see if philosopher can eat

Eat only if HUNGRY and Person on **Left AND Right** are not eating

```
test(int i) {
  if (state[(i+4)%5] != EATING &&
      state[i] == HUNGRY &&
      state[(i+1)%5 != EATING] ) {

   state[i] = EATING;
   self[i].signal();
  }
}
```

Signal a process that was suspended while trying to eat

Atomic transactions

- Mutual exclusion of critical sections ensures their atomic execution
  - As one *uninterruptible unit*

- Also important to ensure, that critical section forms a **single logical unit of work**
  - Either work is performed in **its entirety or not at all**
  - E.g. transfer of funds
    - Credit one account and debit the other

Transaction

- Collection of operations performing a **single logical function**
- Preservation of **atomicity**
  - Despite the possibility of failures

Transaction rollbacks

- An aborted transaction may have **modified** data
- State of accessed data must be **restored**
  - *To what it was* before transaction started executing

Log-based recovery to ensure atomicity: **Rely on stable storage**

- Record info describing **all** *modifications* made by transaction to various accessed data.

- Each log record describes a **single** write
  - Transaction name
  - Data item name
  - Old value
  - New value

- Other log records exist to record significant events
  - Start of transaction, commit, abort etc

Rationale for checkpointing

- When failure occurs we consult the log for undoing or redoing

- But if done naively, we need to search *entire* log!
  - Time consuming
  - Recovery takes longer
    - Though no harm done by redoing (idempotency)

Concurrent atomic transactions

- Since each transaction is atomic
  - Executed serially in some arbitrary order
    - **Serializability**
  - Maintained by executing each transaction within a critical section
    - Too restrictive
- Allow transactions to **overlap** while maintaining serializability
  - **Concurrency control algorithms**

Serializability

- Serial schedule: Each transaction executes atomically

  $n!$ schedules for n independent transactions

T0	T1
read(A)	
write(A)	
read(B)	
write(B)	
	read(A)
	write(A)
	read(B)
	write(B)

Non-serial schedule: Allow two transactions to overlap

- Does not imply incorrect execution
  - Define the notion of conflicting operations

- O_i and O_j **conflict** if they access same data item
  - AND at least one of them is a `write` operation

- If O_i and O_j do not conflict; we can ***swap*** their order
  - To create a new schedule

Concurrent serializable schedule

T0	T1
read(A)	
write(A)	
read(B)	
write(B)	
	read(A)
	write(A)
	read(B)
	write(B)

Serial Schedule

T0	T1
read(A)	
write(A)	
	read(A)
	write(A)
read(B)	
write(B)	
	read(B)
	write(B)

Conflict serializability

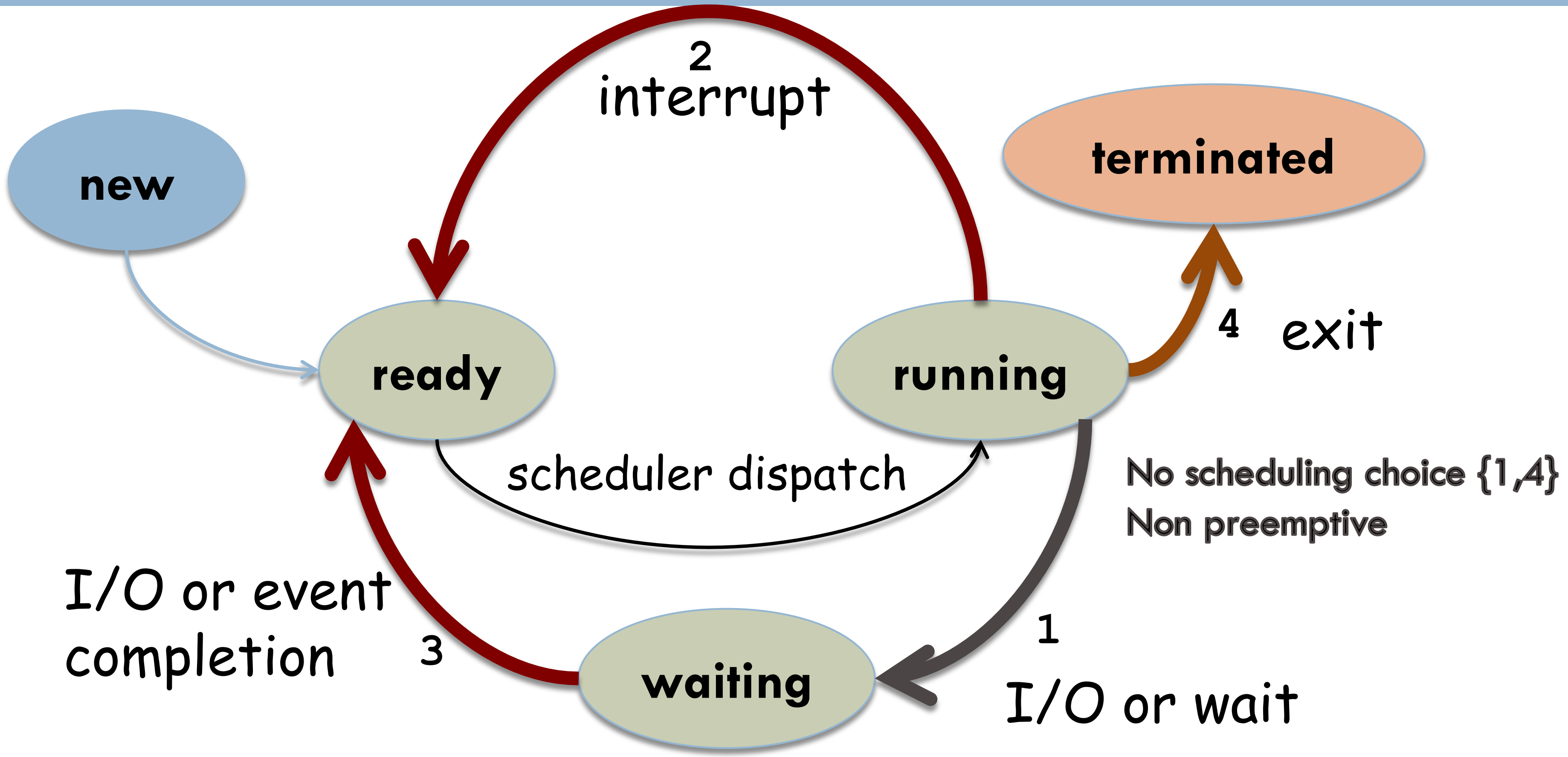
- If schedule **S** can be **transformed** into a serial schedule **S'**
  - By a series of swaps of non-conflicting operations

CPU Scheduling Algorithms

Objectives:

- Assess scheduling criteria including fairness and time quanta.
- Explain and contrast different approaches to scheduling: preemptive and non-preemptive
- Explain and assess scheduling algorithms: FCFS, shortest jobs, priority, round-robin, multilevel feedback queues, and the Linux completely fair scheduler.
- Understand how CPU scheduling algorithms function on multiprocessors.

CPU scheduling takes places under the following circumstances



Nonpreemptive or cooperative sheduling

- Process **keeps** CPU *until it relinquishes* it when:
  1. It terminates
  2. It switches to the waiting state
- Sometimes the *only* method on certain hardware platforms
  - E.g. when they don't have a hardware timer
- Used by initial versions of OS
  - Windows: Windows 3.x
  - Mac OS

Preemptive scheduling

- Pick a process and let it run for a **maximum of some fixed time**
- If it is still running at the end of time interval?
  - **Suspend** it ..
- Pick another process to run

Preemptive scheduling: Requirements

- A **clock interrupt** at the end of the time interval to give control of CPU back to the scheduler
- If no hardware timer is available?
  - Nonpremptive scheduling is the only option

Preemptive scheduling incurs some costs: Affects the design of the OS

- System call processing
  - Kernel may be changing kernel data structure (I/O queue)
- Process preempted in the middle AND
  - Kernel needs to read/modify same structure?
- SOLUTION: **Before** context switch
  - Wait for system call to complete OR
  - I/O blocking to occur

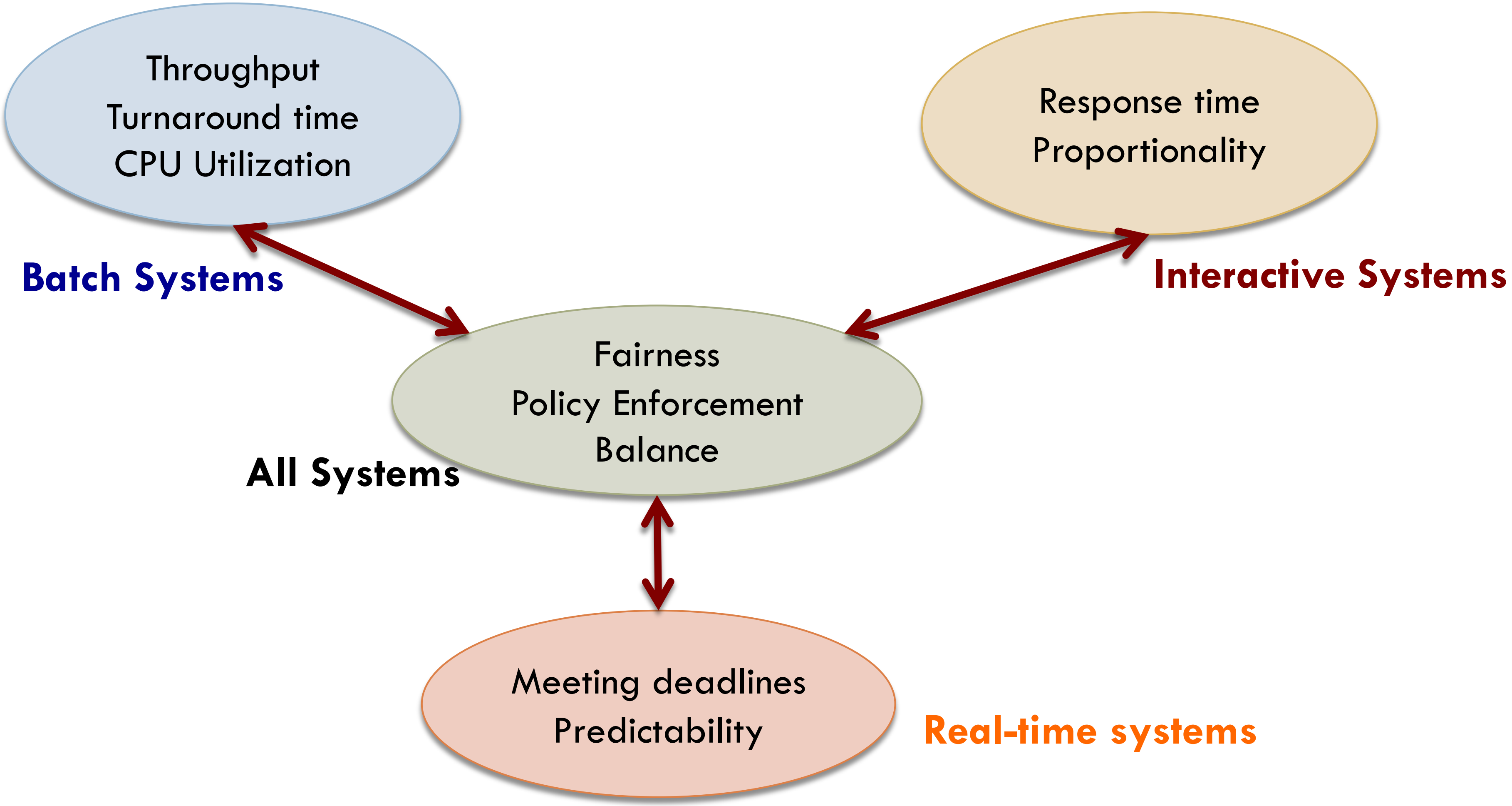
Preemptive scheduling incurs some costs: Interrupt processing

- Interrupts can occur at **any** time
  - Cannot always be ignored by kernel
    - Consequences: Inputs lost or outputs overwritten
- Guard code affected by interrupts from simultaneous use:
  - Disable interrupts during entry
  - Enable interrupts at exit
  - CAVEAT: Should not be done often, and critical section must contain few instructions

The dispatcher is invoked during **every** process switch

- **Gives control** of CPU to process selected by the scheduler
- Operations performed:
  - Switch context
  - Switch to user mode
  - Restart program at the right location
- Dispatch latency
  - Time to stop one process and start another

Scheduling Algorithms: Goals



CPU Utilization

- Difference between elapsed time and idle time
- Average over a period of time
  - Meaningful only within a context

Scheduling Criteria: Choice of scheduling algorithm may favor one over another

- **CPU Utilization**: Keep CPU as busy as possible? For example:
  - 40% for lightly loaded system
  - 90% for heavily loaded system
- **Throughput**: Number of completed processes per time unit? For example:
  - Long processes: 1/hour
  - Short processes: 10/second

Scheduling Criteria: Choice of scheduling algorithm may favor one over another

- Turnaround time
  - $t_{completion} - t_{submission}$
- **Waiting** time
  - Total time spent waiting in the ready queue
- Response time
  - Time to start responding
  - $t_{first\_response} - t_{submission}$
  - Generally *limited* by speed of output device

Scheduling Algorithms

- **Decides** which process in the ready queue is allocated the CPU
- Could be preemptive or nonpreemptive
- Optimize ***measure*** of interest
- We will use **Gantt charts** to illustrate *schedules*
  - Bar chart with start and finish times for processes

First-Come, First-Served Scheduling (FCFS)

- Process requesting CPU first, gets it first
- Managed with a FIFO queue
  - When process **enters** ready queue?
    - PCB is tacked to the **tail** of the queue
  - When CPU is **free**?
    - It is allocated to process at the **head** of the queue
- Simple to write and understand

Average waiting times in FCFS

Process	Burst Time
P1	24
P2	3
P3	3

Wait time = (0 + 24 + 27)/3 = 17

Wait time = (6 + 0 + 3)/3 = 3

Disadvantages of the FCFS scheme (1)

- Once a process gets the CPU, it keeps it
  - Till it terminates or does I/O
  - Unsuitable for time-sharing systems
- Average waiting time is generally not minimal
  - **Varies substantially** if CPU burst times vary greatly

Disadvantages of the FCFS scheme (2)

- Poor performance in certain situations
  - 1 CPU-bound process and many I/O-bound processes
  - **Convoy effect**: Smaller processes wait for the one big process to get off the CPU

Shortest Job First (SJF) scheduling algorithm

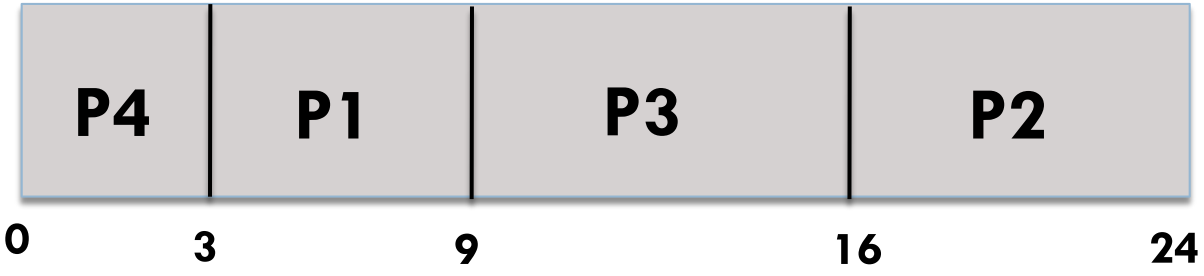
- When CPU is available it is assigned to process with **smallest CPU burst**

- Moving a short process before a long process?
  - Reduction in waiting time for short process
    GREATER THAN
    Increase in waiting time for long process

- Gives us **minimum average waiting time** for a **set** of processes that arrived *simultaneously*
  - Provably Optimal

Depiction of SJF in action

Process	Burst Time
P1	6
P2	8
P3	7
P4	3



Wait time = (3 + 16 + 9 + 0)/4 = 7

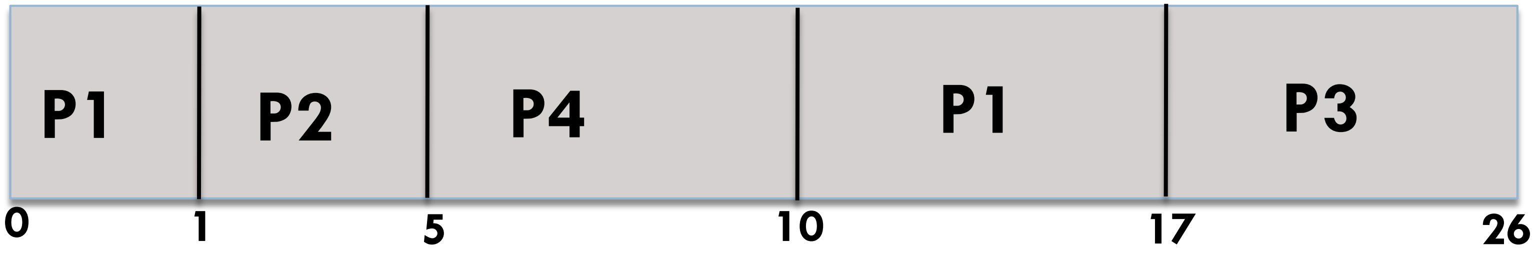
SJF is optimal ONLY when ALL the jobs are available simultaneously

- Consider 5 processes **A**, **B**, **C**, **D** and **E**
  - Run times are: 2, 4, 1, 1, 1
  - Arrival times are: 0,0, 3, 3, 3

- SJF will run jobs: **A**, **B**, **C**, **D** and **E**
  - Average wait time: (0 + 2 + 3 + 4 + 5)/5 = 2.8
  - **But** if you run **B**, **C**, **D**, **E** and **A** ?
    - Average wait time: (7 + 0 + 1 + 2 +3)/5 = 2.6!

Preemptive SJF

- A new process arrives in the ready queue
  - If it is shorter than the currently executing process
    - Preemptive SJF will preempt the current process



Process	Arrival	Burst
P1	0	8
P2	1	4
P3	2	9
P4	3	5

```
Wait time =
[(10-1) + (1-1) + (17-2) + (5-3)]/4
= 26/4 = 6.5
```

Use of SJF in long term schedulers

- Length of the process time limit
  - Used as CPU burst estimate
- Motivate users to accurately estimate time limit
  - Lower value will give faster response times
  - Too low a value?
    - Time limit exceeded error
    - Requires resubmission!

The SJF algorithm and short term schedulers

- **No way to know** the length of the next CPU burst
- So try to **predict** it
- Processes scheduled *based on predicted* CPU bursts

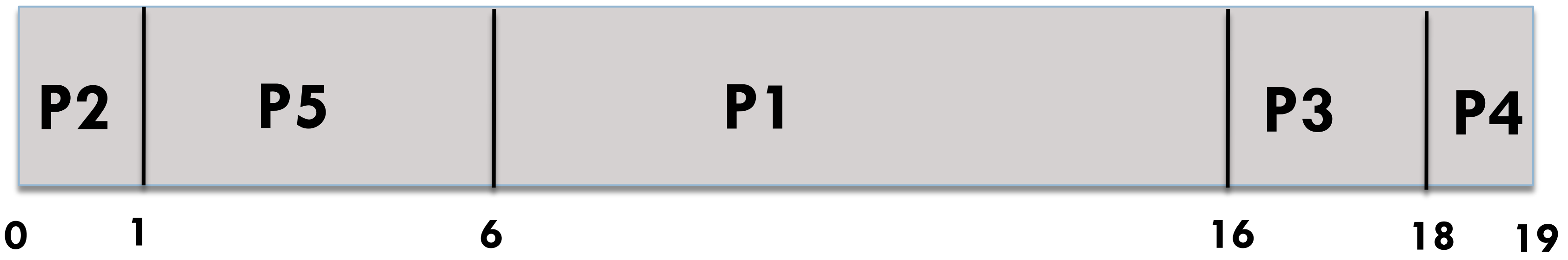
Priority Scheduling

- **Priority** associated with each process
- CPU allocated to process with **highest** priority
- Can be preemptive or nonpreemptive
  - If preemptive: Preempt CPU from a lower priority process when a higher one is ready

Depiction of priority scheduling in action

Process	Burst Time	Priority
P1	10	3
P2	1	1
P3	2	4
P4	1	5
P5	5	2

Here: Lower number means higher priority



`Wait time = (6 + 0 + 16 + 18 + 1)/5 = 8.2`

How priorities are set

- Internally defined priorities based on:
  - **Measured** quantities
  - Time limits, memory requirements, # of open files, ratio (averages) of I/O to CPU burst
- External priorities
  - Criteria outside the purview of the OS
  - Importance of process, $ paid for usage, politics, etc.

Issue with priority scheduling

- Can leave lower priority processes waiting indefinitely
- Perhaps apocryphal tale:
  - MIT's IBM 7094 shutdown (1973) found processes from 1967!

Coping with issues in priority scheduling: Aging

- **Gradually increase priority** of processes that wait for a long time
- Example:
  - Process with priority of 127 and increments every 15 minutes
  - Process priority becomes 0 in no more than 32 hours

Round-Robin Scheduling

- Similar to FCFS scheduling
  - **Preemption** to enable switch between processes
- Ready queue is implemented as **FIFO**
  - Process Entry: PCB at *tail* of queue
  - Process chosen: From *head* of the queue
- CPU scheduler goes around ready queue
  - Allocates CPU to each process *one after the other*
    - CPU-bound up to a maximum of 1 **quantum**

Round Robin: Choosing the quantum

- Context switch is **time consuming**
  - Saving and loading registers and memory maps
  - Updating tables
  - Flushing and reloading memory cache
- What if quantum is 4 ms and context switch overhead is 1 ms?
  - 20% of CPU time thrown away in administrative overhead

Round Robin: Improving efficiency by increasing quantum

- Let's say quantum is 100 ms and context-switch is 1ms
  - Now wasted time is only 1%
- But what if 50 concurrent requests come in?
  - Each with widely varying CPU requirements
  - 1st one starts immediately, 2nd one 100 ms later, …
  - The last one may have to wait for 5 seconds!
  - A shorter quantum would have given them better service

If quantum is set longer than mean CPU burst?

- **Preemption will not happen very often**
- Most processes will perform a blocking operation before quantum runs out
- Switches happens only when process blocks and cannot continue

Quantum: Summarizing the possibilities

- Too short?
  - Too *many* context switches
  - Lowers CPU efficiency
- Too long?
  - *Poor* responses to interactive requests

Deadlocks

Objectives:

- Explain deadlock characterization
- Contrast and explain schemes for deadlock prevention
- Evaluate approaches to deadlock avoidance
- Understand recovery from deadlocks

System model

- **Finite** number of resources
  - Distributed among *competing processes*

- Resources are *partitioned* into different ***types***
  - Each *type* has a number of identical instances
  - Resource type examples:
    - Memory space, files, I/O devices

A process must utilize resources in a sequence

- **Request**
  - Requesting resource must *wait until it can acquire* resource
  - `request(),open(),allocate()`
- **Use**
  - Operate on the resource
- **Release**
  - `release(),close(),free()`

For kernel managed resources, the OS maintains a system resource table

- Is the resource free?
  - Record process that the resource is allocated to

- Is the resource allocated?
  - Add to queue of processes waiting for resource

- For resources not managed by the OS
  - Use `wait()` and `signal()` on semaphores

Preemptable resources

- Can be taken away from process owning it with no ill effects
- Example: Memory
  - Process **B**'s memory can be taken away and given to process **A**
    - Swap **B** from memory, write contents to backing store, swap **A** in and let it use the memory

Non-preemptable resources

- Cannot be taken away from a process without causing the process to fail
- If a process has started to burn a CD
  - Taking the CD-recorder away from it and giving it to another process?
    - Garbled CD
    - CD recorders are not preemptable at an arbitrary moment
- In general, **deadlocks involve non-preemptable resources**

Some notes on deadlocks

- The OS typically does not provide deadlock prevention facilities
- Programmers are *responsible* for designing deadlock free programs

Deadlock: Formal Definition

- *A set of processes is deadlocked if each process in the set is waiting for an event that only another process in the set can cause.*

- Because all processes are waiting, none of them can cause events to wake any other member of the set
  - Processes continue to **wait forever**

Deadlocks: Necessary Conditions (I)

- **Mutual Exclusion**
  - At least one resource held in *nonsharable* mode
  - When a resource is being used
    - Another requesting process must wait for its release
- **Hold-and-wait**
  - A process must hold one resource
  - Wait to acquire additional resources
    - Which are currently held by other processes

Deadlocks: Necessary Conditions (II)

- **No preemption**
  - Resources cannot be preempted
  - Only voluntary release by process holding it

- **Circular wait**
  - A set of $\{P_0, P_1, \ldots, P_n\}$ waiting processes must exist
    - $P_0 \rightarrow P_1$; $P_1 \rightarrow P_2$, …, $P_n \rightarrow P_0$
  - Implies hold-and-wait

Methods for handling deadlocks

- Use protocol to **prevent** or **avoid** deadlocks
  - Ensure system never enters a deadlocked state
- Allow system to enter deadlocked state; BUT
  - **Detect** it and **recover**
- Ignore problem, pretend that deadlocks never occur

When is ignoring the problem viable?

- When they occur infrequently (once per year)
  - Ignoring is the *cheaper* solution
  - Prevention, avoidance, detection and recovery
    - Need to run constantly

Four strategies for dealing with deadlocks

- Ignore the problem
  - May be if you ignore it, it will ignore you
- Detection and Recovery
  - Let deadlocks occur, detect them, and take action
- Deadlock avoidance
  - By careful resource allocation
- Deadlock prevention
  - By structurally negating one of the four required conditions

Deadlock Prevention

- Ensure that **one** of the necessary conditions for deadlocks *cannot* occur
  1. Mutual exclusion
  2. Hold and wait
  3. No preemption
  4. Circular wait

Mutual exclusion must hold for non-sharable resources, but …

- Sharable resources do not require mutually exclusive access
  - *Cannot be involved* in a deadlock
- A process never needs to wait for sharable resource
  - Read-only files
- Some resources are *intrinsically nonsharable*
  - So denying mutual exclusion often not possible

Deadlock Prevention: Ensure hold-and-wait never occurs in the system [Strategy 1]

- Process must request and be allocated all its resources **before** execution
  - Resource requests must precede other system calls

- E.g. copy data from DVD drive, sort file & print
  - Printer needed only at the end
  - BUT process will hold printer for the *entire* execution

Deadlock Prevention: Ensure hold-and-wait never occurs in the system [Strategy 2]

- Allow a process to request resources *only when it has none*
  - *Release* all resources, *before requesting* additional ones
- E.g. copy data from DVD drive, sort file & print
  - First request DVD and disk file
    - Copy and release resources
  - Then request file and printer

Disadvantages of protocols doing hold-and-wait

- **Low resource utilization**
  - Resources are allocated but unused for long durations

- **Starvation**
  - If a process needs several popular resources
    - Popular resource might always be *allocated to some other* process

Deadlock Prevention: Eliminate the preemption constraint [1/2]

- {C1} If a process is holding some resources
- {C2} Process requests another resource
    - Cannot be immediately allocated

- All resources currently held by process is **preempted**
    - Preempted resources added to list of resources process is waiting for

Deadlock Prevention: Eliminate the preemption constraint [2/2]

- Process requests resources that are not currently available
  - If resources allocated to another waiting process
    - Preempt resources from the second process and assign it to the first one
- Often applied when resource state can be ***saved and restored***
  - CPU registers and memory space
  - Unsuitable for tape drives

Deadlock Prevention: Eliminating Circular wait

- Impose **total ordering** of all resource types
  - Assign each resource type a unique number
  - One-to-one function `F:R→N`

```
F(tape drive) = 1;
F(printer) = 12
```

1. Request resources in ***increasing* order**
2. If several instances of a resource type needed?
   - Single request for all them must be issued

Deadlock Prevention: **Summary**

- Prevent deadlocks by **restraining** how requests are made.
  - Ensure at least 1 of the 4 conditions cannot occur

- Side effects:
  - Low device utilization
  - Reduced system throughput

Deadlock avoidance

- Require *additional* information about **how** resources are to be requested
- Knowledge about sequence of requests and releases for processes
  - Allows us to decide if resource allocation *could cause a future deadlock*
  - Process P: Tape drive, then printer
  - Process Q: Printer, then tape drive

Deadlock avoidance: Handling resource requests

- For each resource request:
  - Decide whether or not process should wait
    - To avoid possible **future** deadlock

- Predicated on:
  1. Currently available resources
  2. Currently allocated resources
  3. Future requests and releases of each process

Avoidance algorithms differ in the amount and type of information needed

- **Resource allocation state**
  - Number of available and allocated resources
  - Maximum demands of processes
- Dynamically **examine** resource allocation state
  - Ensure circular-wait cannot exist
- Simplest model:
  - Declare maximum number of resources for each type
  - Use information to avoid deadlock

Safe sequence

- **Sequence** of processes $<P_1, P_2, \ldots, P_n>$ for the current allocation state
- Resource requests made by P_i can be satisfied by:
  - Currently available resources
  - Resources held by P_j where $j < i$
    - If needed resources not available, P_i can wait
  - In general, when P_i terminates, P_{i+1} can obtain its needed resources
- If no such sequence exists: system state is **unsafe**

Safe states and deadlocks

- A system is safe ONLY IF there is a **safe sequence**
- A safe state is not a deadlocked state
  - Deadlocked state is an unsafe state
  - Not all unsafe states are deadlocks

Unsafe states

- A unsafe state *may lead* to deadlock
- **Behavior** of processes controls unsafe states
- Cannot prevent processes from requesting resources such that deadlocks occur

Banker's Algorithm

- Designed by Dijkstra in 1965
- Modeled on a small-town banker
  - Customers have been extended lines of credit
  - Not ALL customers will need their maximum credit immediately
- Customers make loan requests from time to time

Crux of the Banker's Algorithm

- Consider each request as it occurs
  - See if granting it is safe
- If safe: grant it;   If unsafe: postpone
- For safety banker checks if he/she has **enough** to satisfy some customer
  - If so, that customer's loans are assumed to be repaid
  - Customer closest to limit is checked next
  - **If all loans can be repaid; state is safe: loan approved**

Banker's Algorithm: Managing the customers.
Banker has only reserved 10 units instead of 22

	Has	Max
A	0	6
B	0	5
C	0	4
D	0	7

Free: 10

SAFE

	Has	Max
A	1	6
B	1	5
C	2	4
D	4	7

Free: 2

Delay all requests except C

SAFE

	Has	Max
A	1	6
B	2	5
C	2	4
D	4	7

Free: 1

UNSAFE

A customer may not need the entire credit line. But the banker cannot count on this behavior

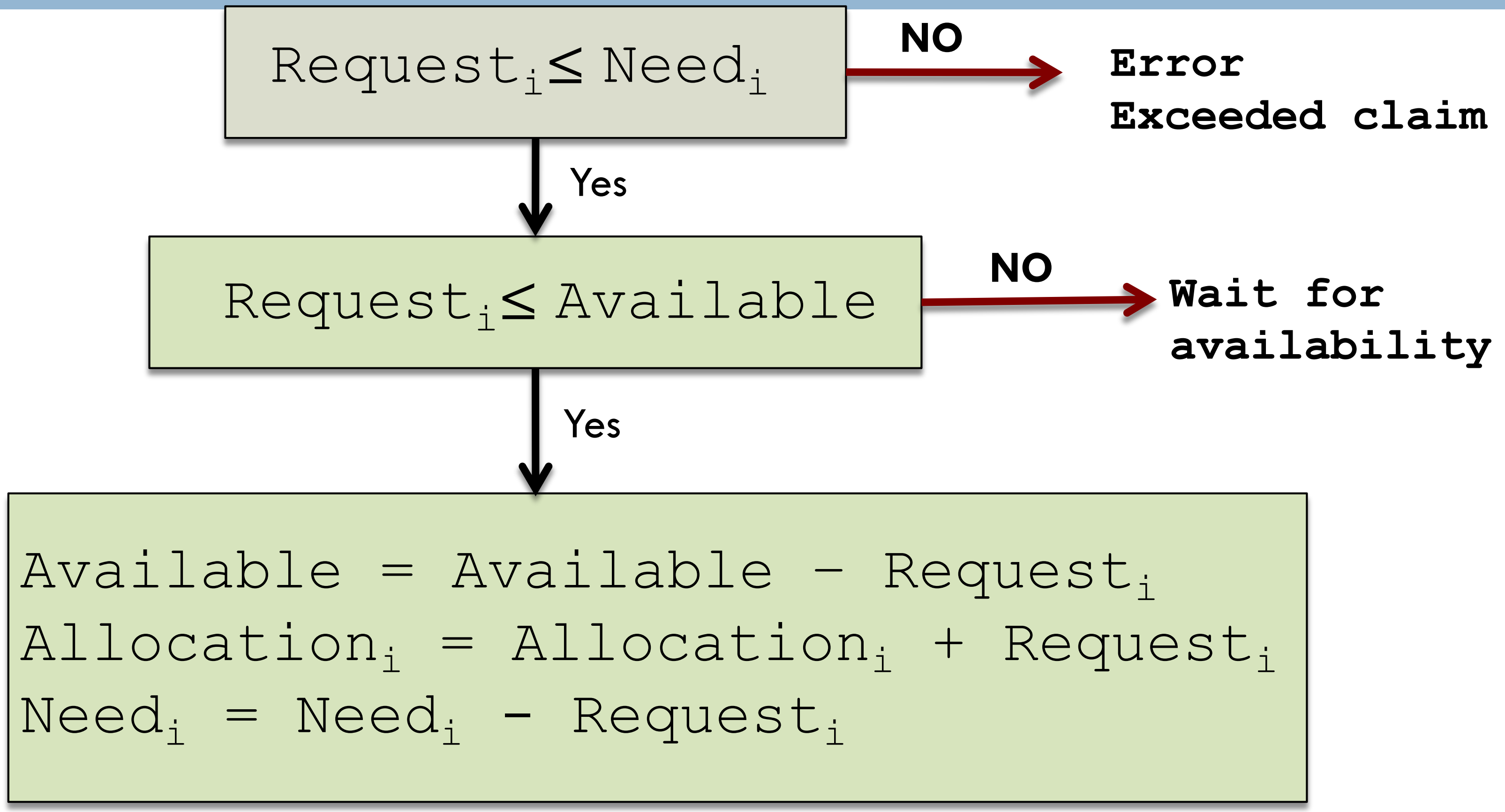
There is ONLY ONE resource: Credit

Banker's algorithm: Crux

- Declare **maximum** number of resource instances needed
  - Cannot exceed resource thresholds

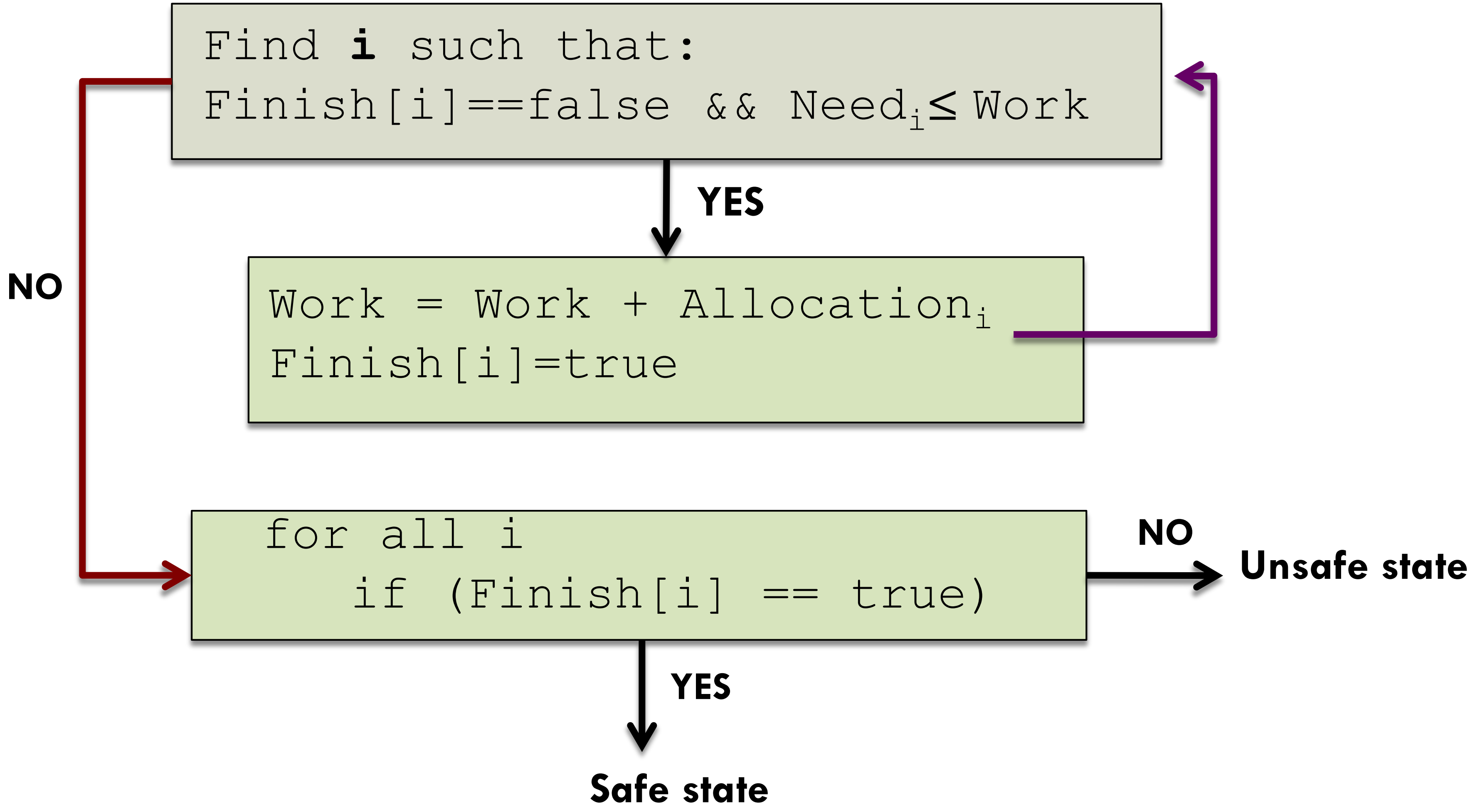
- Determine if resource allocations leave system in a safe state

Bankers Algorithm: Resource-request



Bankers Algorithm: Safety

Initialize `Work = Available`



Recovery from deadlock

- Automated or manual

- OPTIONS
  - Break the circular wait: **Abort** processes
  - **Preempt** resources from deadlocked process(es)

Breaking circular wait: Process termination

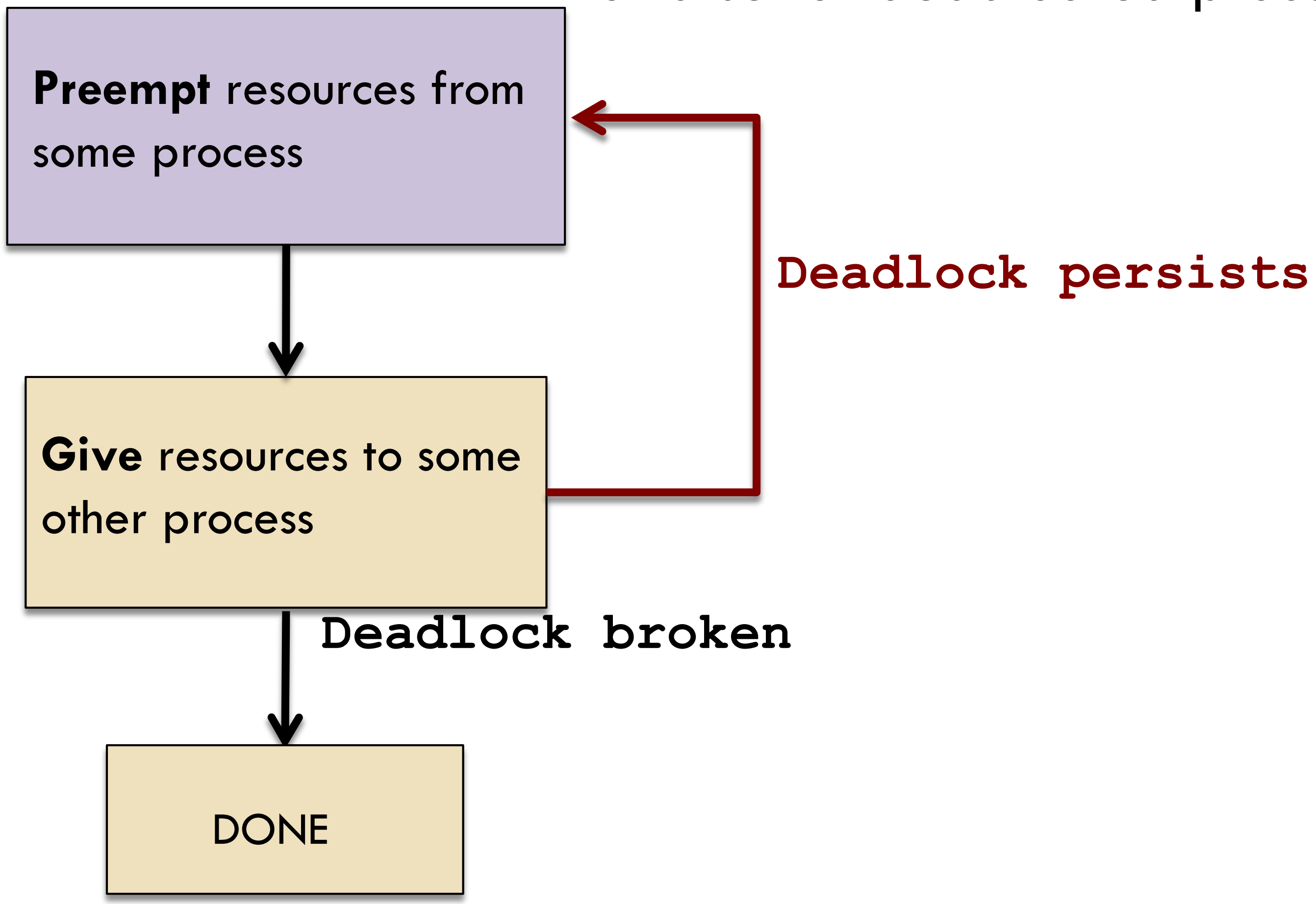
- Abort **all** deadlocked processes

- Abort processes **one at a time**
  - After each termination, check if deadlock *persists*

- <u>Reclaim all resources</u> allocated to terminated process

Deadlock recovery: Resource preemption

For a set of deadlocked processes



Resource preemption: Issues

- Selecting a victim
  - Which resource and process
  - Order of preemption to minimize cost
- Starvation
  - Process can be selected for preemption *finite* number of times

Livelocks

- Polling (busy waits) used to enter critical section or access a resource
  - Typically used for a short time when overhead for suspension is considered greater
- In a livelock two processes need each other's resource
  - Both run and make no progress, but neither process blocks
  - **Use CPU quantum over and over without making progress**

Livelocks do occur

- If `fork` fails because process table is full
  - Wait for some time and try again
- But there could be a collection of processes each trying to do the same thing

Memory Management

Objectives:

- Understand address binding and address spaces
- Explain contiguous memory allocations: including their advantages and disadvantages
- Analyze the key constructs underpinning paging systems including hardware support, shared pages, and structure of page tables
- Explain memory protection in paging environments
- Explain segmentation based approaches to memory management alongside settings in which they are particularly applicable

Memory Management: Why?

- Main objective of system is to execute programs
- Programs and data must be **in memory** (*at least partially*) during execution
- To improve CPU utilization and response times
  - **Several** processes need to be memory resident
  - Memory needs to be **shared**

Memory Unit

- Sees only a **stream** of memory addresses
- Oblivious to
  - ***How*** these addresses are generated
    - Instruction counter, indexing, indirection, etc.
  - ***What*** they are for
    - Instructions or data

Why processes must be memory resident

- Storage that the CPU can access **directly**
  1. Registers in the processor
  2. Main memory
- Machine instructions take memory addresses as arguments
  - <u>None operate on disk addresses</u>
- Any instructions in execution *plus* needed data
  - Must be in memory

Processes and memory

- To execute, a program needs to be **placed** inside a process
- Process **executes**
  - Access instructions and data from memory
- Process **terminates**
  - Memory reclaimed and declared available

Binding is a mapping from one address space to the next

- Processes can reside in **any part** of the physical memory
  - First address of process need not be `x0000`
- Addresses in source program are **symbolic**
- Compiler binds symbolic addresses to **relocatable** addresses
- Loader binds relocatable addresses to **absolute** addresses

Binding can be done at … [1/2]

- Compile time
  - Known that the process will reside at location **R**
    - If location changes: recompile
  - MS-DOS .COM programs were bound this way

- Load time
  - Based on compiler generated relocatable code

Binding can be done at … [2/2]: Execution-time

- Process can be moved around during execution
  - Binding *delayed* until run time
  - Special hardware needed
  - Supported by most OS

Partitioning of memory

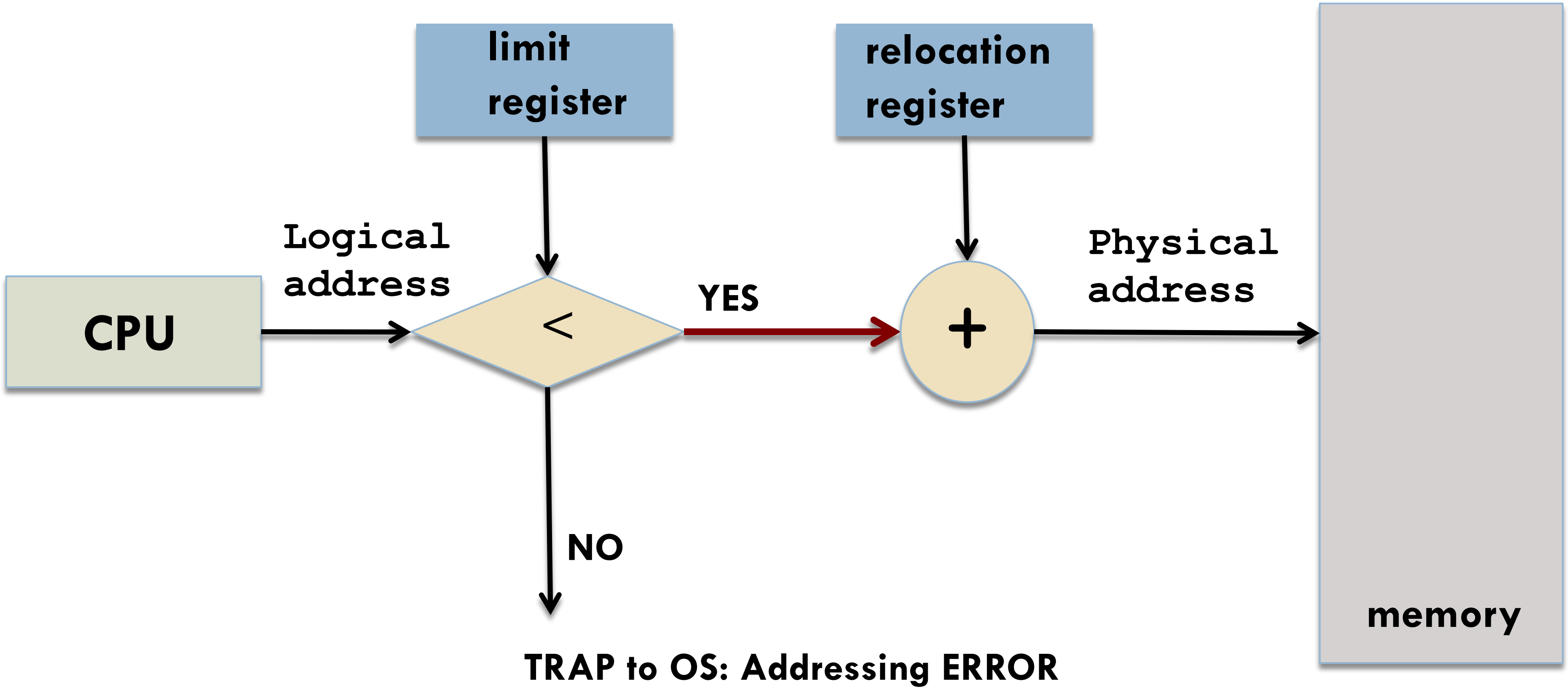
- Main memory needs to **accommodate** the OS and user processes

- Divided into two partitions
  - Resident OS
    - Usually low memory
  - User processes

Memory Mapping and Protection

- When CPU scheduler selects a process for execution
  - Relocation and limit registers reloaded as part of context switch
- Every address generated by the CPU
  - Checked against the relocation/limit registers

Memory Mapping and Protection



E.g.: relocation=100040 and limit=74600

Address spaces

- **Logical**
  - Addresses *generated* by the program running on CPU
- **Physical**
  - Addresses *seen* by the memory unit
- Logical address space
  - Set of logical addresses generated by program
- Physical address space
  - Set of physical addresses corresponding to the logical address space

Generation of physical and logical addresses

- Compile-time and load-time
  - *Identical* logical and physical addresses
- Execution time
  - Logical addresses *differ* from physical addresses
  - Logical address referred to as **virtual** address
- Runtime mapping performed in hardware
  - Memory management unit (**MMU**)

Memory management unit

- Mapping converts logical to physical addresses
- User program ***never sees*** real physical address
  - Create pointer to location
  - Store in memory, manipulate and compare
- When used as a **memory address** (load/store)
  - Relocated to physical memory

Dynamic Storage Allocation Problem

- Satisfying a request of size ***n*** from the set of available spaces
  - First fit
  - Best fit
  - Worst fit

First fit

- Scan list of segments until you find a memory-hole that is big enough
- Hole is broken up into two pieces
  - One for the process
  - The other is unused memory

Best Fit

- Scan the entire list from beginning to the end
- Pick the smallest memory-hole that is adequate to host the process

Comparing Best Fit and First Fit

- Best fit is **slower** than first fit
- Surprisingly, it also results in more **wasted memory** than first fit
  - Tends to fill up memory with tiny, useless holes

Worst fit

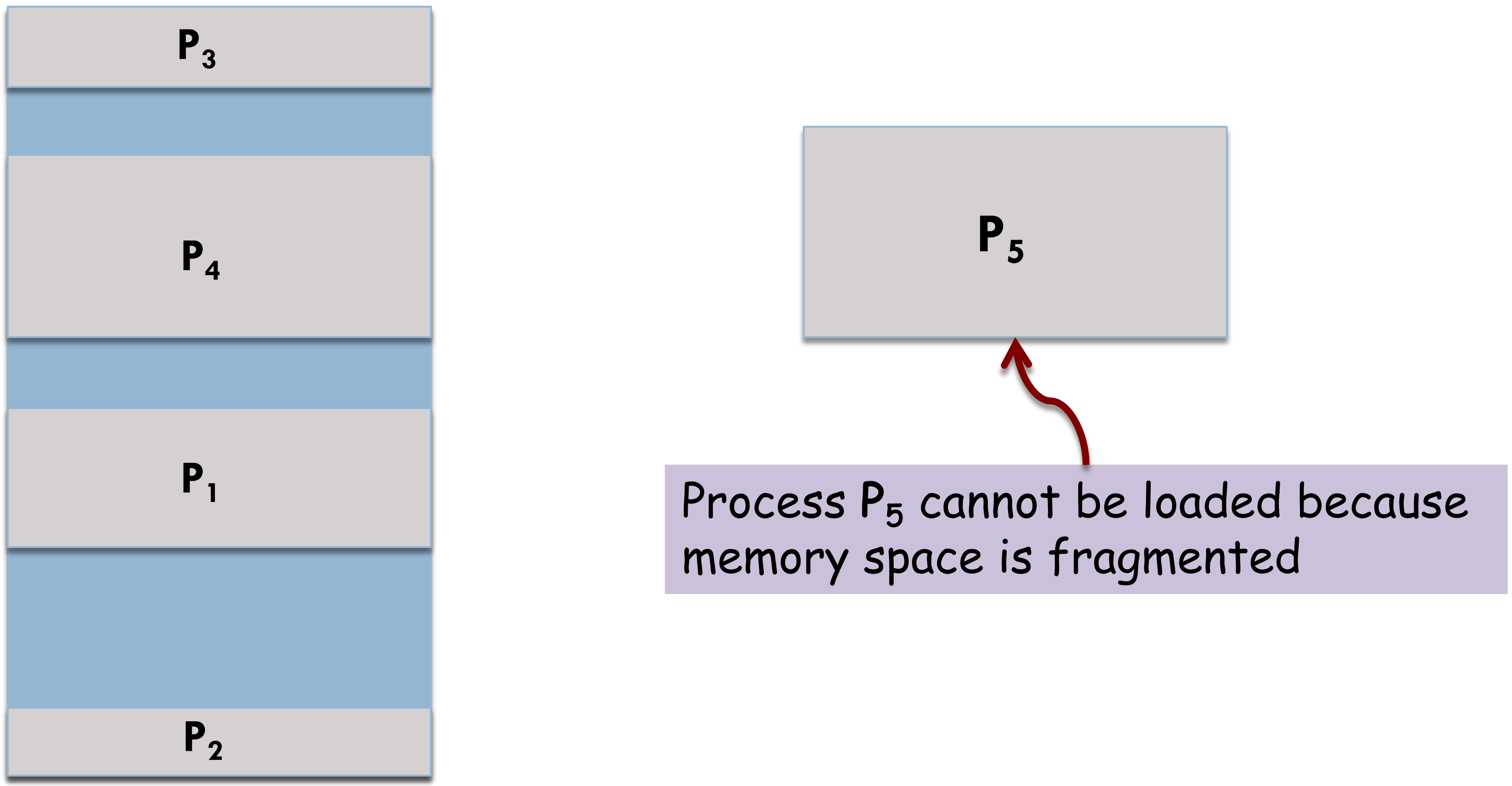
- How about going to the other extreme?
  - Always take the largest available memory-hole
  - Perhaps, the new memory-hole would be useful
- Simulations have shown that worst fit is not a good idea either

Contiguous Memory Allocation: Fragmentation

- As processes are loaded/removed from memory
  - Free memory space is **broken** into small pieces

- **External fragmentation**
  - Enough space to satisfy request; BUT
  - Available spaces are *not contiguous*

Fragmentation: Example



Fragmentation can be internal as well

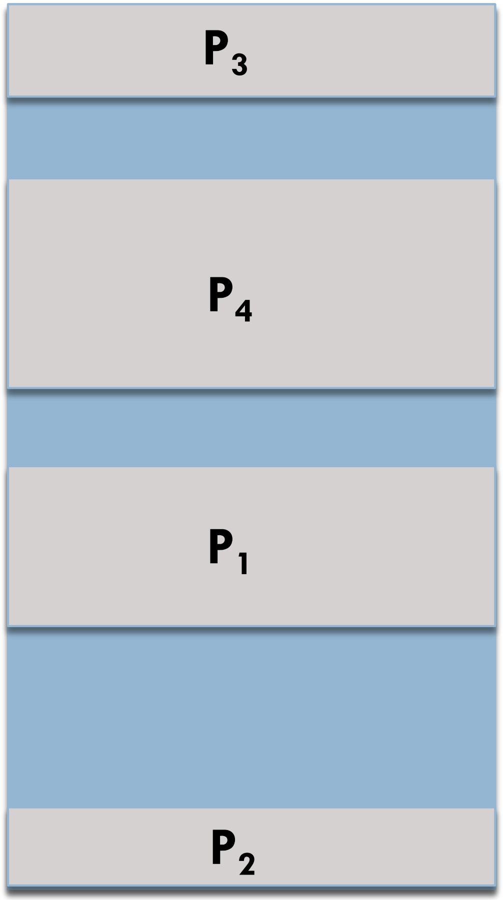
- Memory allocated to process may be *slightly larger* than requested

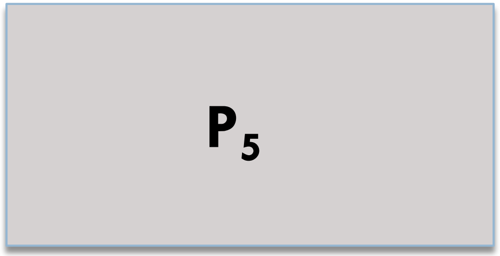
- **Internal fragmentation**
  - Unused memory is internal to blocks

Compaction: Solution to external fragmentation

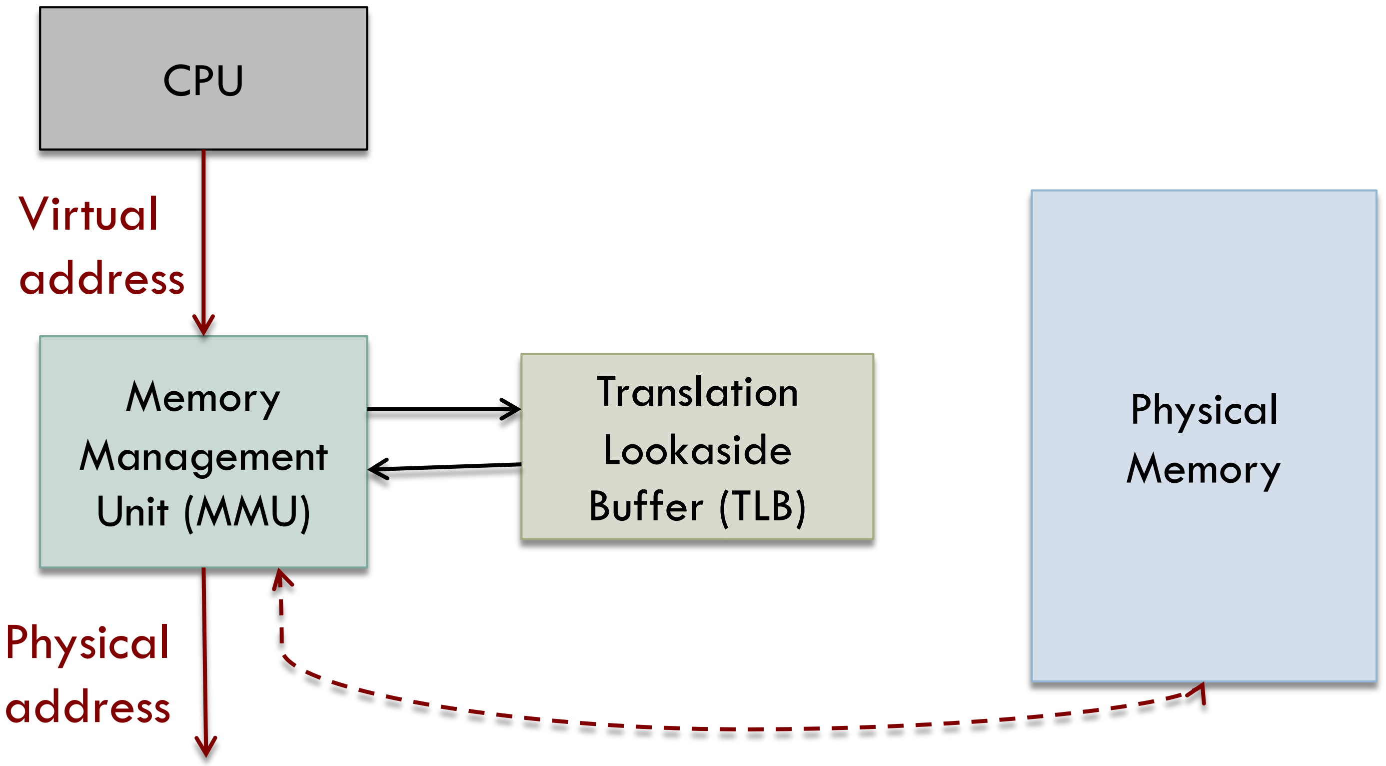
- **Shuffle** memory contents
  - Place free memory into large block
- Not possible if relocation is static
  - Load time
- Approach involves moving:
  1. Processes towards one end
  2. Gaps towards the other end

Compaction: Example





Overview of how mapping of logical and physical addresses is performed



MMU may access Physical Memory to perform translations
{PageTable may be stored there}

The Paging memory management scheme

- Physical address space of process can be **non-contiguous**

- Solves problem of fitting variable-sized memory chunks to backing store
  - Backing store has fragmentation problem
    - Compaction is impossible

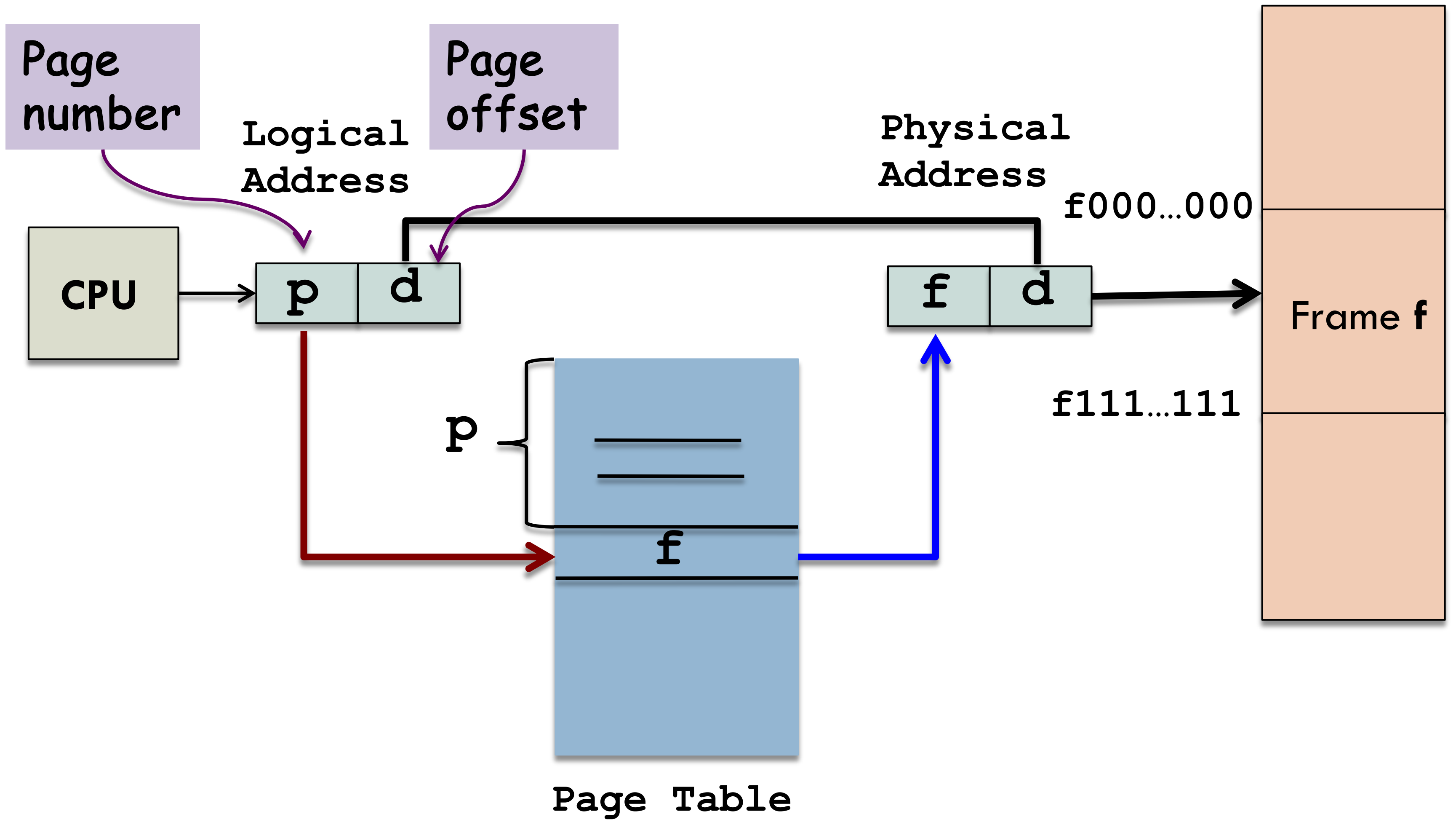
Basic method for implementing pages

- Break memory into **fixed-sized** blocks
  - Physical memory: **frames**
  - Logical memory: **pages**

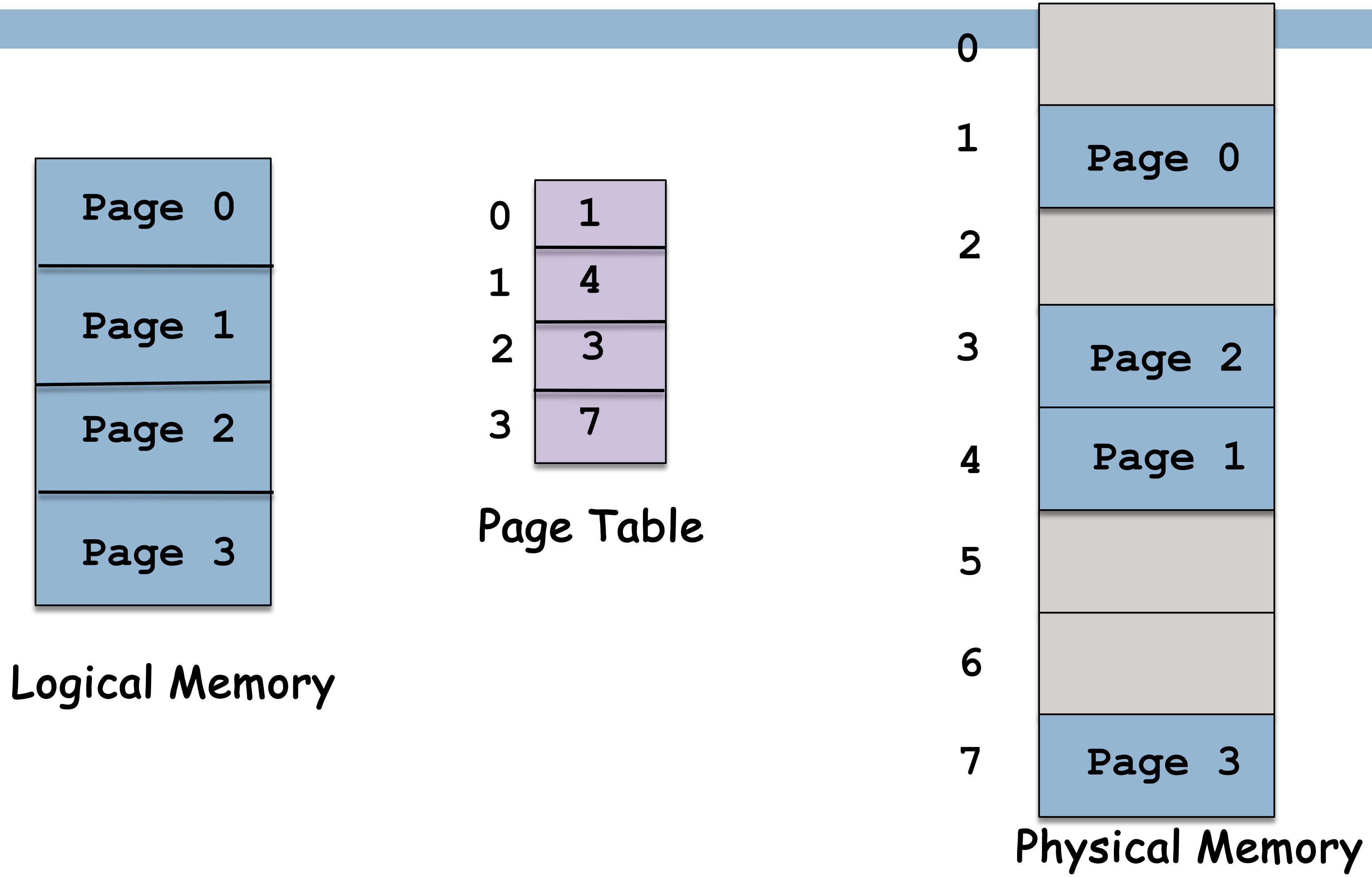
Same size

- Backing store is also divided the same way

Paging Hardware: Paging is a form of dynamic relocation



Paging: Logical and Physical Memory



Page size

- Usually a **power of 2**
  - 512 bytes – 16 MB
- Size of logical address: 2^m
- Page size: 2^n

Page number	Page offset	
m – n	**n**	**m** bits

Logical address

Paging and Fragmentation

- **No external fragmentation**
  - Free frame available for allocation to other processes
- **Internal fragmentation possible**
  - *Last frame* may not be full
  - If process size is independent of page size
    - Internal fragmentation = ½ page per process

Paging: User program views memory as a single space

- Program is **scattered** throughout memory
- User view and physical memory **reconciled** by
  - Address-translation hardware
- Process has *no way* of addressing memory outside of its page table

OS manages the physical memory

- Maintains **frame-table**; one entry per frame
  - Free or allocated?
  - If allocated: Which page of which process

- Maintains a page table for ***each process***
  - Used by CPU dispatcher to define hardware page table when process is CPU-bound
    - Paging increases context switching time

The purpose of the page table is to map virtual pages onto physical frames

- Think of the page table as a **function**
  - Takes virtual page number as an argument
  - Produces physical frame number as result

- Virtual page field in virtual address replaced by frame field
  - Physical memory address

Two major issues facing page tables

- Can be **extremely large**
  - With a 4 KB page size, a 32-bit address space has 1 million pages
  - Also, each process has its own page table
- The **mapping must be fast**
  - Virtual-to-physical mapping must be done on *every memory reference*
  - Page table lookup should not be a bottleneck

Translation look-aside buffer
Small, fast-lookup hardware cache

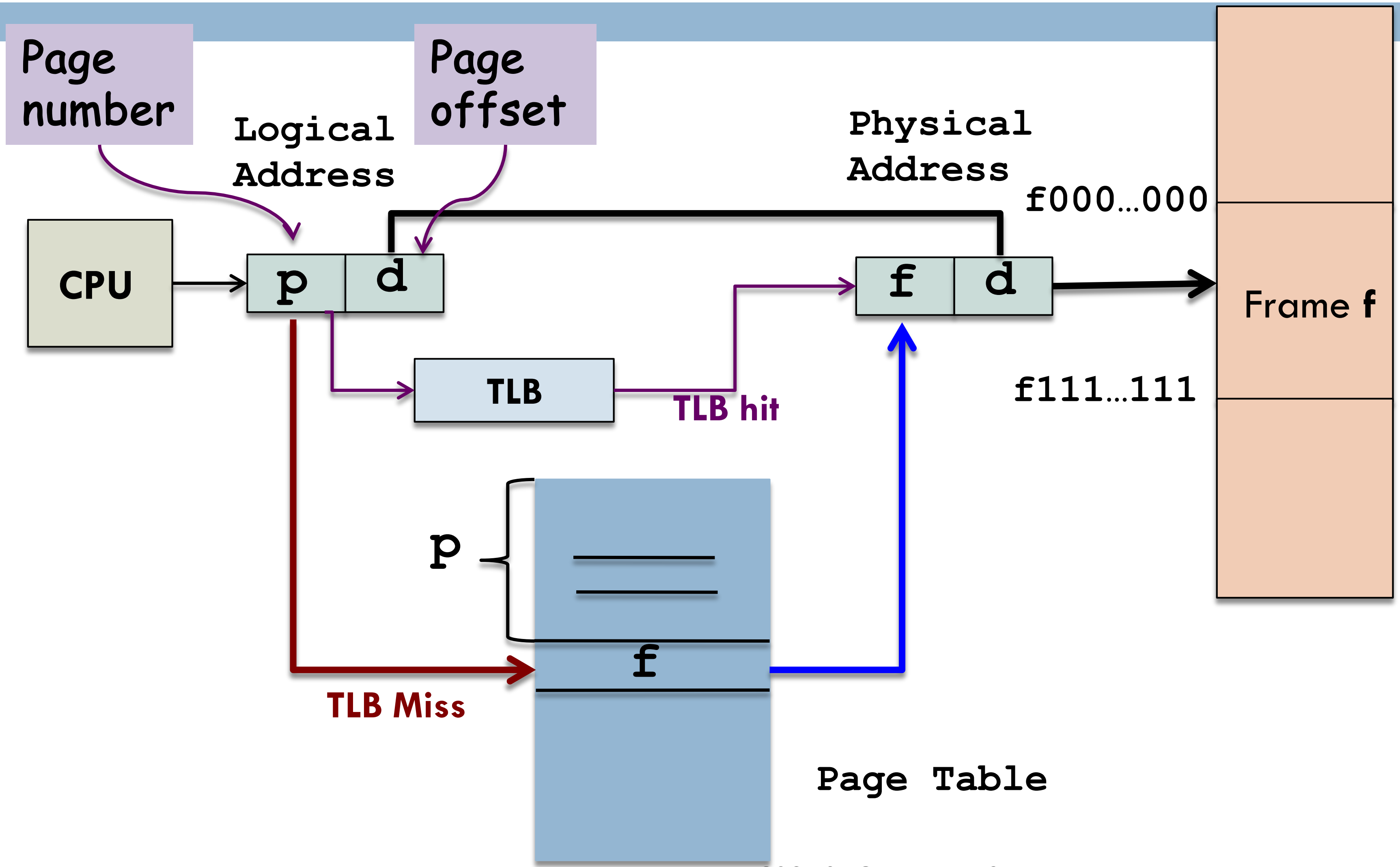
- Number of TLB entries is small (64 ~ 1024)
  - Contains few page-table entries
- Each entry of the TLB consists of 2 parts
  - A key and a value
- When the associative memory is presented with an item
  - Item is compared with all keys *simultaneously*

The purpose of the page table is to map virtual pages onto page frames

- Think of the page table as a **function**
  - Takes virtual page number as an argument
  - Produces physical frame number as result

- Virtual page field in virtual address replaced by frame field
  - Physical memory address

Paging Hardware with a TLB



Protection bits are associated with each frame

- Kept in the page table
- Bits can indicate
  - Read-write, read-only, execute
  - Illegal accesses can be trapped by the OS
- Valid-invalid bit
  - Indicates if page is in the process's logical address space

Protection Bits: Page size=2K; Logical address space = 16K

Program restricted to 0 – 10468

Logical Memory
Page 0
Page 1
Page 2
Page 3
Page 4
Page 5

Logical Memory

10K = 10240

	Frame Number	Valid/ Invalid bit
0	2	v
1	3	v
2	4	v
3	7	v
4	8	v
5	9	v
6	0	i
7	0	i

Page Table

	Physical Memory
0	
1	
2	Page 0
3	Page 1
4	Page 2
5	
6	
7	Page 3
8	Page 4
9	Page 5
	…
	Page n

Physical Memory

Reentrant Code [1/2]

- A computer program or subroutine is called **reentrant** if:
  - It can be *interrupted* in the middle of its execution and
  - Then safely called again ("re-entered") *before* its previous invocations complete execution

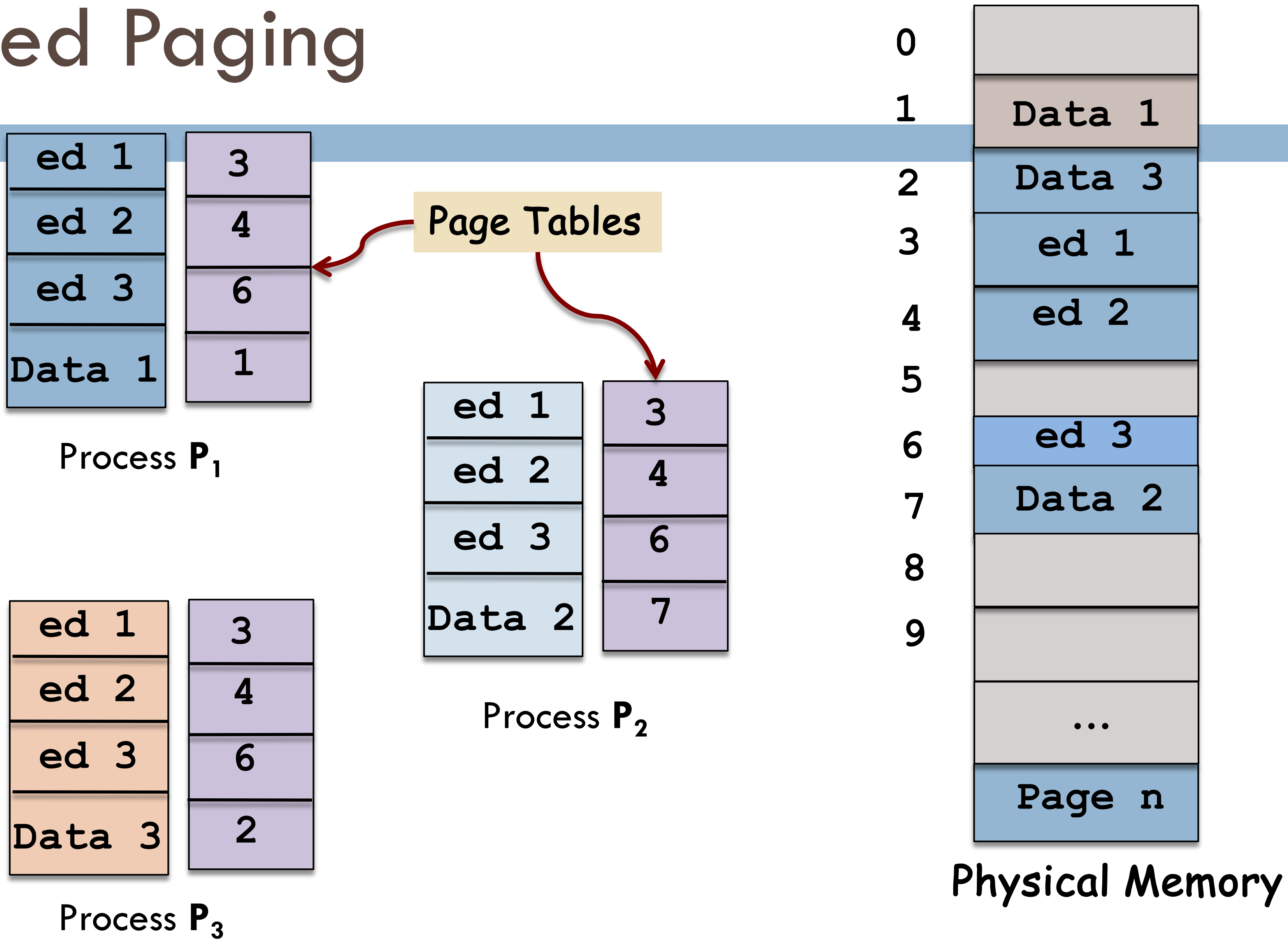
Reentrant Code [2/2]

- **Non-self-modifying**
  - Does not change during execution
- Two or more processes can:
  1. Execute same code at same time
  2. Will have different data
- Each process has:
  - Copy of registers and data storage to hold the data

Shared Pages

- System with N users
  - Each user runs a text editing program
- Text editing program
  - 150 KB of code
  - 50 KB of data space
- 40 users
  - Without sharing: 8000 KB space needed
  - With sharing : 150 + 40 x 50 = 2150 KB needed

Shared Paging



Shared Paging

- Other heavily used programs can be shared
  - Compilers, runtime libraries, database systems, etc.

- To be shareable:
  1. Code must be *reentrant*
  2. The OS *must enforce read-only* nature of the shared code

Overheads in paging: Page table and internal fragmentation

- Average process size = s
- Page size = p
- Size of each page entry = e
- Pages per process = s/p
  - se/p: Total page table space

- Total Overhead = $se/p + p/2$

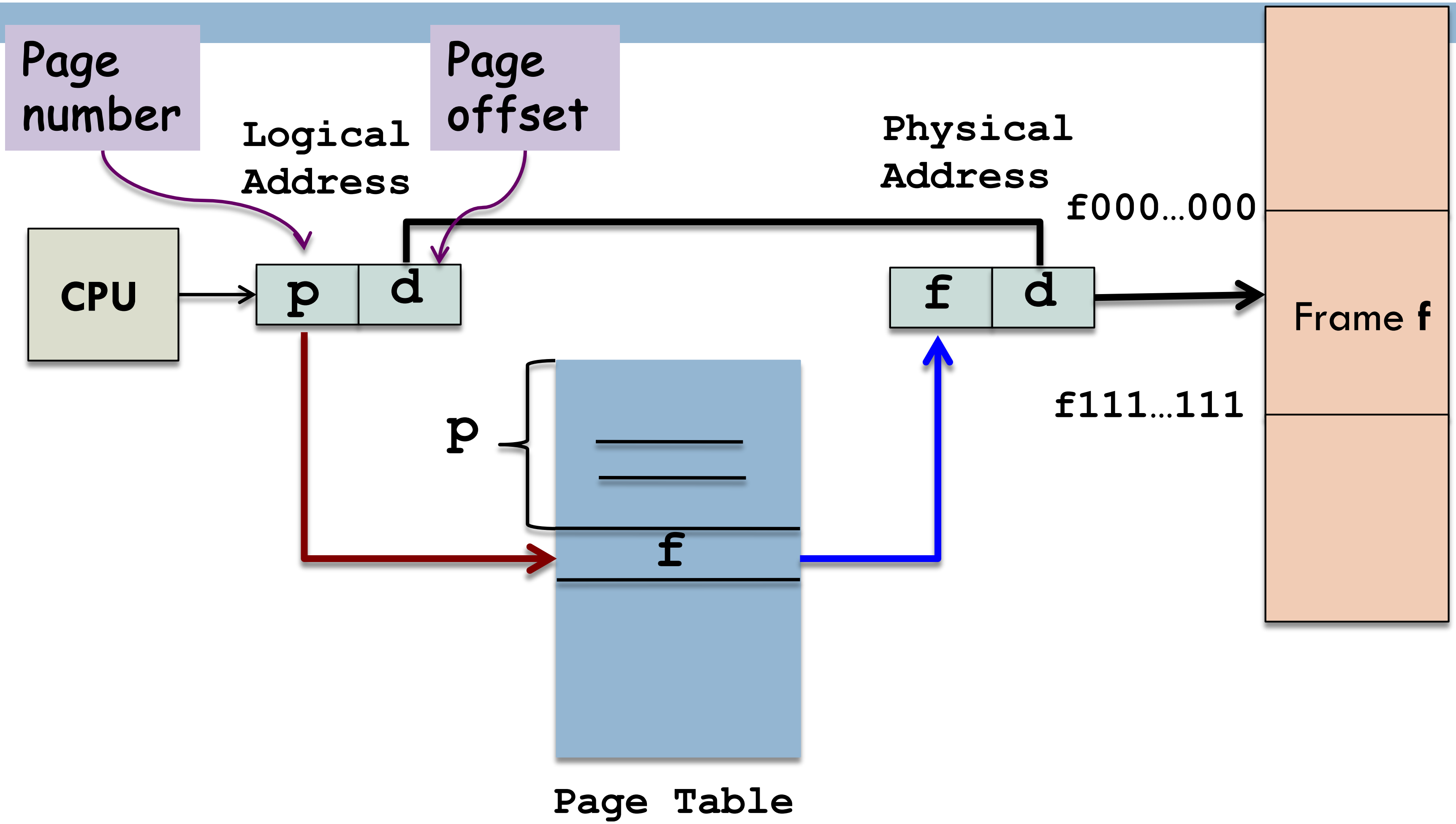
Page table overhead

Internal fragmentation loss

Typical use of the page table

- Process refers to addresses through pages' **virtual** address
- Process has page table
- Table has entries for pages that process uses
  - One slot for each page
    - Irrespective of whether it is valid or not
- Page table sorted by virtual addresses

Paging Hardware: Paging is a form of dynamic relocation



Hierarchical Paging

- Logical address spaces: $2^{32} \sim 2^{64}$
- Page size: 4KB = 2^2x 2^{10}= 2^{12}
- Number of page table entries?
  - Logical address space size/page size
  - $2^{32}/2^{12} = 2^{20} \approx 1$ million entries
- Page table entry = 4 bytes
  - Page table for process = 2^{20} x 4 = 4 MB

Issues with large page tables

- Cannot allocate page table **contiguously** in memory

- Solution:
  - Divide the page table into smaller pieces
    - **Page the page-table**

Two-level Paging

Page number	Page offset
20	12

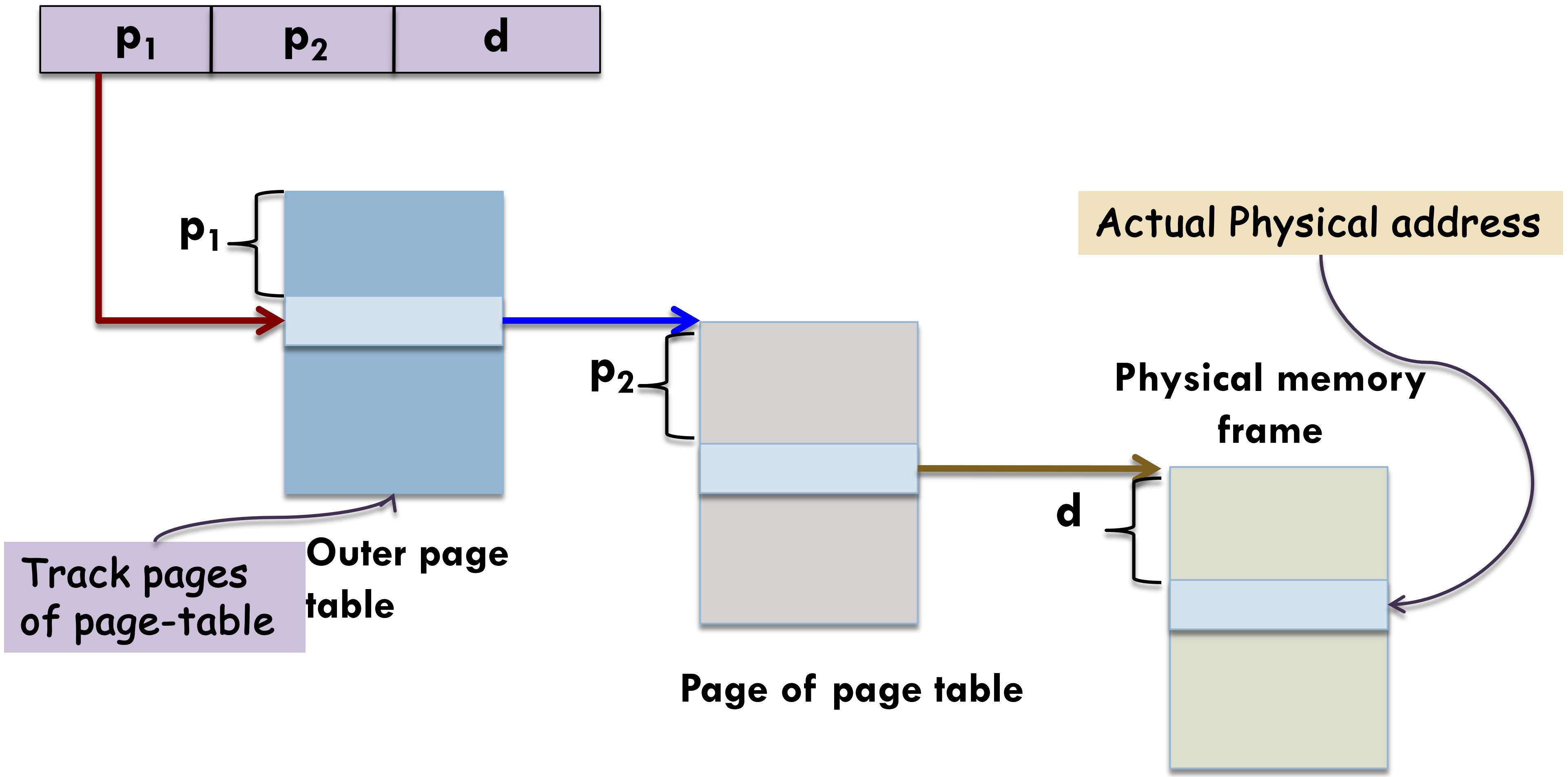
32-bit logical address

Two-level Paging

Outer Page	Inner Page	Page offset
10	10	12

32-bit logical address

Address translation in two-level paging



x86-64

- Intel: IA-64 Itanium
  - Not much traction
- AMD: x86-64
  - Intel adopted AMD's x86-64 architecture
- 64-bit address space: 2^{64} (16 exabytes)
- Currently x86-64 provides
  - 48–bit virtual address
  - Page sizes: 4 KB, 2 MB, and 1 GB
  - 4-level paging hierarchy

ARM architectures

- iPhone and Android systems use this
- 32-bit ARM
  - 4 KB and 16 KB pages
  - 1 MB and 16 MB pages

2-level paging

1-level paging

There are two levels for TLBs:
A separate TLB for data
Another for instructions

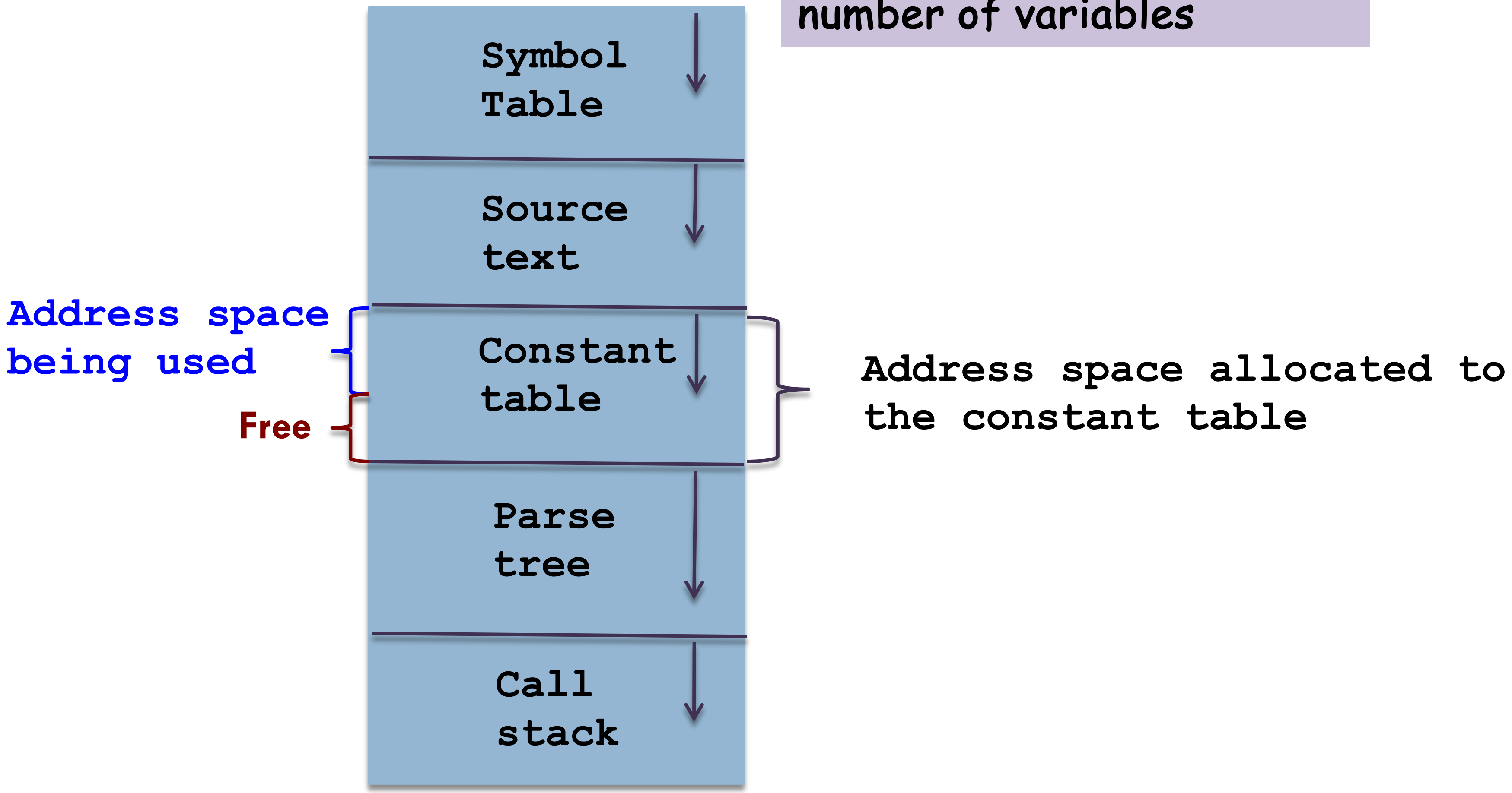
In our discussions so far …

- Virtual memory is **one-dimensional**
  - Logical addresses go from `0` to some `max` value

- Many problems can benefit from having two or more **separate** virtual address spaces

One dimensional address space with growing tables

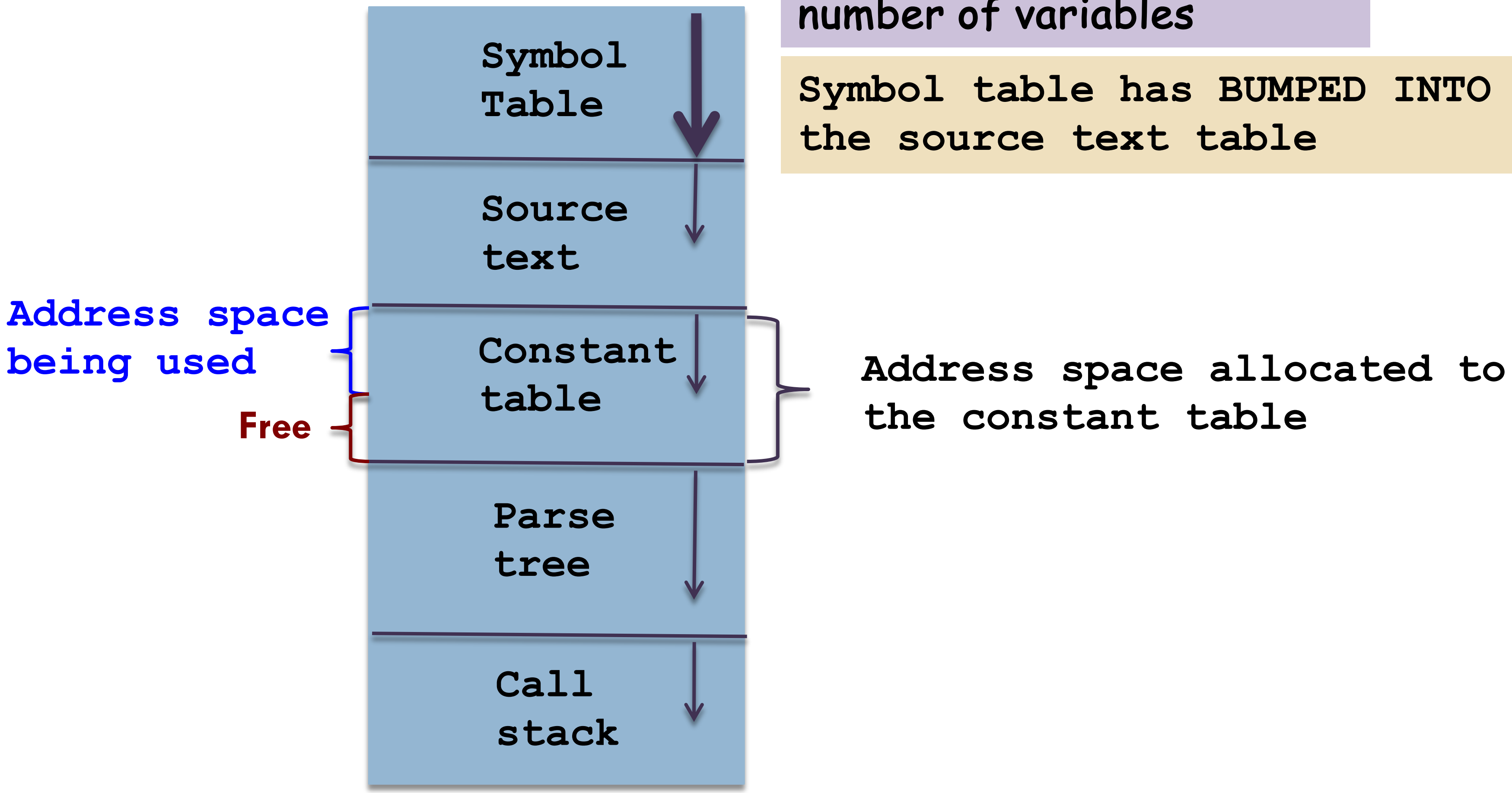
Program has an exceptional number of variables



One dimensional address space with growing tables

Program has an exceptional number of variables

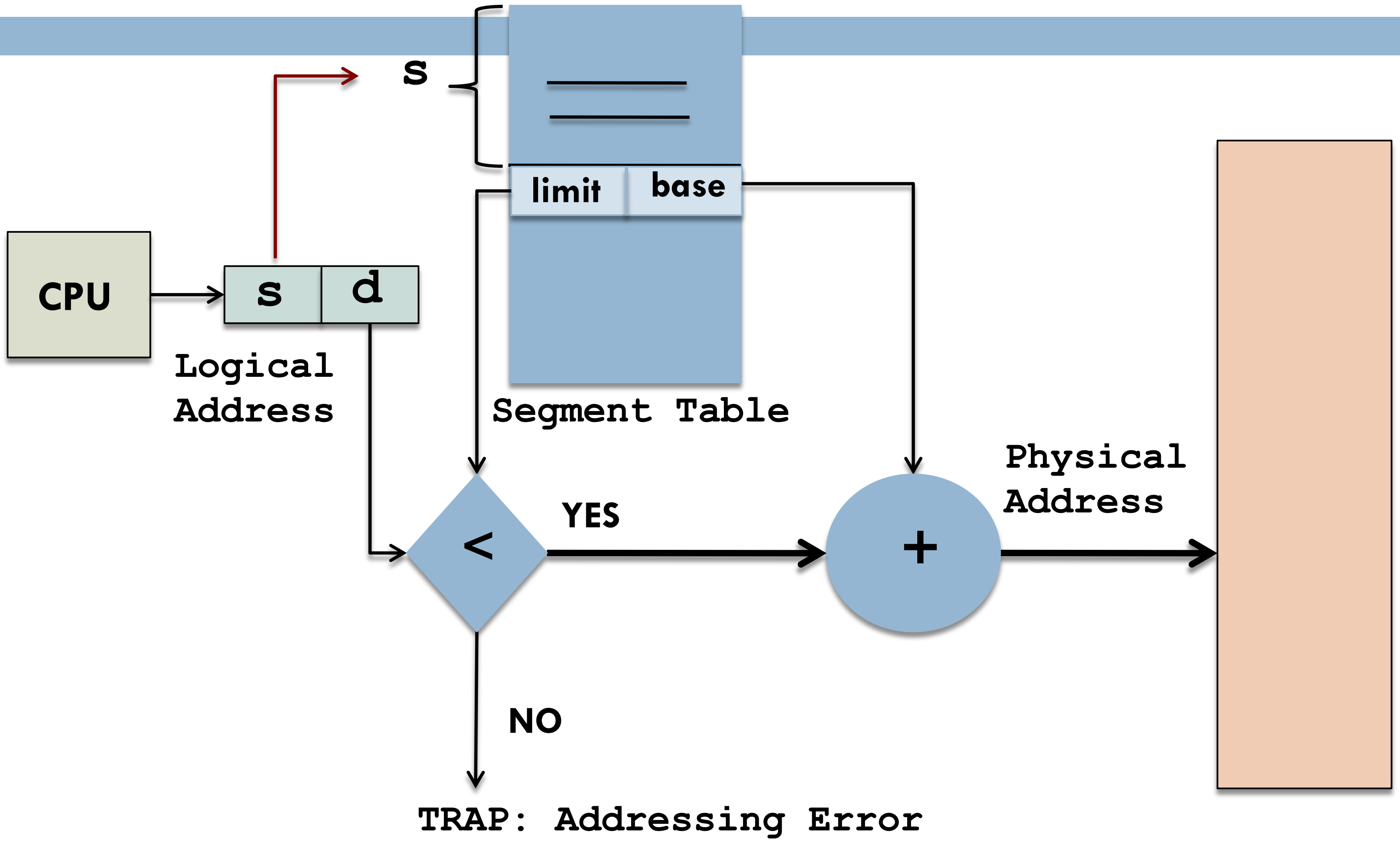
Symbol table has BUMPED INTO the source text table



Segmentation

- Logical address space is a collection of segments
- Segments have name and length
- Addresses specify
  - Segment name
  - Offset within the segment
- Tuple: `<segment-number, offset>`

Segmentation Hardware



Rationale for Paging and Segmentation

- Get a large linear address space **without** having to buy more physical memory
  - PAGING
- Allow programs and data to be broken up into **logically independent** address spaces
  - Aids Sharing AND Protection
    - Segmentation

Comparison of Paging and Segmentation

Consideration	Paging	Segmentation
How many linear address spaces are there?	1	Many
Can total address space exceed physical memory	YES	YES
Can procedures and data be distinguished and protected separately?	NO	YES
Can fluctuating table sizes be accommodated?	NO	YES

Comparison of Paging and Segmentation

Consideration	Paging	Segmentation
Should the programmer be aware the the technique is being used?	NO	YES
Is sharing of procedures between users facilitated?	NO	YES
Why was this technique invented?	To get a large linear address space without having to buy more physical memory	To allow programs and data to be broken up into logically independent address spaces and to allow sharing and protection

Segmentation with Paging

- Multics: Each program can have up to 256K independent segments
  - Each with 64K 36-bit words

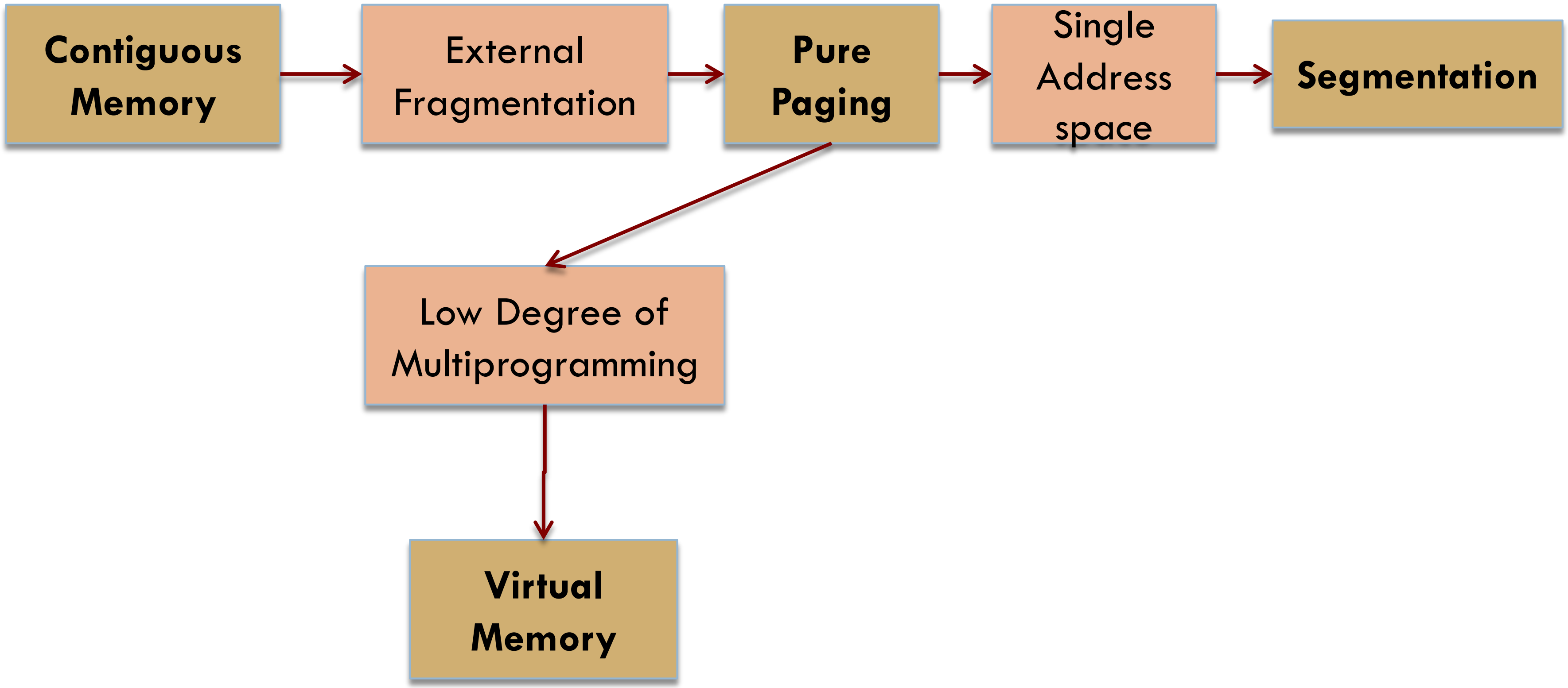
- Intel Pentium
  - 16K independent segments
  - Each segment has 10^9 32-bit words
  - Few programs need more than 1000 segments, but many programs need large segments

Virtual Memory

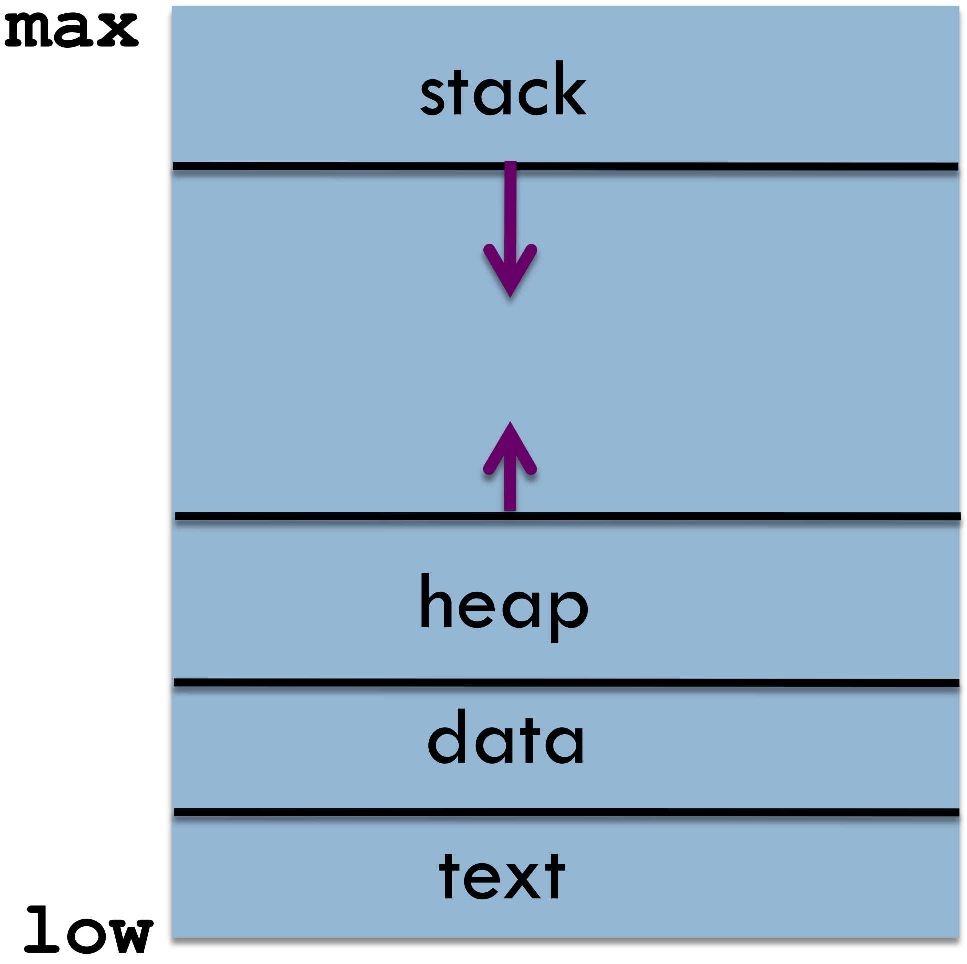
Objectives:

- Explain demand paging and page faults
- Contrast page replacement algorithms and explain Belady's anomaly
- Justify the rationale for stack algorithms
- Explain frame allocations
- Synthesize the concepts of thrashing and working sets

How we got here …



Logical view of a process in memory



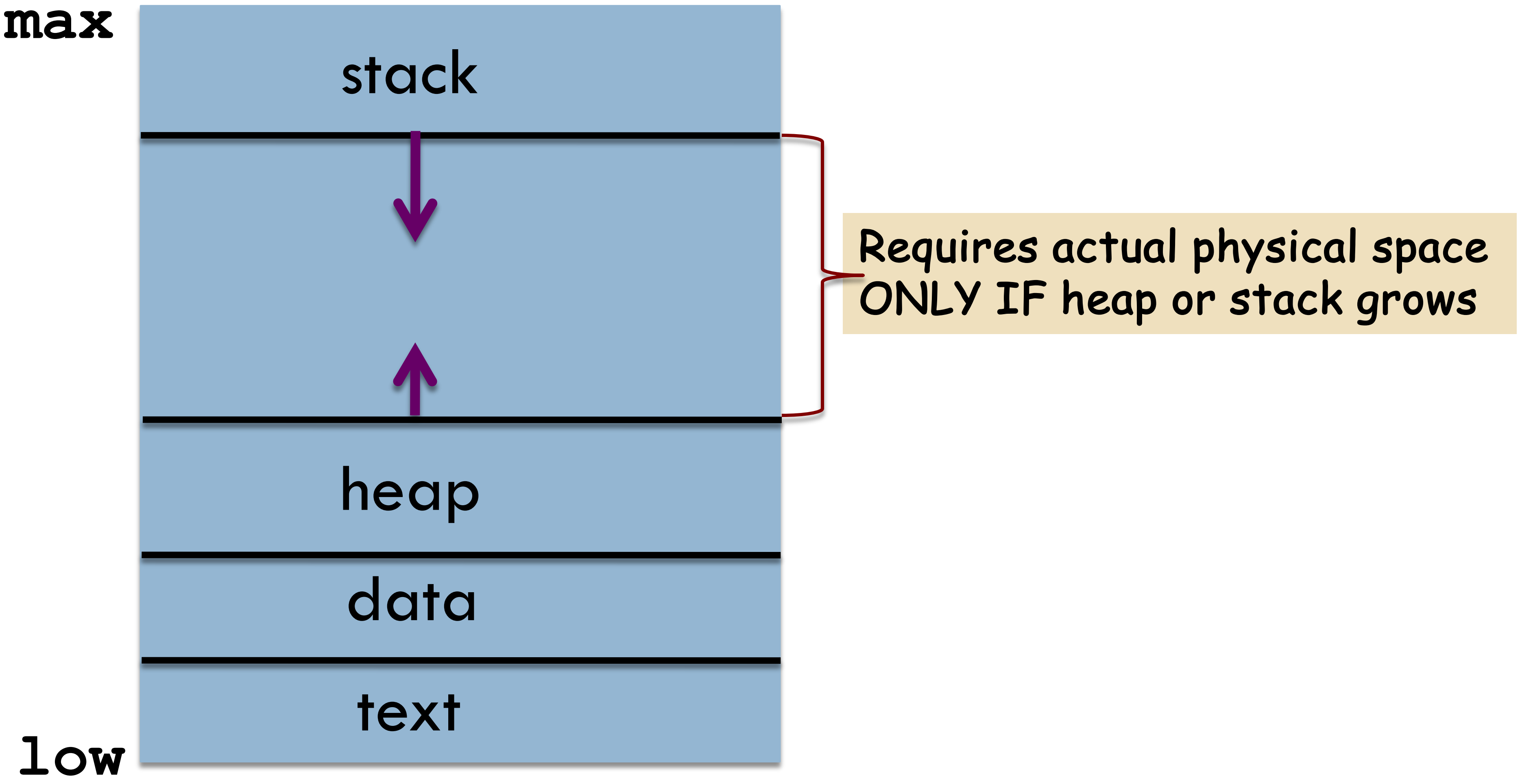
{Function parameters,
return addresses,
and local variables}

{Memory allocated dynamically during runtime}

{Global variables}

{Program code}

Logical view of a process in memory



Sparse address spaces

- Virtual address spaces with holes
- Harnessed by
  - Heap or stack segments
  - Dynamically linked libraries

Loading an executable program into memory

- What if we load the entire program?
  - We may not need the entire program

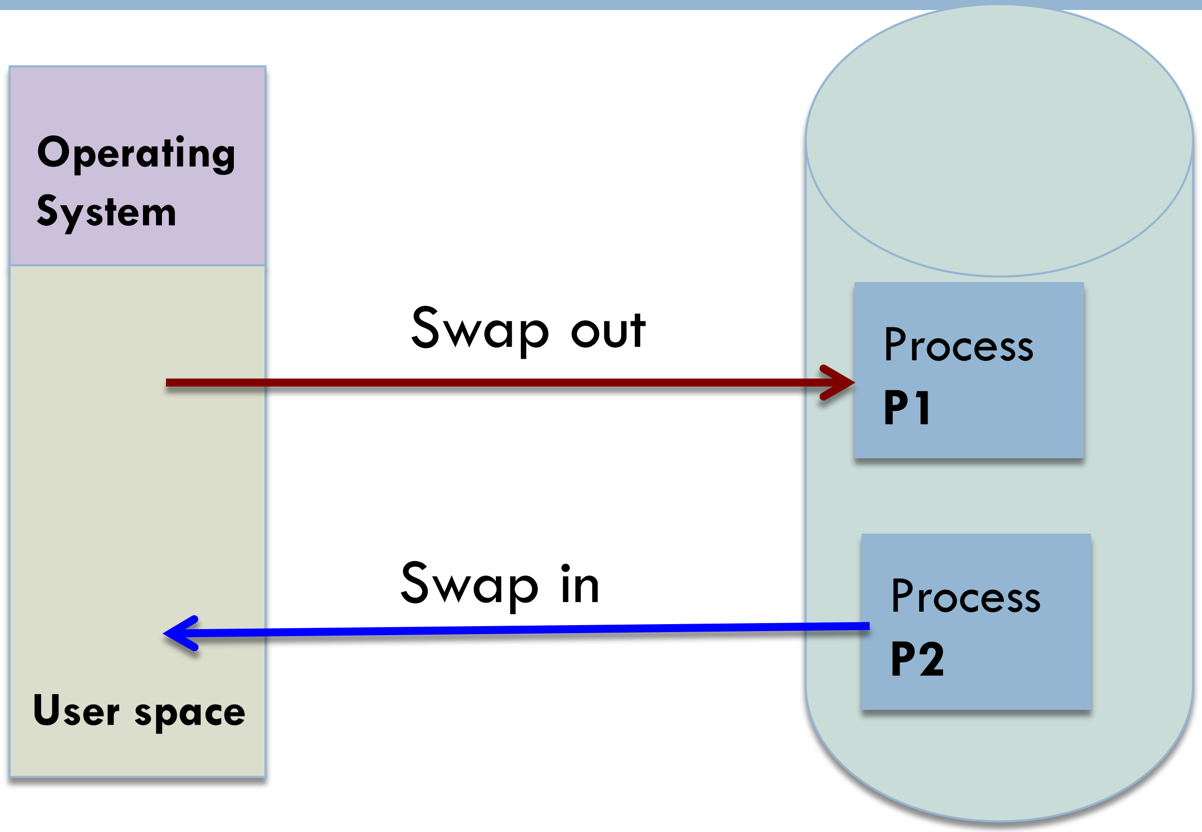
- Load pages only when they are needed
  - **Demand Paging**

Differences between the swapper and pager

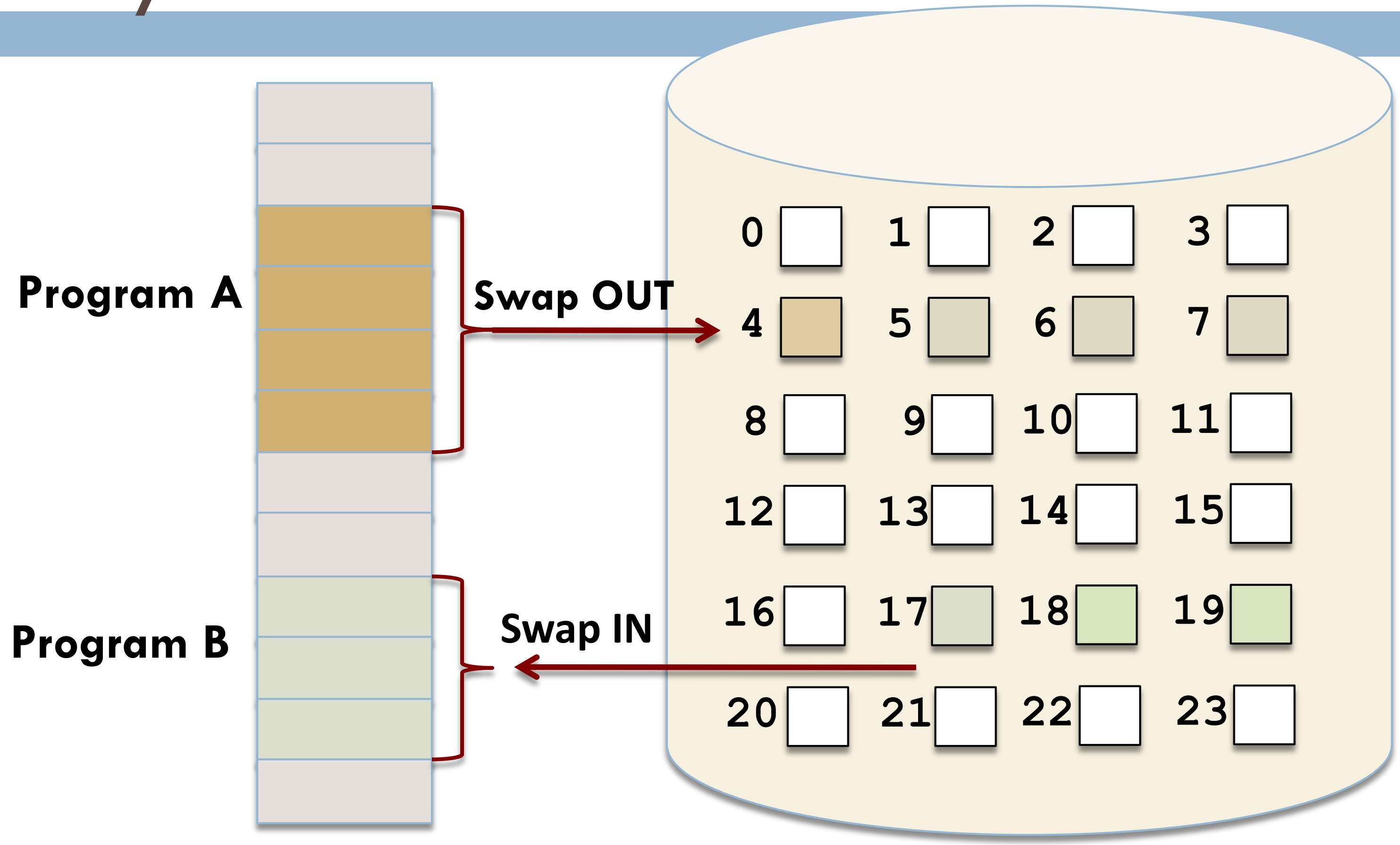
- Swapper
  - Swaps the *entire program* into memory

- **Pager**
  - Lazy swapper
  - Never swap a page into memory *unless* it is actually *needed*

Swapping: Temporarily moving a process out of memory into a backing store



Pager swapping pages in and out of physical memory



Demand Paging: Basic concepts

- **Guess** pages to be utilized by process
  - Before the process will be swapped out

- **Avoid** reading unused pages
  - Better physical memory utilization
  - Reduced I/O
    - Lower swap times

Distinguishing between pages in memory and those on disk

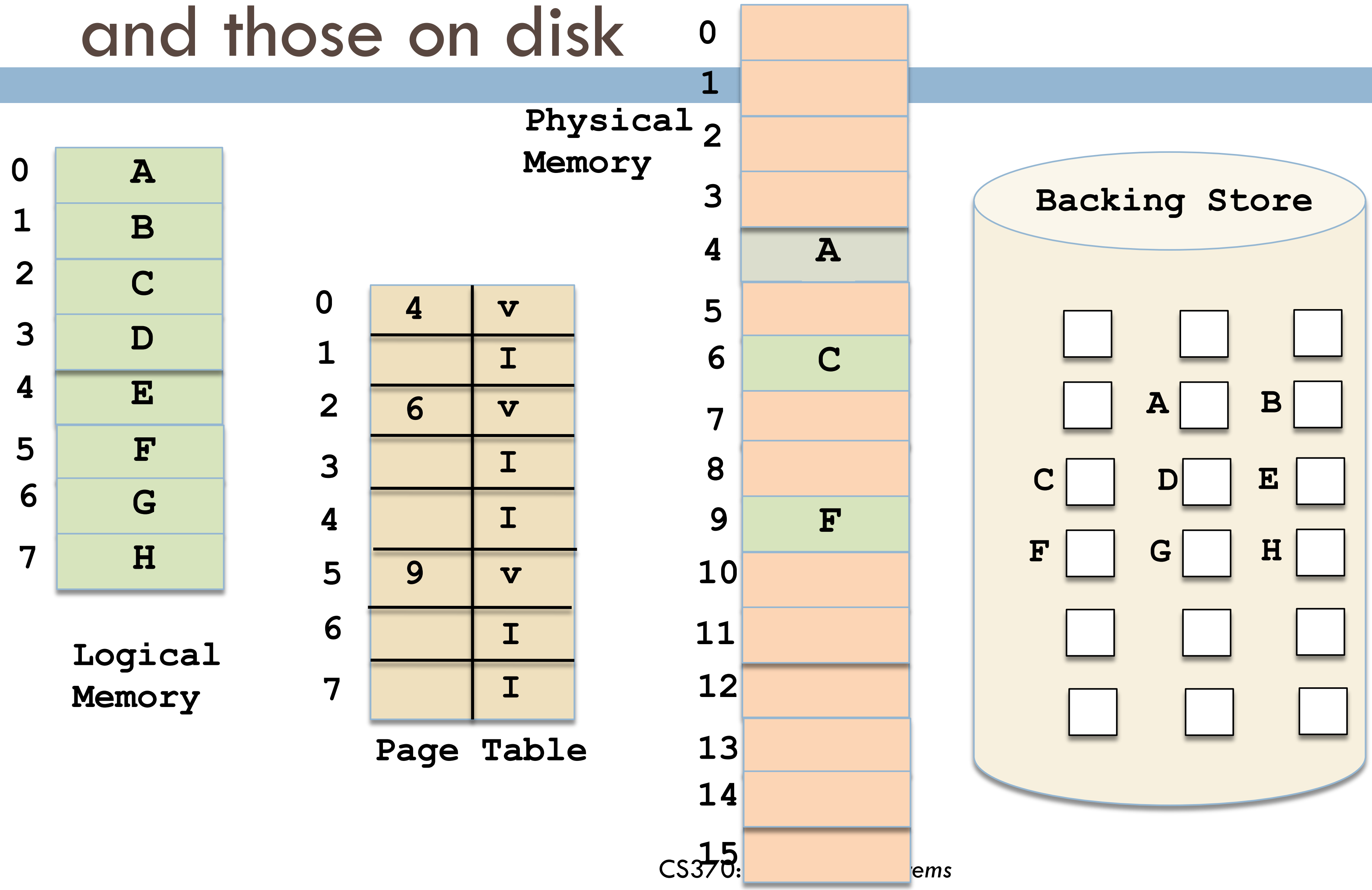
- Valid-Invalid bits
  - Associated with entries in the page table
- **Valid**
  - Page is both legal and in memory
- **Invalid**

  1. Page is *not in logical address space* of process

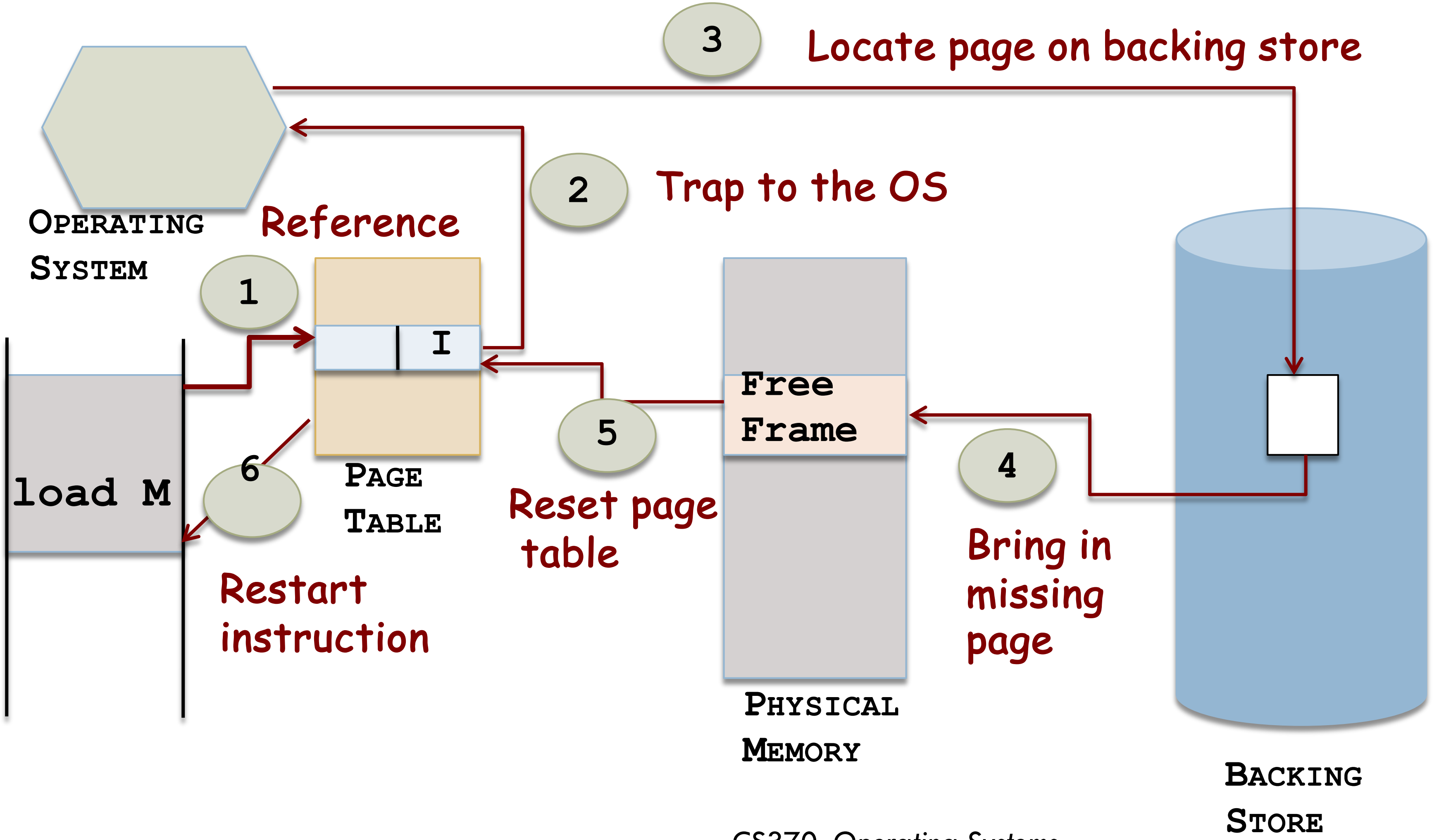
     OR

  2. Valid BUT currently *on disk*

Distinguishing between pages in memory and those on disk



Handling page faults



Pure demand paging

- Never bring a page into memory unless it is required

- Execute process with no pages in memory
  - First instruction of process will fault for the page

- Page fault to load page into memory and execute

Potential problems with pure demand paging

- Multiple page faults per instruction execution
  - One fault for instruction
  - Many faults for data

- Multiple page faults per instruction are **rare**
  - **Locality of reference**

Hardware requirements to support demand paging

- Page Table

- Secondary memory
  - Section of disk known as **swap space** is used

Restarting instructions after a page fault

- Page faults occur at **memory reference**
- Use PCB to save state of the interrupted process
- Restart process in *exactly* the same place
  - Desired page is now in memory and accessible

Effective access times

- **Without** page faults, effective access times are equal to memory access times
  - 200 nanoseconds approximately

- With page faults
  - Account for fault servicing with disk I/O

Calculating the effective access times with demand paging

p : probability of a page fault

ma : memory access time

Effective access time =

$$(1-p) \times ma + p \times \text{page-fault-time}$$

Components of page-fault servicing

Service interrupt	Read in the page	Restart process
1~100 μS	Latency : 3 mS Seek : 5 mS	1~100 μS

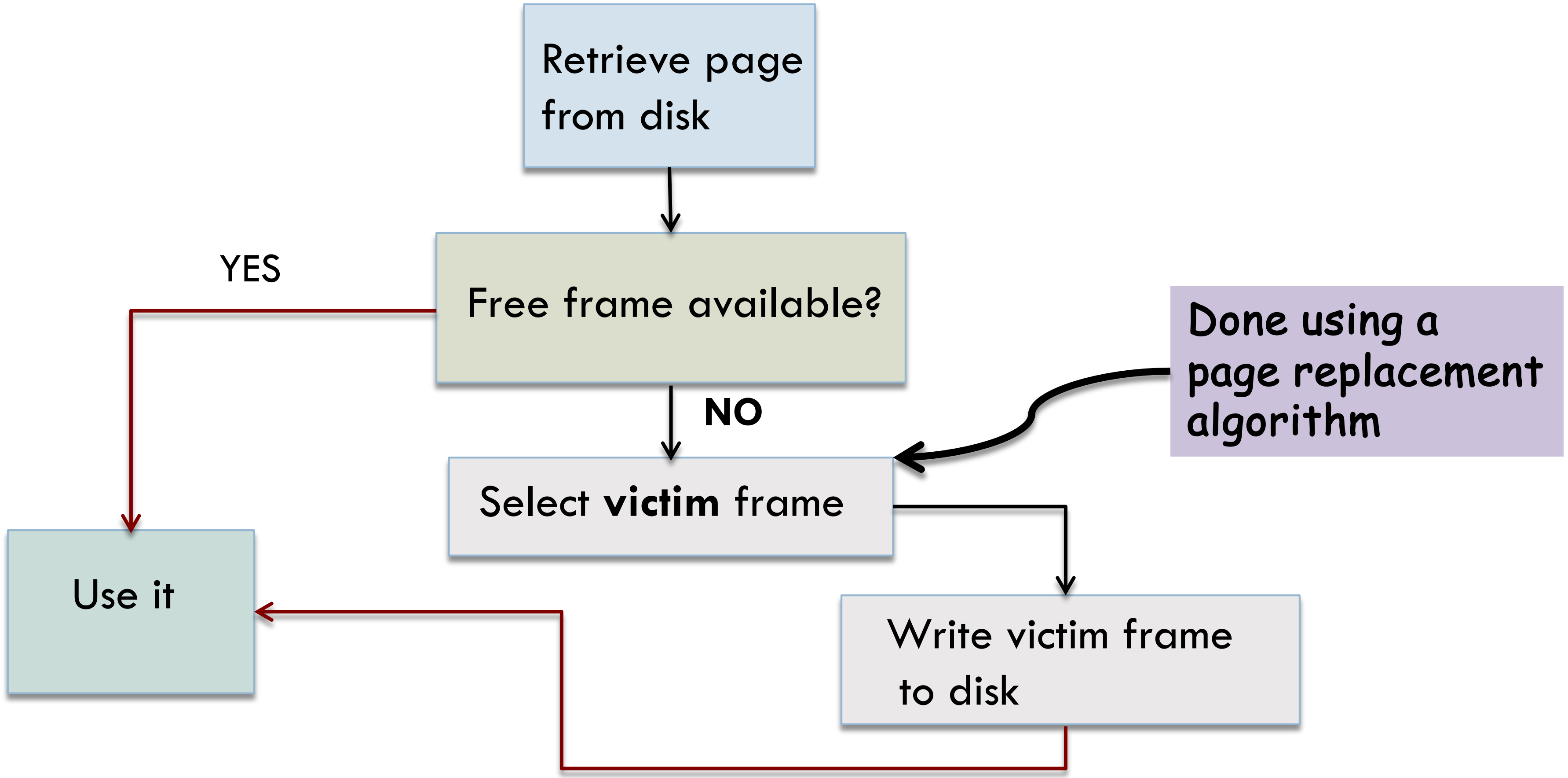
Page replacement

- If no frame is free
  - Find one that is not currently being used
    - Use it

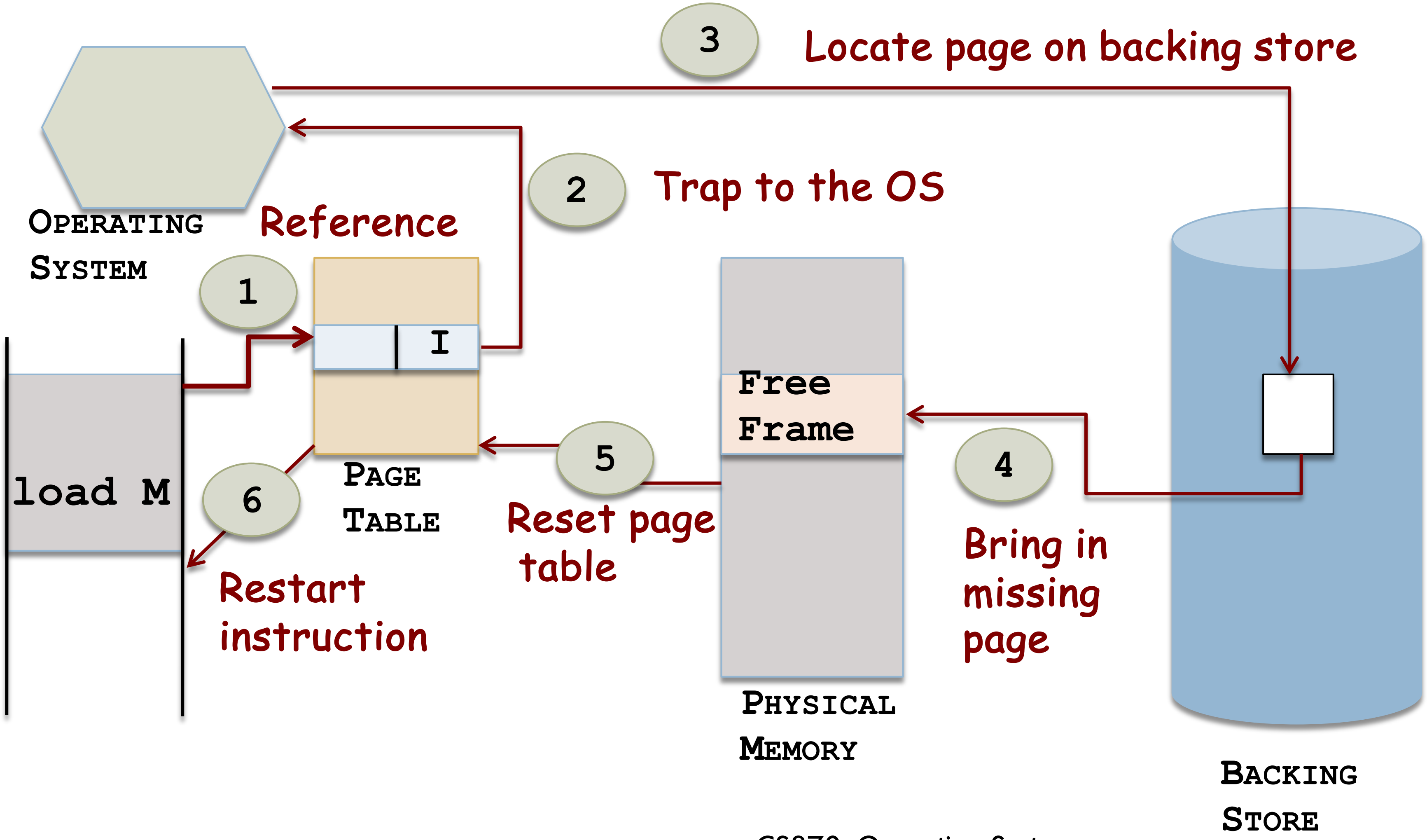
Freeing a physical memory frame

- Write frame contents to swap space
- Change page table of process
  - To reflect that page is no longer in memory
- Freed frame can now hold some other page

Servicing a page fault



Page replacement is central to demand paging



Page replacement algorithms:

- What are we looking for?
  - **Low page-fault rates**
- How do we evaluate them?
  - Run algorithm on a string of memory references
    - **Reference string**
  - Compute number of page faults

FIFO page replacement algorithm: Out with the old; in with the new

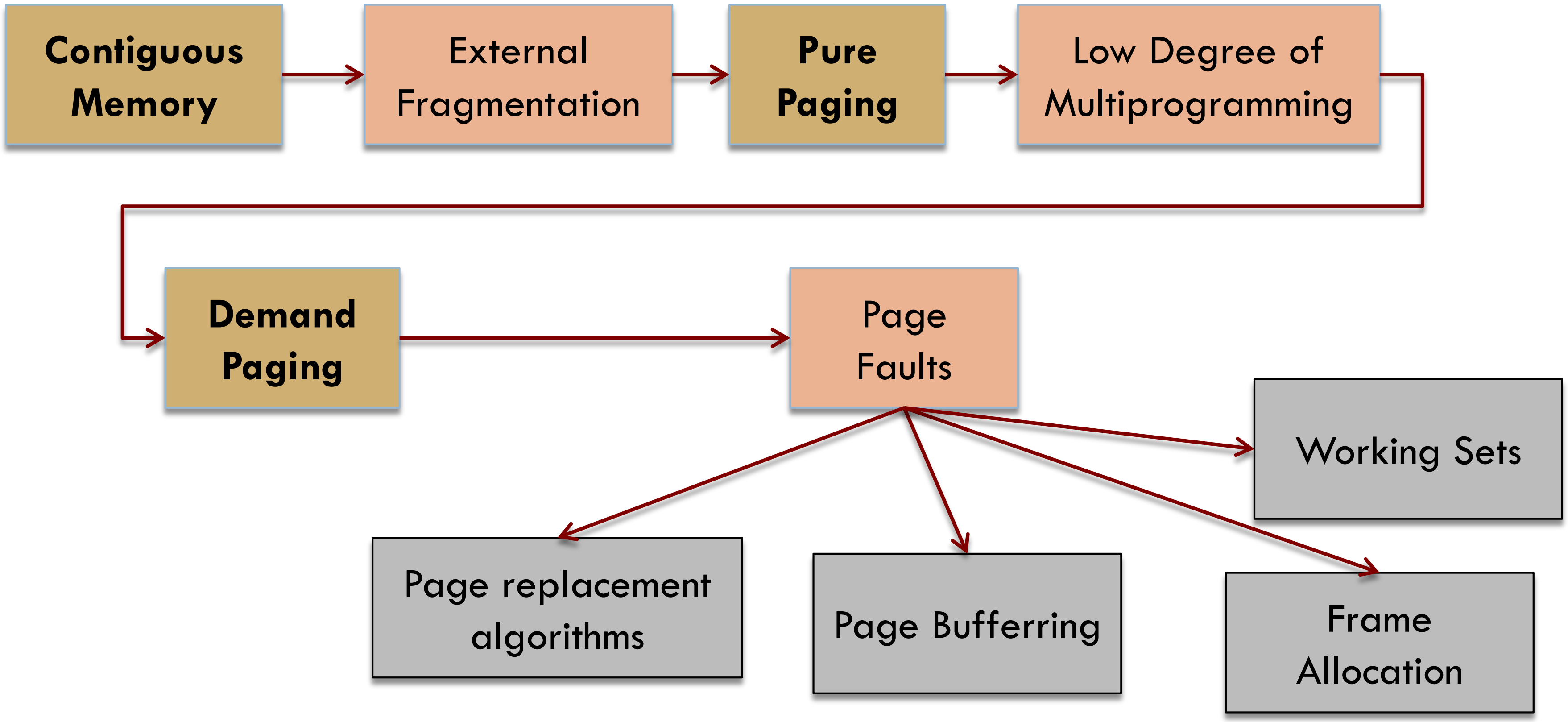
- When a page must be replaced
  - Replace the **oldest** one
- OS maintains list of all pages currently in memory
  - Page at head of the list: Oldest one
  - Page at the tail: Recent arrival
- During a page fault
  - Page at the head is removed
  - New page added to the tail

FIFO example: 3 memory frames

Reference String	7	0	1	2	0	3	0	4	2	3	0	3	2	1	2	0	1	7	0	1
Youngest	7	0	1	2	2	3	0	4	2	3	0	0	0	1	2	2	2	7	0	1
		7	0	1	1	2	3	0	4	2	3	3	3	0	1	1	1	2	7	0
Oldest			7	0	0	1	2	3	0	4	2	2	2	3	0	0	0	1	2	7

No page fault

How we got here …



Intuitively the greater the number of memory frames, the lower the faults

- Surprisingly this is **not always** the case
- In 1969 Belady, Nelson and Shedler discovered counter example* in FIFO
  - FIFO caused more faults with 4 frames than 3
- This strange situation is now called **Belady's anomaly**

* *An anomaly in space-time characteristics of certain programs running in a paging machine*. Belady, Nelson and Shedler.

Belady's anomaly: FIFO
Same reference string, different frames

Numbers in **this color**:
No page fault

	0	1	2	3	0	1	4	0	1	2	3	4
Youngest	0	1	2	3	0	1	4	**4**	**4**	2	3	**3**
		0	1	2	3	0	1	**1**	**1**	4	2	**2**
Oldest			0	1	2	3	0	**0**	**0**	1	4	**4**

9 page faults
with 3 frames

	0	1	2	3	0	1	4	0	1	2	3	4
Youngest	0	1	2	3	**3**	**3**	4	0	1	2	3	4
		0	1	2	**2**	**2**	3	4	0	1	2	3
			0	1	**1**	**1**	3	3	4	0	1	2
Oldest				0	**0**	**0**	1	2	3	4	0	1

10 page faults
with 4 frames

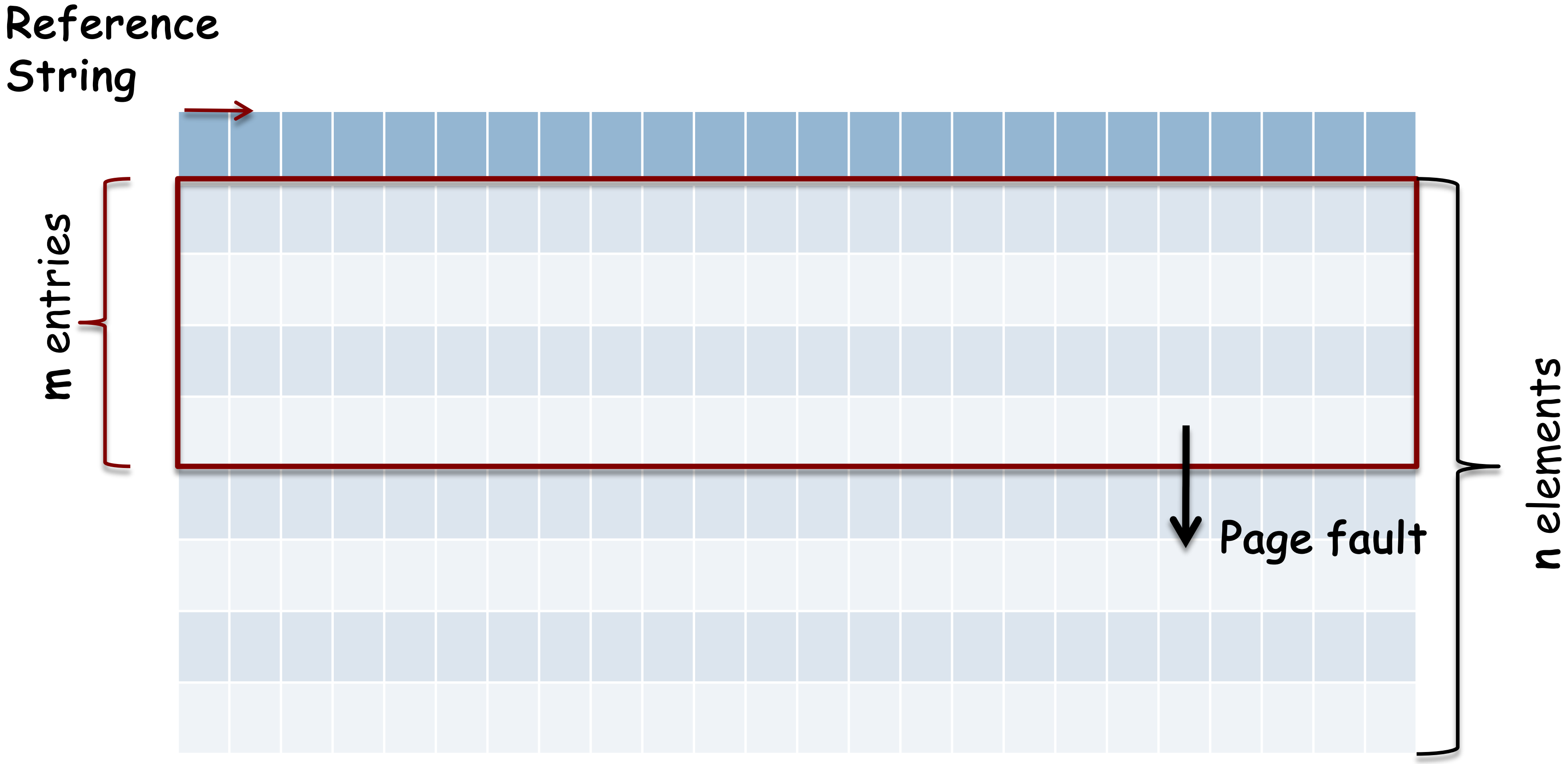
Belady's anomaly

- Led to a whole theory on paging algorithms and properties
- **Stack algorithms**

The Model

- There is an array M
  - Keeps track of the state of memory
- M has as many elements as pages of virtual memory
- Divided into two parts
  - Top part: m entries {Pages currently in memory}
  - Bottom part: n-m entries
    - Pages that were referenced BUT paged out

The model



Tracking the state of the array M over time

Properties of the model

- When a page is referenced
  - Move to the **top** entry of $\mathbf{M}$
- If the referenced page is already in $\mathbf{M}$
  - All pages above it ***moved down*** one position
  - Pages below it are not moved
- **Transition** from within box to outside of it
  - Page eviction from main memory

The model

0	2	1	3	5	4	6	3	7	4	7	3	3	5	5	3	1	1	1	7	2	3	4	1
0	2	1	3	5	4	6	3	7	4	7	3	3	5	5	3	1	1	1	7	2	3	4	1
	0	2	1	3	5	4	6	3	7	4	7	7	3	3	5	3	3	3	1	7	2	3	4
		0	2	1	3	5	4	6	3	3	4	4	7	7	7	5	5	5	3	1	7	2	3
			0	2	1	3	5	4	6	6	6	6	4	4	4	7	7	7	5	3	1	7	2
				0	2	1	1	5	5	5	5	5	6	6	6	4	4	4	4	5	5	1	7
					0	2	2	1	1	1	1	1	1	1	1	6	6	6	6	4	4	5	5
						0	0	2	2	2	2	2	2	2	2	2	2	2	2	6	6	6	6
							0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

The optimal page replacement algorithm

- The best possible algorithm
- Easy to describe but **impossible to implement**
- **Crux:**
  Put off unpleasant stuff for as long as possible
- Idea: evict "Furthest-in-the-future"

The optimal page replacement algorithm description

- When a page fault occurs some set of pages are in memory
- One of these pages will be referenced next
  - Other pages may be not be referenced until 10, 100 or 1000 instructions later
- **Label** each page with the <u>number of instructions</u> to be executed *before* it will be referenced
  - Page with the highest label should be removed

The Least Recently Used (LRU) page replacement algorithm

- Approximation of the optimal algorithm
- Observation
  - Pages used heavily in the last few instructions
    - Probably will be used heavily in the next few
  - Pages that have not been used
    - Will probably remain unused for a long time
- When a page fault occurs?
  - Throw out page that has been **unused the longest**

LRU example: 3 memory frames

Reference String

	7	0	1	2	0	3	0	4	2	3	0	3	2	1	2	0	1	7	0	1
Recent	7	0	1	2	0	3	0	4	2	3	0	3	2	1	2	0	1	7	0	1
		7	0	1	2	0	3	0	4	2	3	0	3	2	1	2	0	1	7	0
Least Used			7	0	1	2	2	3	0	4	2	2	0	3	3	1	2	0	1	7

Using Logical clocks to implement LRU

- Each page table entry has a **time-of-use** field
  - Entry updated when page is referenced
    - Contents of clock register are copied
- Replace the page with the smallest value
  - Time increases monotonically
    - **Overflows** must be accounted for
- Requires <u>search of page table</u> to find LRU page

Stack based approach

- Keep stack of page numbers
- When page is referenced
  - Move to the top of the stack
- Implemented as a doubly linked list
- No search done for replacement
  - Bottom of the stack is the LRU page

Problems with clock/stack based approaches to LRU replacements

- Inconceivable without hardware support
  - Few systems provide requisite support for true LRU implementations
- Updates of clock fields or stack needed at **every** memory reference
- If we use interrupts and do software updates of data structures things would be very slow
  - Would slow down every memory reference
    - At least 10 times slower

Summary of Page Replacement Algorithms

Algorithm	**Comment**
Optimal	Not implementable, but useful as a benchmark
NRU (Not Recently Used)	Very crude approximation of LRU
FIFO (First-In, First-Out)	Might throw out important pages
Second chance	Big improvement over FIFO
Clock	Realistic
LRU (Least Recently Used)	Excellent, but difficult to implement
NFU (Not Frequently Used)	Fairly crude approximate to LRU
Aging	Efficient algorithm that approximates LRU well

Page Buffering: Being proactive

- Maintain a list of **modified** pages
- When the paging device is **idle**
  - Write modified pages to disk
- Implications
  - If a page is selected for replacement *increase likelihood* of that page being clean

Page Buffering: Reuse what you can

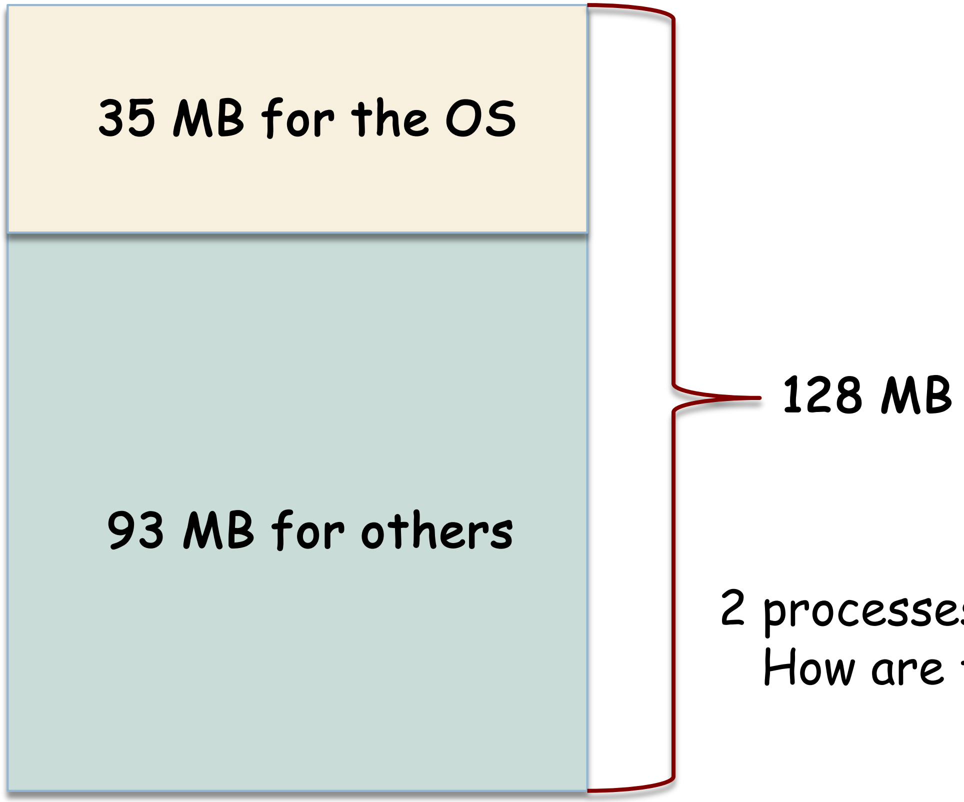
- Keep pool of free frames as before
  - BUT **remember** which pages they held
- Frame contents are not modified when page is written to disk
- If page needs to come back in?
  - **Reuse** the same frame if it was not used to hold some other page

Buffering and applications

- Applications often understand their memory/disk usage <u>better</u> than the OS
  - Provide their own buffering schemes
- If both the OS and the application were to buffer
  - Twice the I/O is being utilized for a given I/O

Frame allocation: How do you divvy up free memory among processes?

Frame size = 1 MB; Total Size = 128 MB



2 processes at T_0
How are frames allocated?

With demand paging all 93 frames would be in the free frame pool

Constraints on frame allocation

- **Max**: Total number of frames in the system
  - Available physical memory

- **Min**: Need to allocate at least a minimum number of frames
  - Defined by the architecture of the underlying system

Minimum number of frames

- As you decrease the number of frames for a process
  - Page fault increases
  - Execution time increases too

- Defined by the **architecture**
  - In some cases instructions and operands (indirect references) straddle page boundaries
    - With 2 operands at least 6 frames needed

Global vs Local Allocation

- Global replacement
  - One process can **take** a memory frame from another process

- Local replacement
  - Process can only choose from the set of frames that was allocated to it

Local vs Global replacement: Based on how often a page is referenced

Pages	Usage Count
A1	10
A2	7
A3	5
A4	3
B1	9
B2	4
B3	2
B4	6
C1	3
C2	5
C3	6

Processes A, B and C

Pages
A1
A2
A3
A5
B1
B2
B3
B4
C1
C2
C3

Local Replacement

Pages
A1
A2
A3
A4
B1
B2
A5
B4
C1
C2
C3

Global Replacement

Process **A** has page faulted and needs to bring in a page

Global vs Local Replacement

	Local	Global
Number of frames allocated to process	Fixed	Varies dynamically
Can process control its own fault rate?	YES	NO
Can it use free frames that are available?	NO	YES
Increases system throughput?	NO	YES

Locality of References

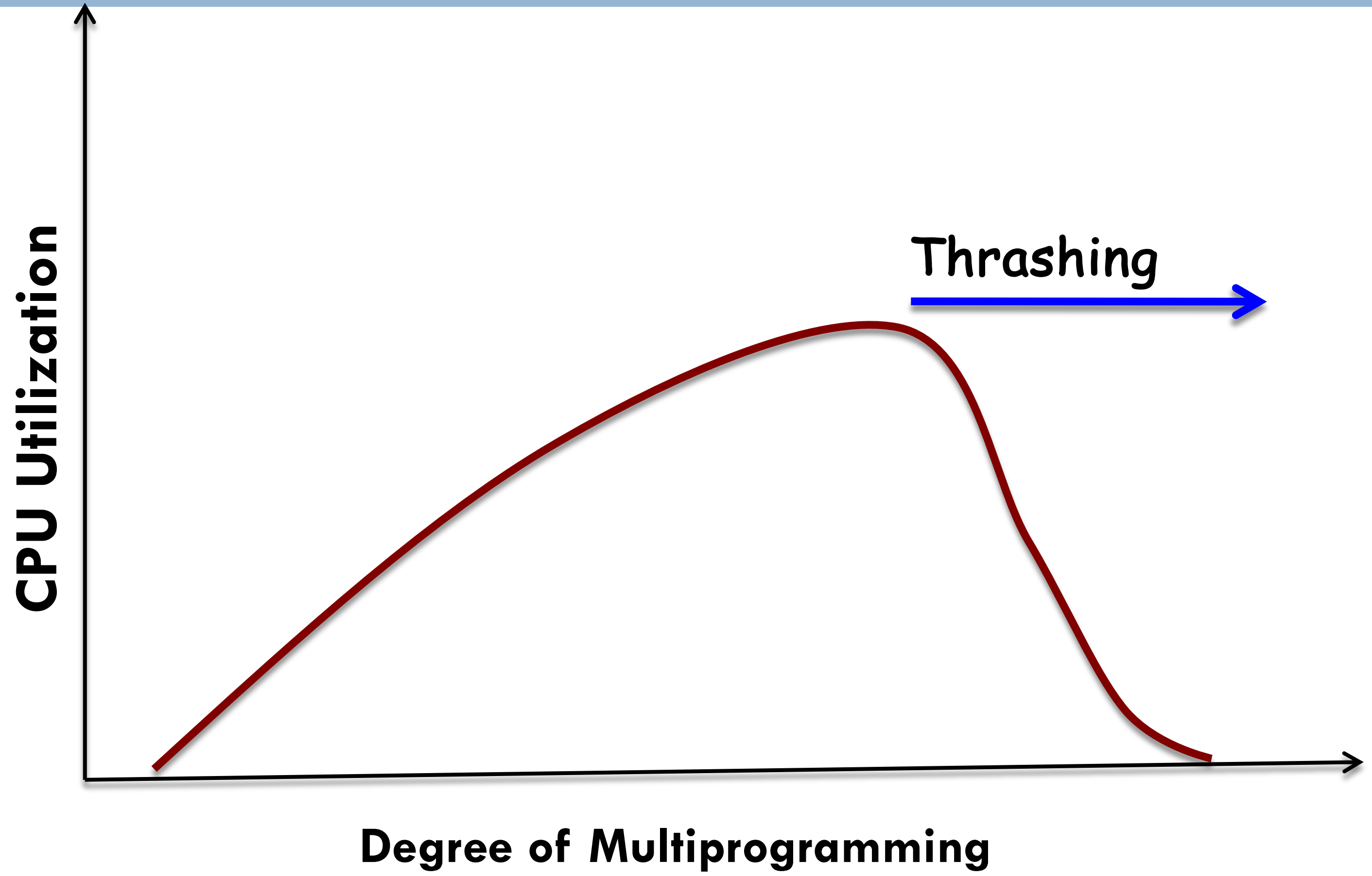
- During any phase of execution a process references a relatively small **fraction** of its pages
- Set of pages that a process is currently using
  - **Working set**
- Working set **evolves** during process execution

Implications of the working set

- If the entire working set is in memory
  - Process will execute without causing many faults
    - Until it moves to *another phase* of execution

- If the available memory is too small to hold the working set?
  1. Process will cause many faults
  2. Run very slowly

Characterizing the affect of multiprogramming on thrashing



Mitigating the effects of thrashing

- Using a local page replacement algorithm
  - One process thrashing does not cause **cascading thrashing** among other processes
  - BUT if a process is thrashing
    - Average service time for a page fault increases
- Best approach
  1. Track a process' working set
  2. Make sure the working set is in memory **before** you let it run

Virtualization

Objectives:

- Explain Virtual Machine Monitors (VMMs)
- Justify the Popek and Goldberg requirements for virtualization
- Explain how Virtualization works in the x86 architecture
- Compare Type-1 and Type-2 Hypervisors

Firms often have multiple, dedicated servers: e-mail, FTP, e-commerce, web, etc.

- **Load**: May be one machine cannot handle all that load
- **Reliability**: Management does not trust the OS to run 24 x 7 without failures
- By putting one server on a separate computer, if one of the server crashes?
  - At least the other ones are not affected
- If someone breaks into the web server, at least sensitive e-mails are still protected
  - **Sandboxing**

But …

- While this approach achieves **isolation** and fault tolerance
  - This solution is expensive and hard to manage because so many machines are also involved
- Other reasons for having separate machines?
  - Organizations depend on more than one OS for their daily operations
    - Web server on Linux, mail server on Windows, e-commerce server on OS X, other services on various flavors of UNIX

What to do?

- A possible (and popular) solution is to use virtual machine technology
- This sounds very hip and modern
  - But the idea is old … dating back to the 1960s
  - Even so, the way we use it today is definitely new

Main idea

- **VMM** (Virtual Machine Monitor) creates the *illusion* of multiple (virtual) machines on the same physical hardware
  - VMM is also known as a **hypervisor**
    - We will look at type 1 hypervisors (bare metal) and type 2 hypervisors (use services and abstractions offered by an underlying OS)
- **Virtualization** allows a single computer to host multiple virtual machines
  - Each potentially running a different OS

Failure in one virtual machines does not bring down any others

- Different servers run on different virtual machines
  - Maintains **partial-failure** model at a lower cost with easier maintainability
- Also, we can run different OS on the same hardware
  - Benefit from virtual machine isolation in the face of attacks
  - Plus enjoy other good stuff: savings, real estate, etc.
  - Convenient for complex software stack with precise system dependencies
    - Think core libraries

Why virtualization works [1/2]

- Service outages are due not to faulty hardware, but due to poor software, emphatically including OSes
  - Ill-designed, unreliable, buggy, and poorly configured software
- Migration to another machine may be easier

Why virtualization works [2/2]

- The only software running in the *highest privilege* is the hypervisor
- Hypervisor has 2 orders of magnitude fewer lines of code than a full operating system
  - Has 2 orders of magnitude fewer bugs
- A hypervisor is simpler than an OS because it *does only one thing*
  - Emulate copies of the bare metal (most commonly the Intel x86 architecture)

Advantages to running software in VMs besides strong isolation

- Few physical machines
  - Saves money on hardware and electricity
  - Takes up less rack space
- For companies such as Amazon or Microsoft
  - Reducing physical demands on data centers represents huge cost savings
  - Companies frequently locate their data centers in the middle of nowhere
    - Just to be close to hydroelectric dams (and cheap energy)

Hypervisors should score well on

- **Safety**
  - Hypervisor should have full control of the virtualized resources
- **Fidelity**
  - Behavior of program on a virtual machine should be identical to the same program running on bare hardware
- **Efficiency**
  - Much of the code in the virtual machine should run *without intervention* from the hypervisor

Safety

- Consider each instruction in turn in an interpreter (such as Bochs) and perform exactly what is needed
  - May execute some instructions (INC) as is, but other instructions must be simulated
- We cannot allow the guest OS to disable interrupts for the entire machine or modify page-table mappings
  - **Trick is to make the guest OS believe that it has**
- Interpreter may be safe, even hi-fi, but performance is abysmal
  - So, VMMs try to execute most code directly

Fidelity [1/2]

- Virtualization has long been a problem on x86
  - Defects in 386 carried forward into new CPUs for 20 years in the name of backward compatibility
- Every CPU with kernel mode and user mode has instructions that behave differently
  - Depending on whether it is executed in kernel/user mode
    - **Sensitive instructions**
  - Some instructions cause a trap when executed in user-mode
    - **Privileged instructions**

A machine is virtualizable only if sensitive instructions are a subset of privileged instructions

Fidelity [2/2]

- If you do something in user mode that you should not
  - The hardware should trap!
  - IBM/370 had this property, Intel's 386 did not
- Several sensitive 386 instructions were ignored if executed in user mode
  - Or executed with a different behavior
  - E.g. POPF instruction replaces flags register which changes the bit that enables/disables interrupts
    - In user-mode this bit was simply not changed
- Also, some instructions could read sensitive state in user mode without causing a trap

Full virtualization

- Trap all instructions
- Fully simulate entire computer
- Trade-off: High overhead
- Benefit: Can virtualize any OS

Paravirtualization [1/2]

- Never aims to present a virtual machine that looks just like the actual underlying hardware
- Present **machine-line software interface** that explicitly exposes that it is a virtualized environment
  - Offers a set of **hypercalls** that allow the guest to send explicit requests to the hypervisor
    - Similar to how a system call offers kernel services to applications
- DRAWBACK: Guest OS has to be aware of the virtual machine API

Paravirtualization [2/2]

- Guests use hypercalls for privileged, sensitive operations like updating page tables
  - But they do it in cooperation with the hypervisor
  - Overall system can be simpler and faster

- Paravirtualization was offered by IBM since 1972

- Idea was revived by Denali (2002) and Xen (2003) hypervisors

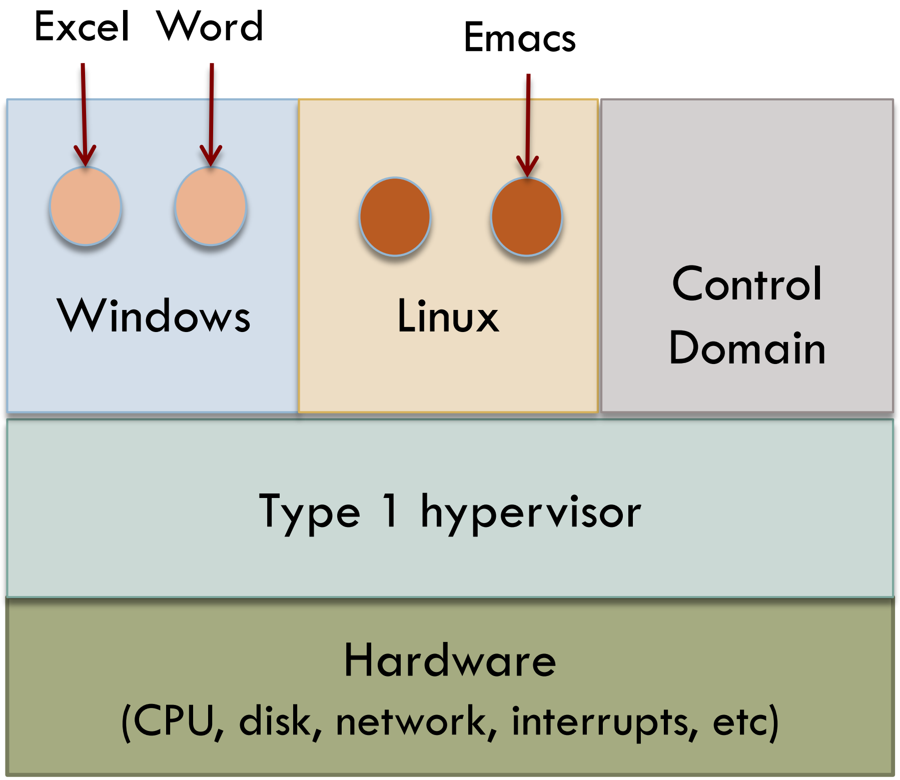
Terms

- **Guest Operating System**
  - The OS running on top of the hypervisor
- **Host Operating System**
  - For a type 2 hypervisor: the OS that runs on the hardware
- **Safe executions**
  - Execute the machine's instruction set in a safe manner
  - Guest OSes may change or mess up its own page tables … but not those of others

Type 1 hypervisor

- Only program running in the most privileged mode
- Support multiple copies of the actual hardware
  - Virtual machines
  - Similar to processes a normal OS would run

Location of Type-1 hypervisor



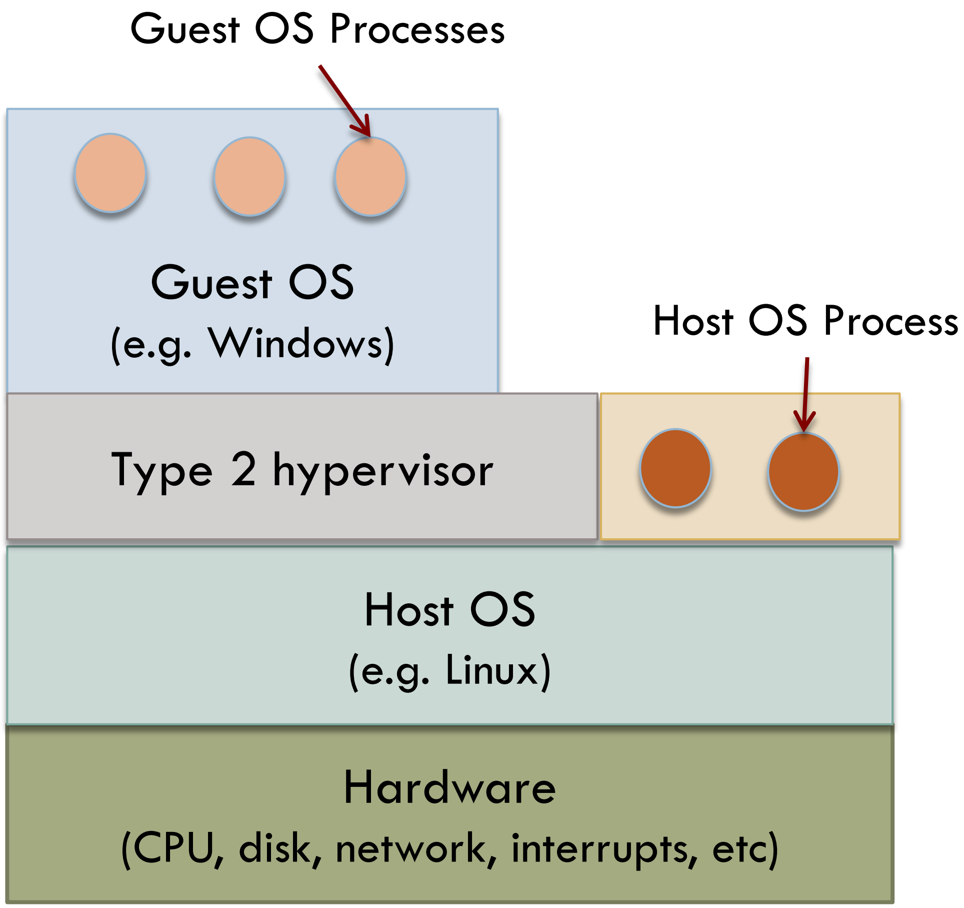
Type 2 hypervisor

- Also referred to a **hosted hypervisor**
- Relies on a host OS, say Windows or Linux, to allocate and schedule resources
- Still pretends to be a full computer with a CPU and other devices

Type 2: Running Guest OS

- When it starts for the first time, acts like a newly booted computer
  - Expects to find a DVD, USB drive or CD-ROM containing an OS
    - The drive could be a virtual device
    - Store the image as an ISO file on the hard drive and have hypervisor pretend its reading from proper DVD drive
- Hypervisor installs the OS to its virtual disk (just a file) by running installation that it found on DVD
- Once guest OS is installed on virtual disk, it can be booted and run

Location of Type-2 hypervisor



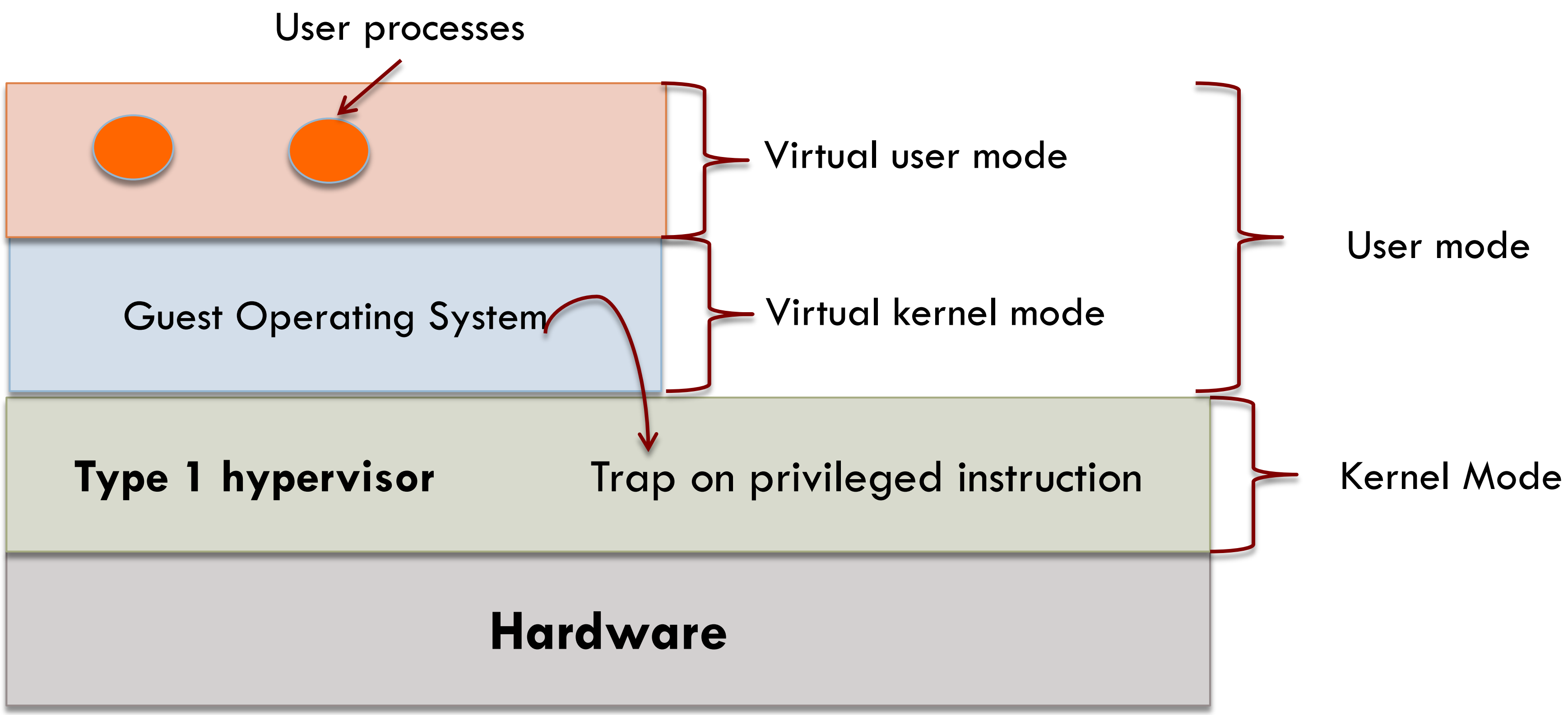
Examples of hypervisors [Partial List]

Virtualization Method	Type 1 hypervisor	Type 2 hypervisor
Virtualization without hardware support	ESX Server 1.0	VMware workstation 1.0
Paravirtualization	Xen 1.0	
Virtualization with hardware support	vSphere, Xen, Hyper-V	VMware Fusion, KVM, Parallels
Process Virtualization		WINE

Type-1 hypervisors

- Virtual machine runs as a user-process in user mode
  - Not allowed to execute sensitive instructions (in the Popek-Goldberg sense)
- But the virtual machine runs a Guest OS that **thinks** it is in kernel mode (although, of course, it is not)
  - **Virtual kernel mode**
- The virtual machine also runs user processes, which think they are in the user mode
  - And really are in user mode

Modes


User processes
Virtual user mode
User mode
Guest Operating System
Virtual kernel mode
Type 1 hypervisor
Trap on privileged instruction
Kernel Mode
Hardware

Execution of kernel model instructions

- What if the Guest OS executes an instruction that is allowed only when the CPU is really in kernel mode?
  - On CPUs without VT (Intel: Virtualization Technology)?
    - Instruction fails and the OS crashes
- On CPUs with VT?
  - A trap to the hypervisor does occur
    - Hypervisor can inspect instruction to see if it was issued:
      - By Guest OS: Arrange for the instruction to be carried out
      - By user-process in that VM: Emulate what hardware would do when confronted with sensitive instruction executed in user-mode

What if the guest is running and an interrupt arrives from an external device?

- Type 2 hypervisor depends on host’s device drivers to handle to the interrupt
- So, the hypervisor **reconfigures hardware** to to run the host OS system code
  - When the device driver runs, it finds everything just as it expected it to be
- Hypervisor behaves just like teenagers throwing a party when parents are away
  - It’s OK to rearrange furniture completely, as long as they put it back as they found it before parents get home

Why do hypervisors work even on unvirtualizable hardware?

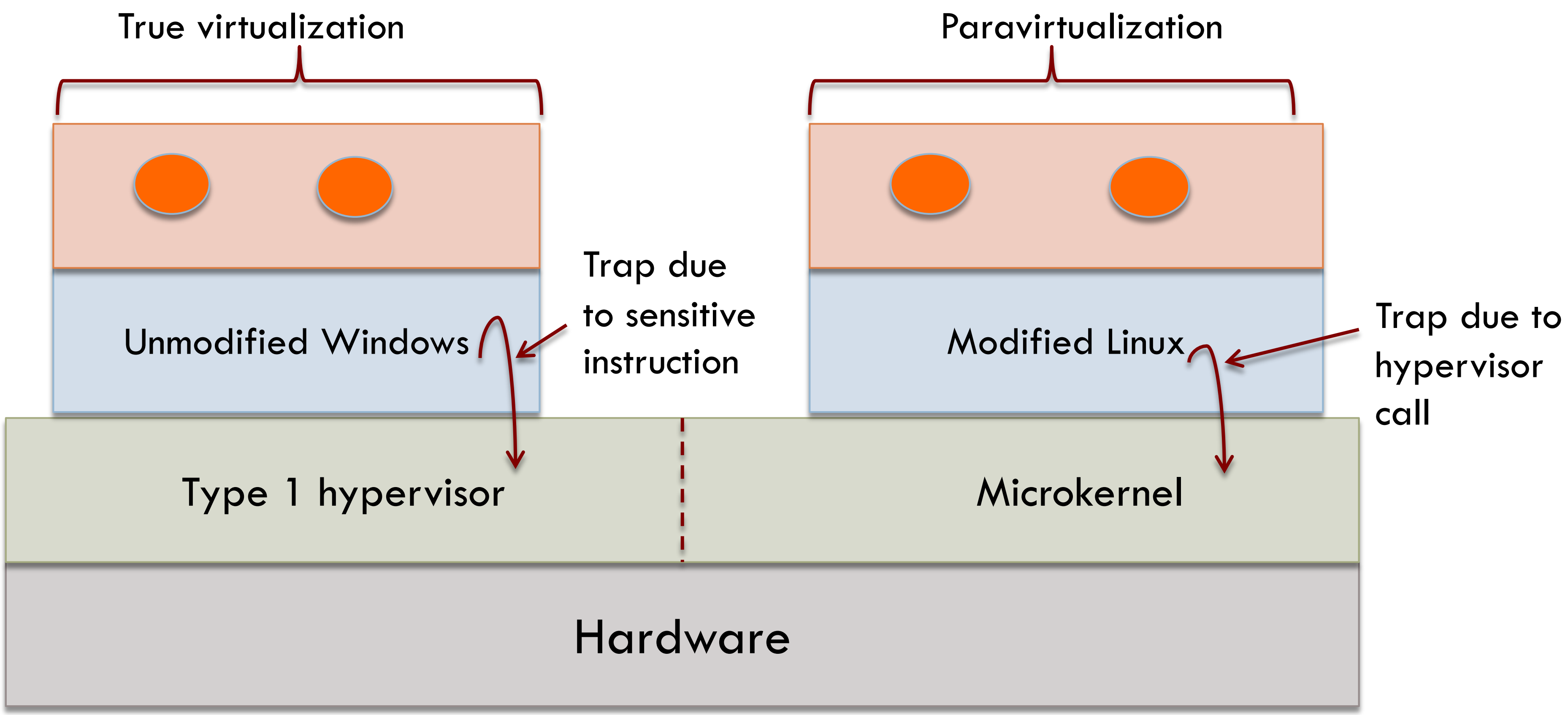
- Sensitive instructions in the guest kernel replaced by calls to procedures that **emulate** these instructions

- No sensitive instructions issued by the guest OS are ever executed directly by true hardware
  - Turned into calls to the hypervisor, which emulates them

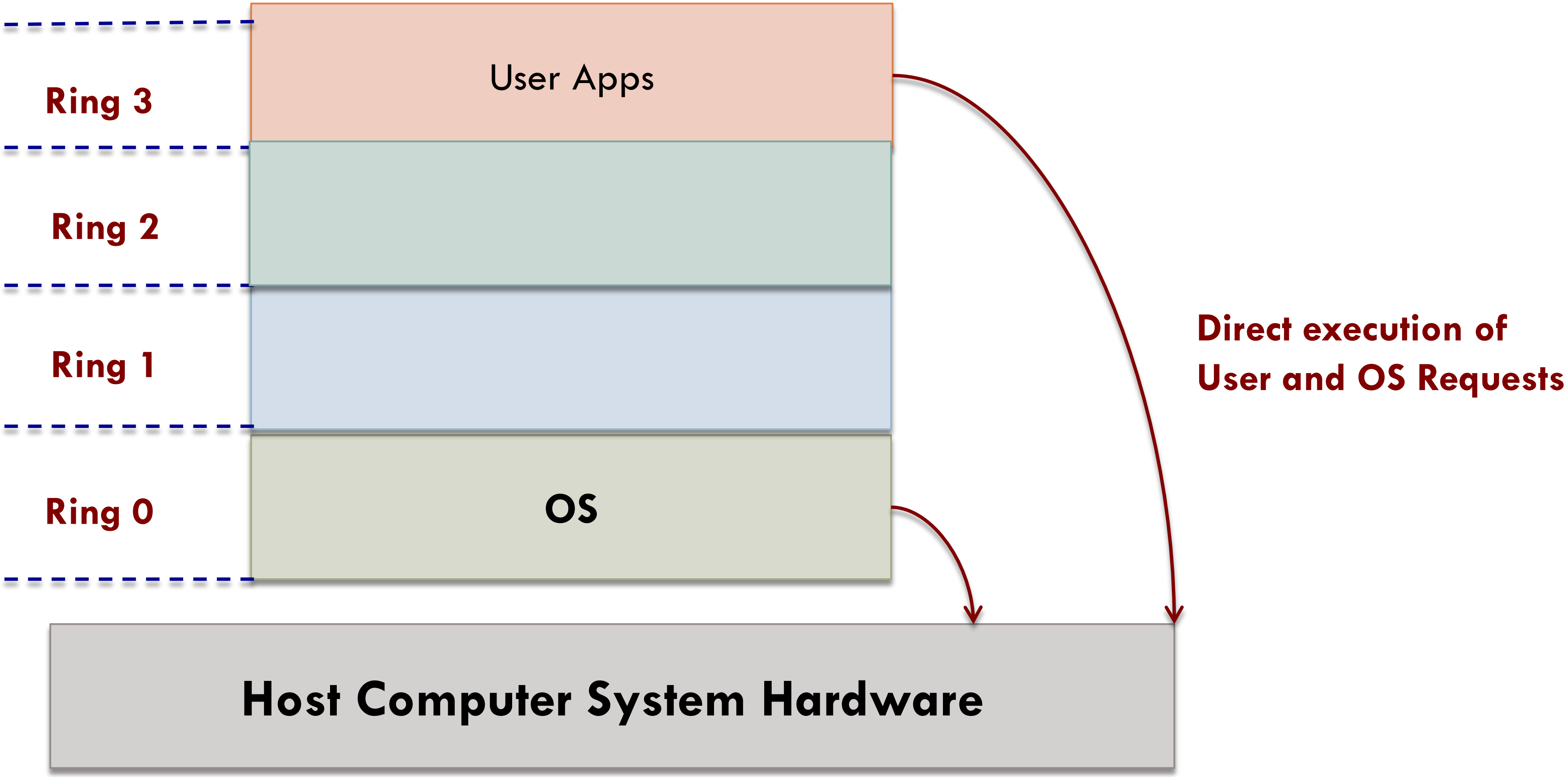
Cost of virtualization

- We expect CPUs with VT would greatly outperform software techniques
- Trap-and-emulate approach used by VT hardware generates a lot of traps … and these are expensive
  - **Ruin CPU caches, TLBs, and branch predictions**
- In contrast, when sensitive instructions are replaced by calls to hypervisor procedures
  - None of this context-switching overhead is incurred

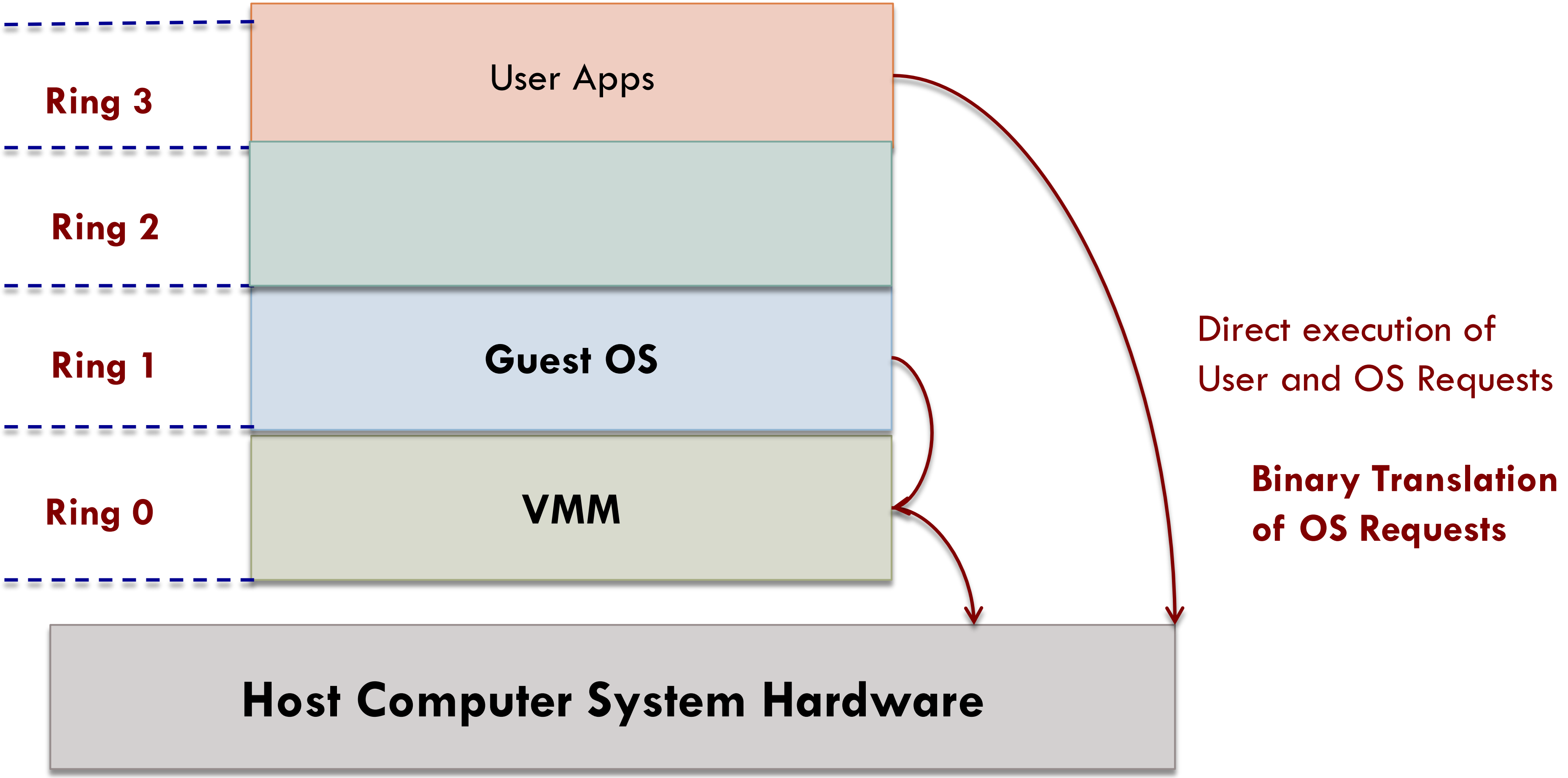
True virtualization & paravirtualization



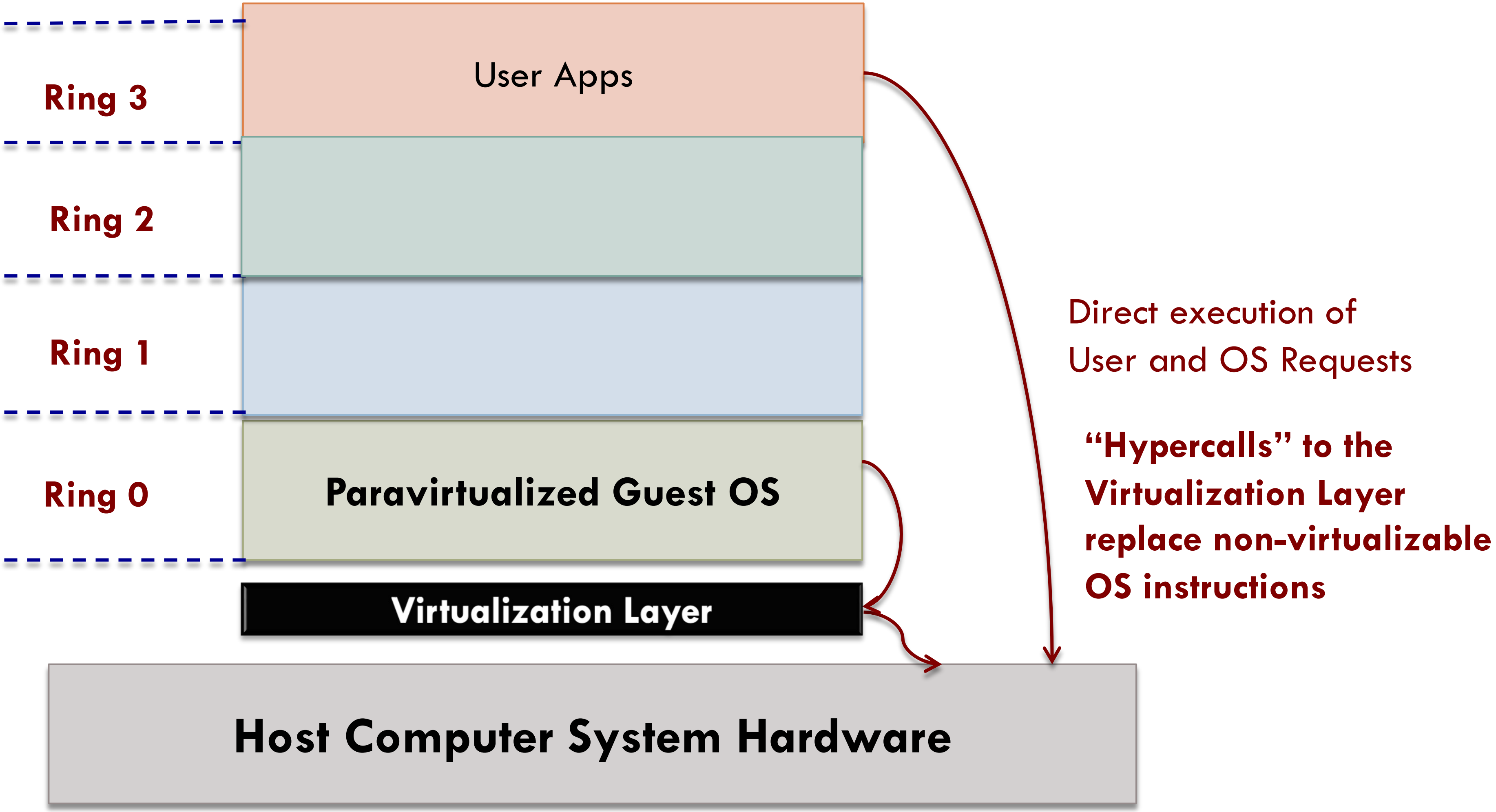
x86 privilege level architecture without virtualization



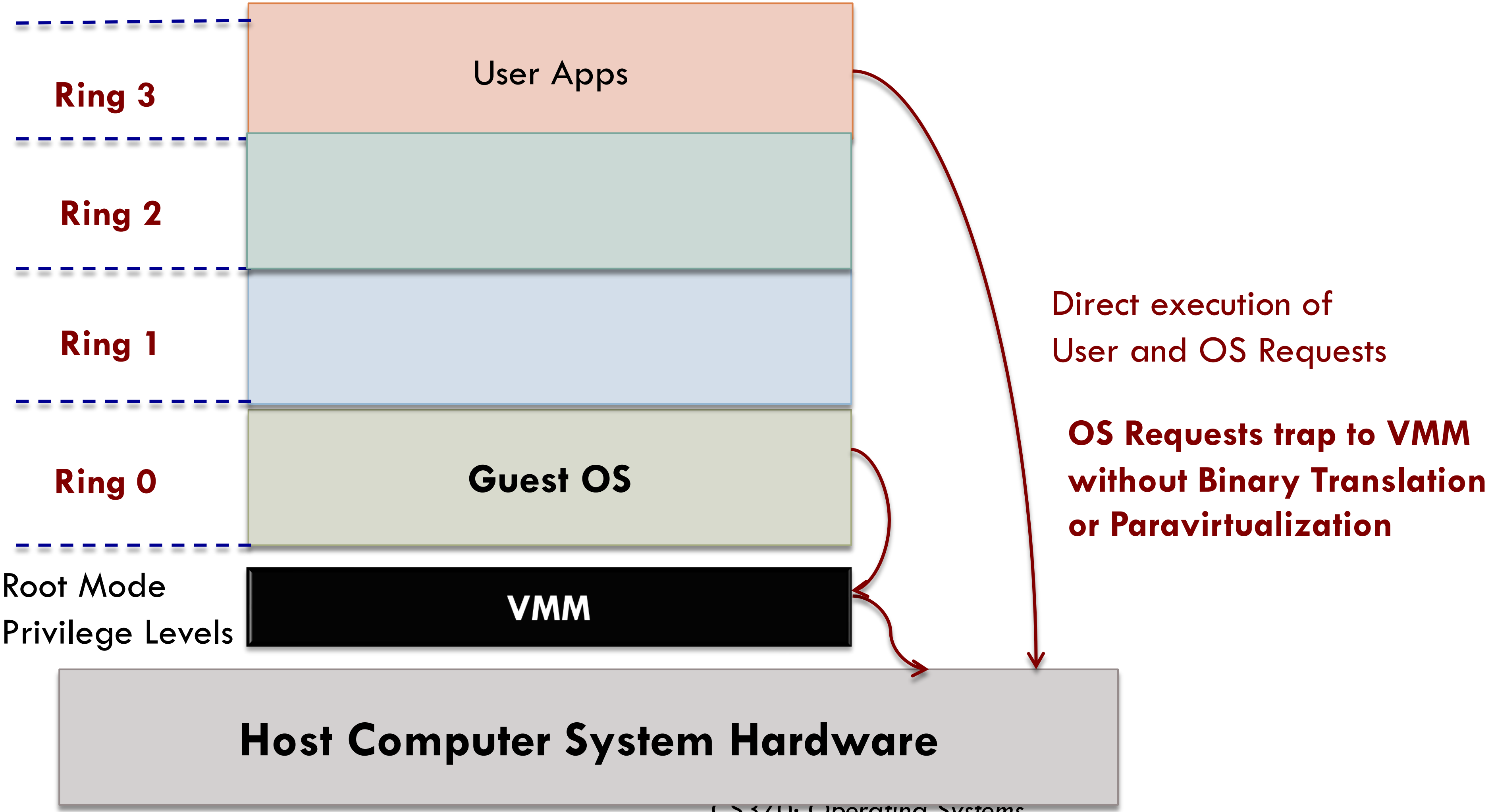
Full Virtualization: Binary translation approach to x86 virtualization



Paravirtualization approach to x86 virtualization



Hardware assisted virtualization



Contrasting the virtualization approaches

	Full virtualization with Binary Translation	**Hardware Assisted Virtualization**	**OS Assisted Virtualization/Para virtualization**
Technique	Binary Translation and Direct Execution	Exit to Root Mode on privileged instructions	Hypercalls
Guest Modification/ Compatibility	Unmodified Guest OS Excellent compatibility	Unmodified Guest OS Excellent compatibility	GuestOS codified to issue Hypercalls so it can't run on native hardware. Compatibility is lacking

Installing application software

- VMs offer a solution to a problem that has long plagued users (especially open source)
  - **How to install application programs**
- Applications are dependent on numerous other applications and libraries
  - Which themselves depend on a host of software packages
- Plus there are dependencies on particular versions of compilers, scripting languages, OS etc.

With VMs …

- Developer can carefully **construct** a virtual machine
  - Load it with required OS, compiler, libraries, and application code
  - **Freeze the entire unit** … ready to run
- Only the software developer has to understand the dependencies

Licensing Issues

- Some software is licensed on a per-CPU basis
  - Especially, software for companies
  - When they buy a program they have the right to run it on just one CPU
    - What is a CPU anyway?
    - Can we run multiple VMs all running on the same physical hardware?
- Problem is even worse, when companies have licenses for N machines running the software
  - VMs come and go on demand

File Systems

Objectives:

- Summarize file system structure
- Contrast contiguous allocation vs indexed allocations
- Explain the Unix File System
- ~~Explain and contrast Windows File Systems: the File Allocation table and NTFS~~

Files are an abstraction mechanism

- Provide a way to store information and read it back later
- Do this is an way that **shields** the user from
  - How and where information is stored on disk
  - How disks really work

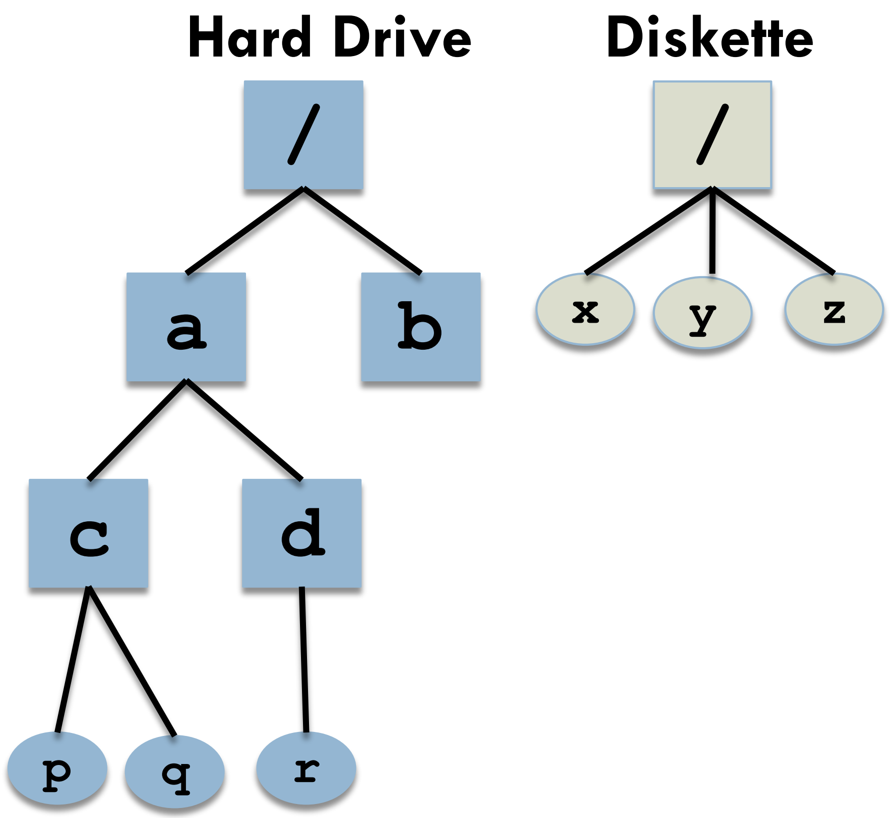
Files can be structured in many ways: Unstructured sequence of bytes

- The OS does not know or care what is in the file
  - Maximum **flexibility**
- OS does not help, but does not get in the way either
- Meaning is imposed by programs
- Most OS support this

Mounting file systems

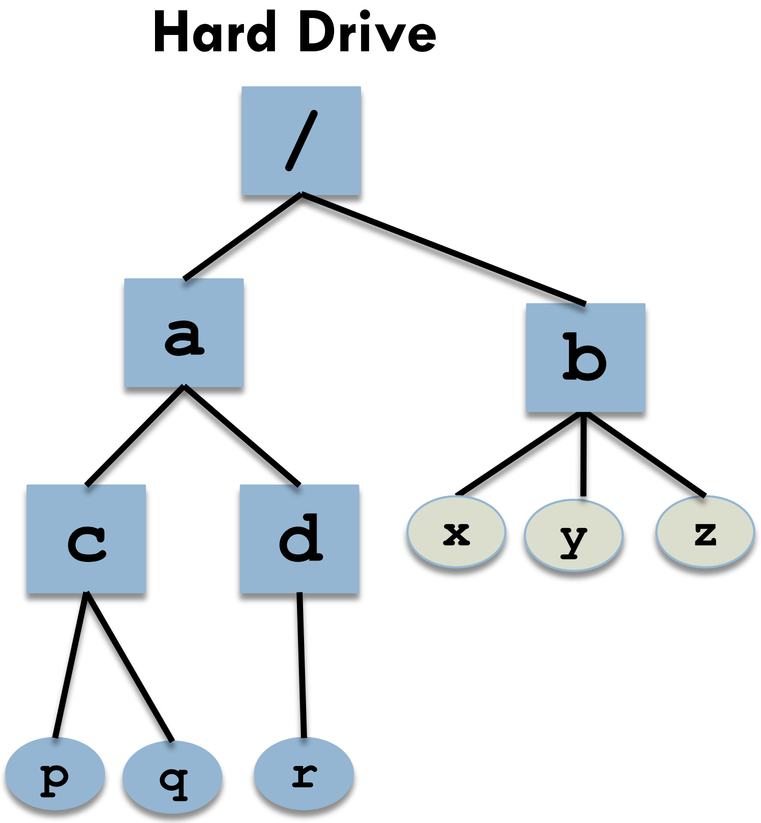
- Many systems have more than one disk
  - How do you handle them?
- **S1**:Keep self contained file system on each disk
  - And keep them separate
- **S2**: Allow one disk to be **mounted** in another disk's file tree

Mounting file systems



`cp D:/x /a/d/x`

H is default

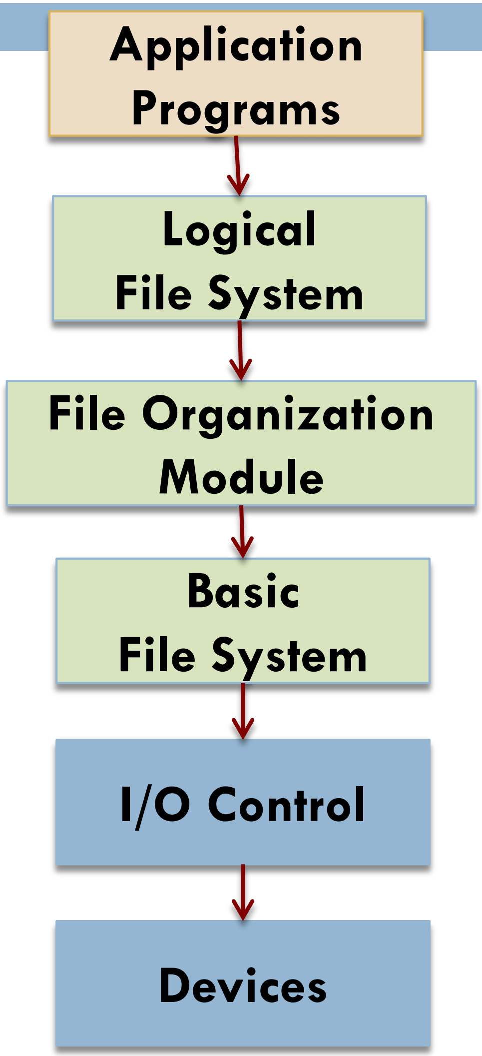


`cp /b/x /a/d/x`

Checks performed during mounting

- OS **verifies** that the device contains a valid file system
- Read device directory
  - Make sure that the format is an expected one
- Windows mounting
  - Each device in a separate name space
  - {Letter followed by a colon e.g. **G:**}

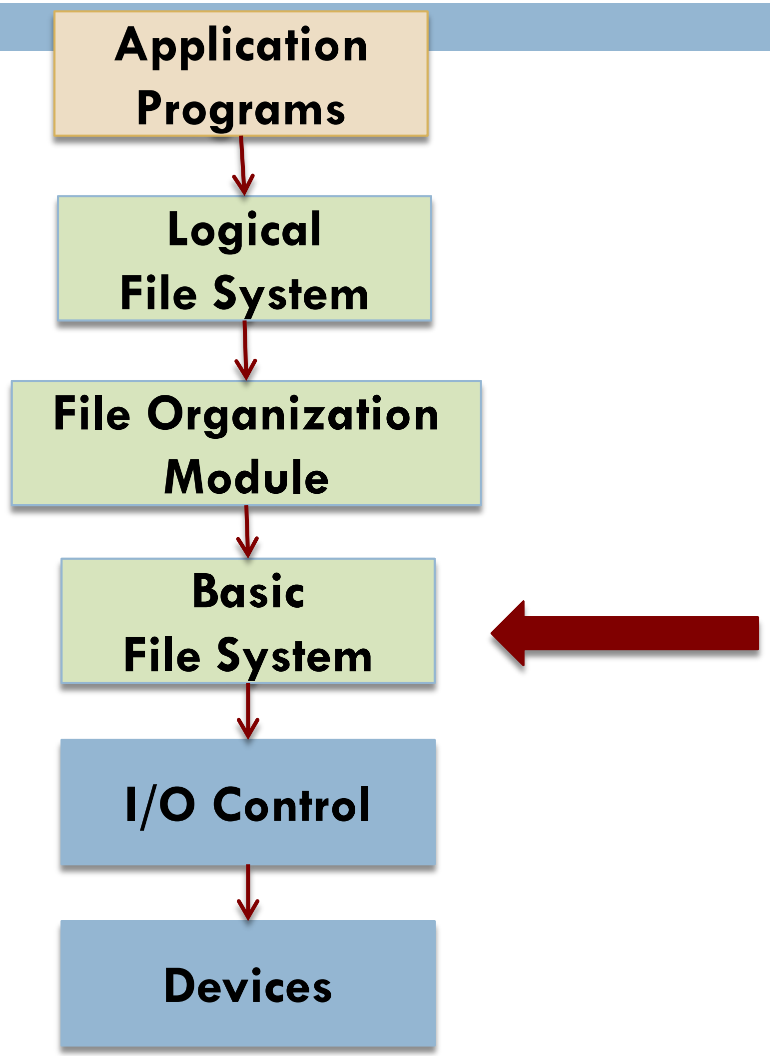
There are many levels that comprise a file system



I/O Control consists of device drivers

- Transfers information *between main memory and disk*
- Receives **high-level** commands
  - Retrieve block 123, etc
- Outputs low-level, hardware-specific instructions
  - Used by the hardware controller
  - Writes bit patterns into specific locations of the I/O controller

There are many levels that comprise a file system

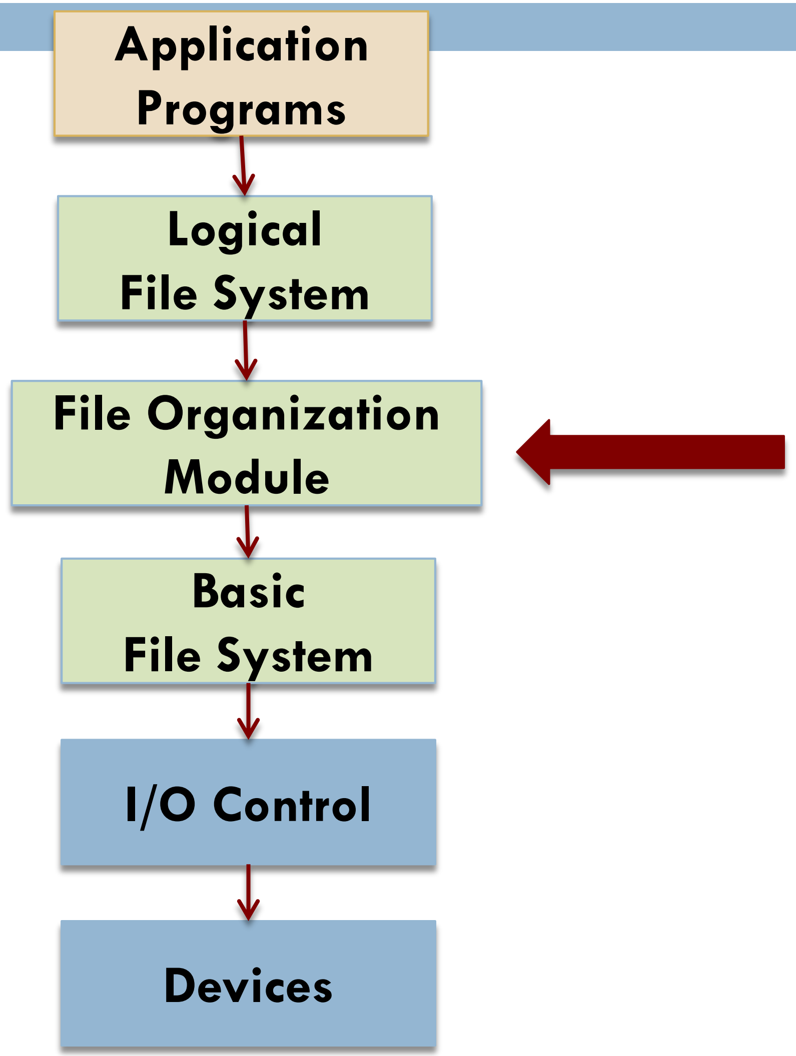


Basic file system issues commands to the device driver

- Read and write physical blocks on disk
  - E.g. Drive 1, cylinder 73, sector 10

- Manages **buffers and caches**
  1. To hold file system, directory and data blocks
  2. Improves performance

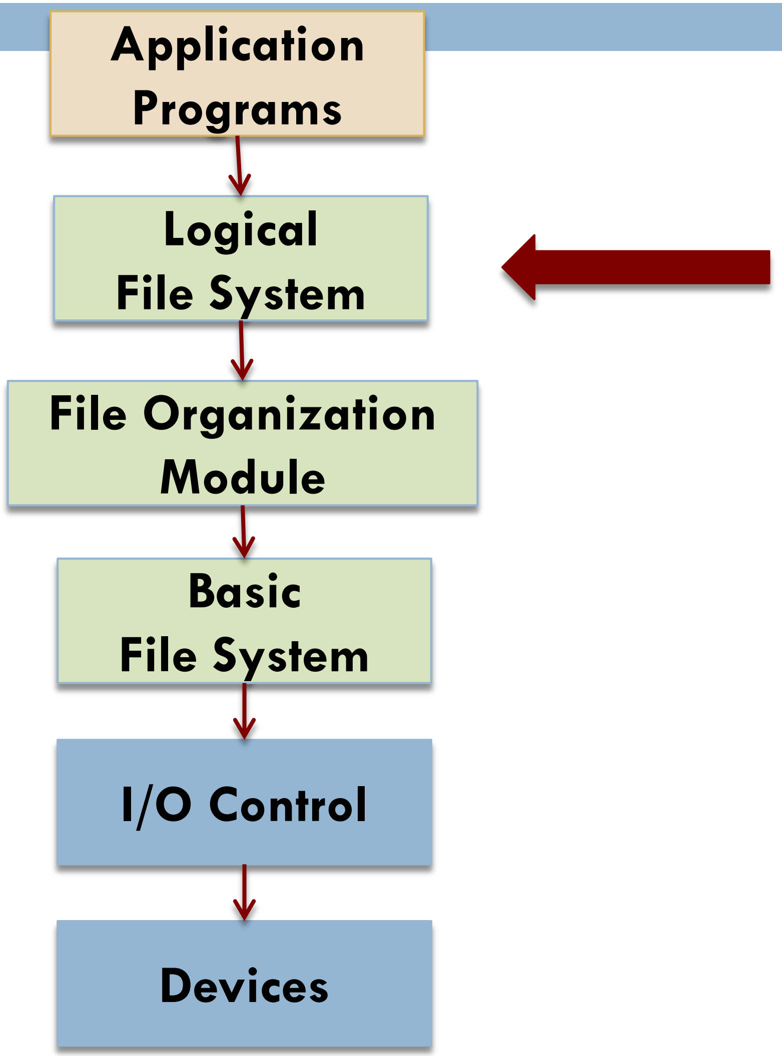
There are many levels that comprise a file system



File organization module

- Knows about files
  - Logical and physical blocks
- **Translate** logical addresses to physical ones
  - Needed for every block
- Includes a **free space manager**
  - Tracks unallocated blocks and allocates as needed

There are many levels that comprise a file system



The logical file system

- Manages **metadata** information
  - Metadata is *data describing the data*

- Maintains file structure via **file control blocks**
  - Info about the file
    - Ownership and permissions
    - Location of file contents
  - **inode** in UNIX file systems

Several file systems are in use

- CD-ROMs written in ISO 9660 format
  - Designed by CD manufacturers
- UNIX
  - Unix file system (**UFS**)
  - Berkley Fast File System (**FFS**)
- Windows: **FAT, FAT32** and **NTFS**
- Linux
  - Supports 40 different file systems
  - Extended file system: **ext2, ext3** and **ext4**

On-disk structures used to implement a file system (1)

- **Boot control block**
  - Information needed to boot an OS from that volume
- **Volume control block**: Volume information
  - Number of blocks in the partition
  - Size of the blocks
  - Free-block count/pointers
  - Free file-control-block count/pointers
  - UFS: **super-block** Windows: **Master file table**

On-disk structures used to implement a file system (2)

- Directory structure to organize files
  - One per file system
- Per file file-control-block
  - Contains details about individual files

In memory structures used to improve performance via caching

- **Mount** table
  - Information about each mounted volume
- Directory structure **cache**
  - Holds information about recently accessed directories
- System-wide **open file** table
  - File control block of each open file
- **Buffers** to hold file-system blocks
  - To read and write to storage

Creation of a new file

- **Allocate** a file-control block (FCB)
- Read appropriate directory into memory
  - Directory is just a file in UNIX
    - Special **type** field
- **Update** directory with new file name and FCB
- Write directory back to disk

Directory implementation: Hash table

- Linear list **and** a hash table is maintained
- Key computed from file name
  - Hash table value returns pointer to entry in linear list
- Things to consider
  1. Account for **collisions** in the hash space
  2. Need to **rehash** the hash table when the number of entries exceed the limit

Contiguous Allocation

- Each file occupies a set of contiguous blocks on the disk
  - If file is of size **`n`** blocks and starts at location **`b`**
    - Occupies blocks **`b`**, **`b+1`**, …, **`b+n-1`**
- Disk head movements
  - None for moving from block **`b`** to (**`b+1`**)
  - Only when moving to a different track

Sequential and direct access in contiguous allocations

- Sequential accesses
  - Remember *disk address* of the last referenced block
  - When needed, read the next block

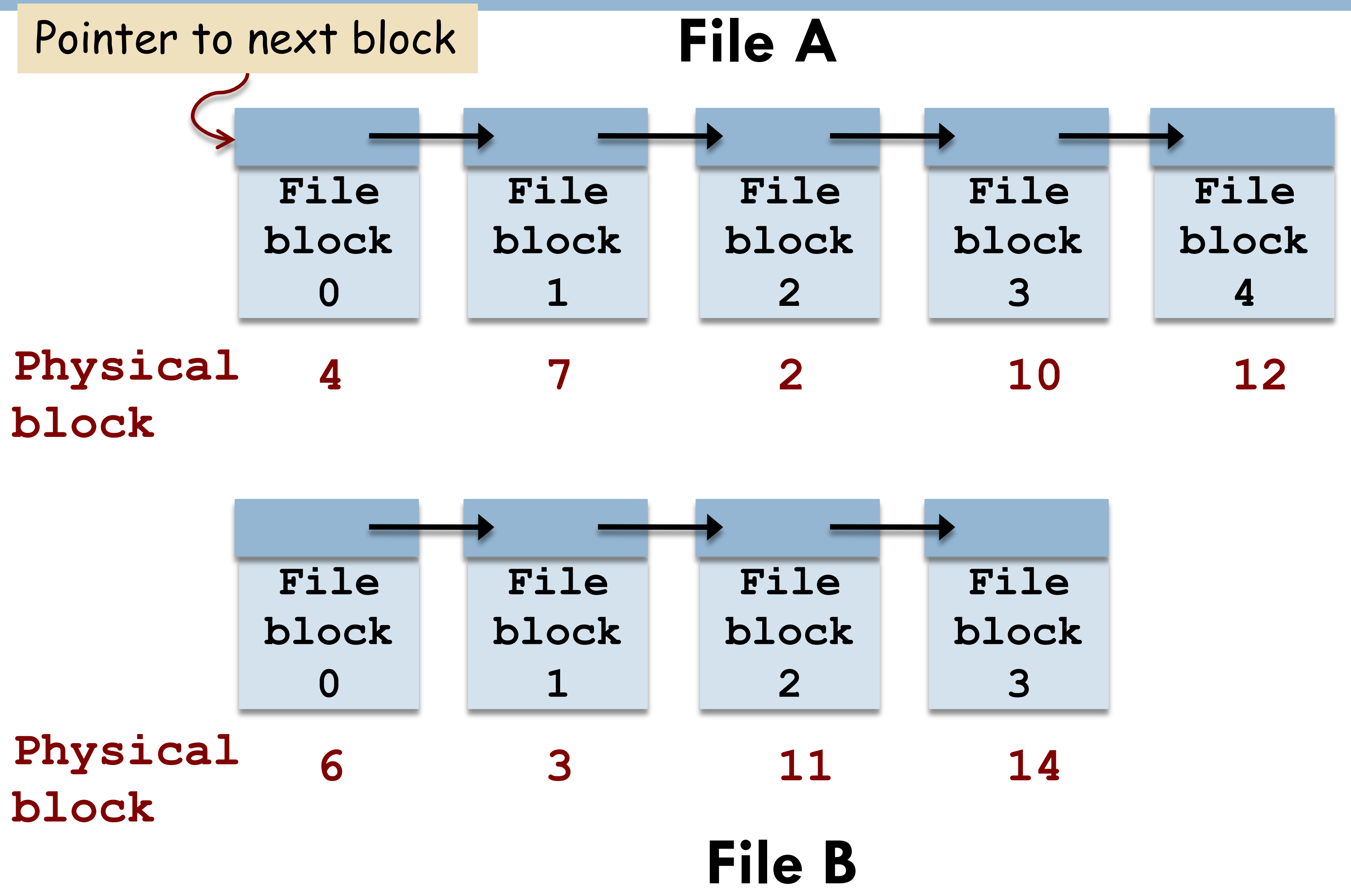
- **Direct access** to block **`i`** of file that starts at block **`b`**

  `b + i`

Contiguous allocations suffer from external fragmentation

- Free space is broken up into chunks
  - Space is **fragmented** into holes
- Largest continuous chunk may be insufficient for meeting request
- **Compaction** is very slow on large disks
  - Needs several hours

Linked Allocation: Each file is a linked list of disk blocks



Linked List Allocations: Advantages

- **Every** disk block can be used
  - No space is lost in external fragmentation
- Sufficient for directory entry to merely store *disk address of first block*
  - Rest can be found starting there

Linked List Allocation: Disadvantages

- Used effectively only for sequential accesses
  - Extremely **slow random access**
- Space in each block set aside for pointers
  - Each file requires *slightly more space*
- Reliability
  - What if a pointer is lost or damaged?

Linked list allocation: Take pointers from disk block and put in table

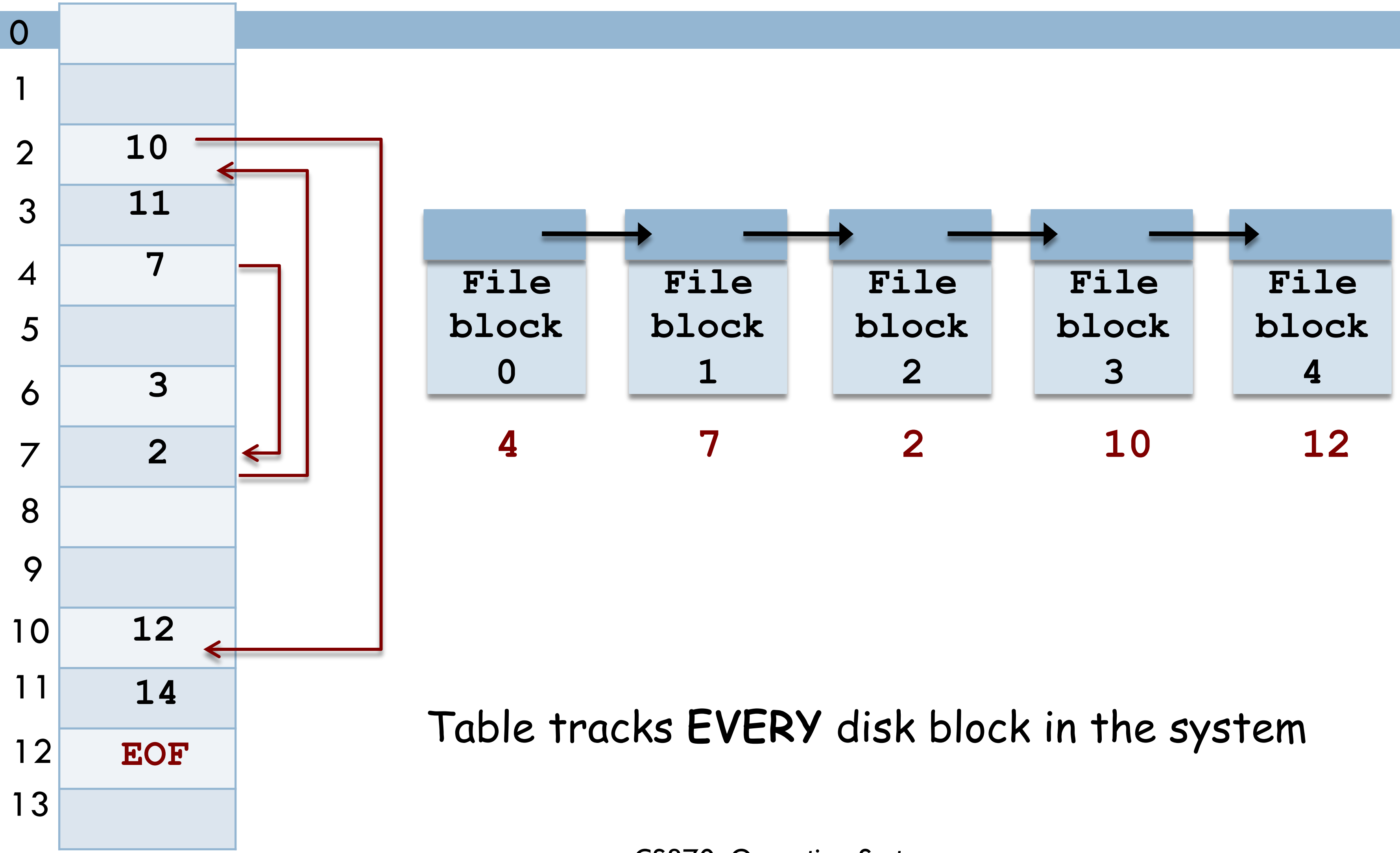


Table tracks **EVERY** disk block in the system

Linked list allocation using an index

- **Entire** disk block is available for data
- Random access is much easier
  - Chain must still be followed
    - But this chain could be cached in memory
- MS-DOS and OS/2 operating systems
  - Use such a file allocation table (FAT)

CS 370: OPERATING SYSTEMS

[FILE SYSTEMS]

Computer Science
Colorado State University

Instructor: Louis-Noel Pouchet
Spring 2024

** Lecture slides created by: SHRIDEEP PALLICKARA

inode

- **Fixed-length** data structure
  - One per file
- Contains information about
  - File **attributes**
    - Size, owner, creation/modification time etc.
  - **Disk addresses**
    - File blocks that comprise file

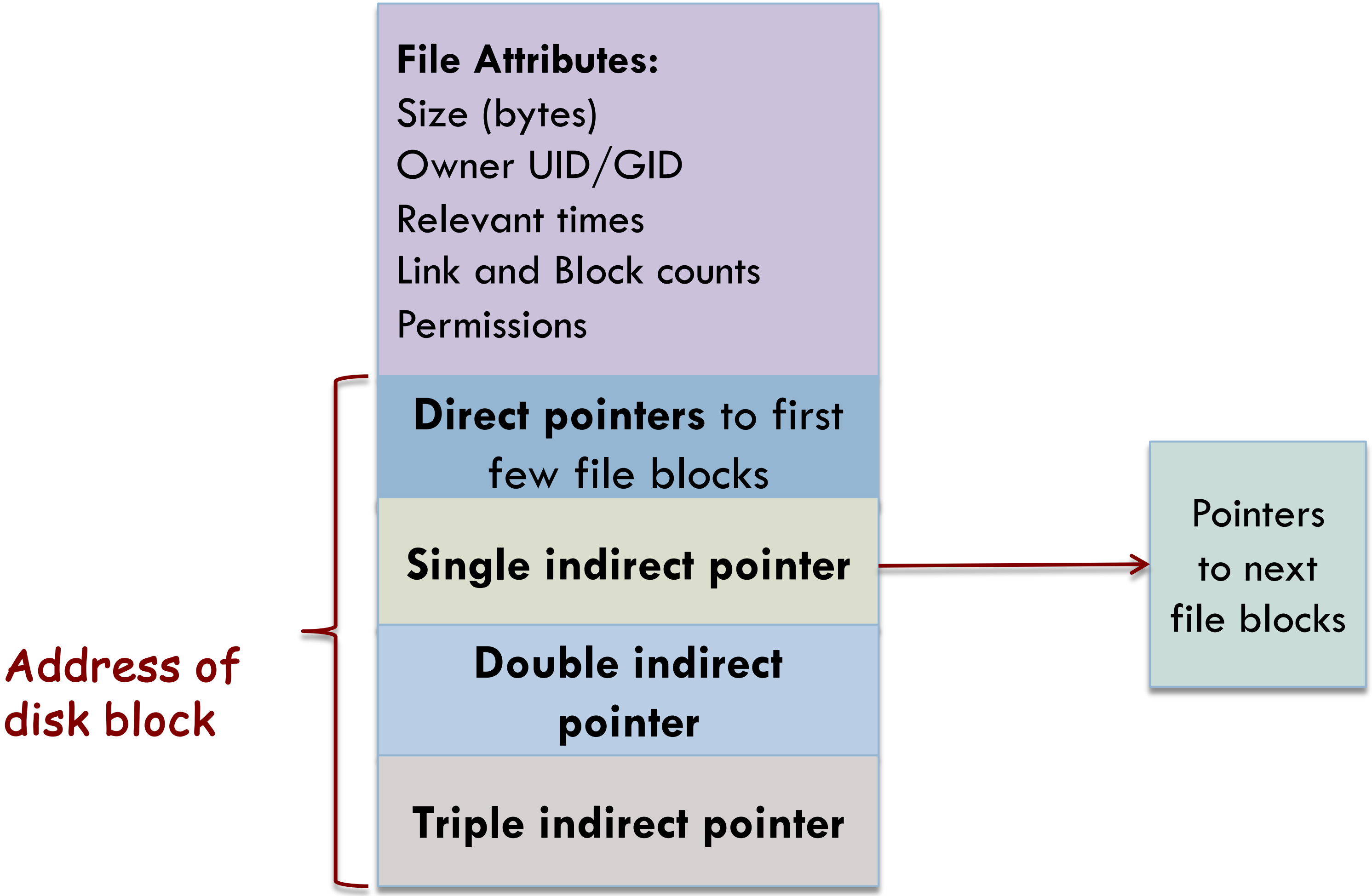
inode

- The inode is used to encapsulate information about a large number of file blocks.
- For e.g.
  - Block size = 8 KB, and file size = 8 GB
  - There would be a million file-blocks
    - inode will store info about the **pointers to these blocks**
  - inode allows us to access info for *all* these blocks
    - Storing pointers to these file blocks also takes up storage

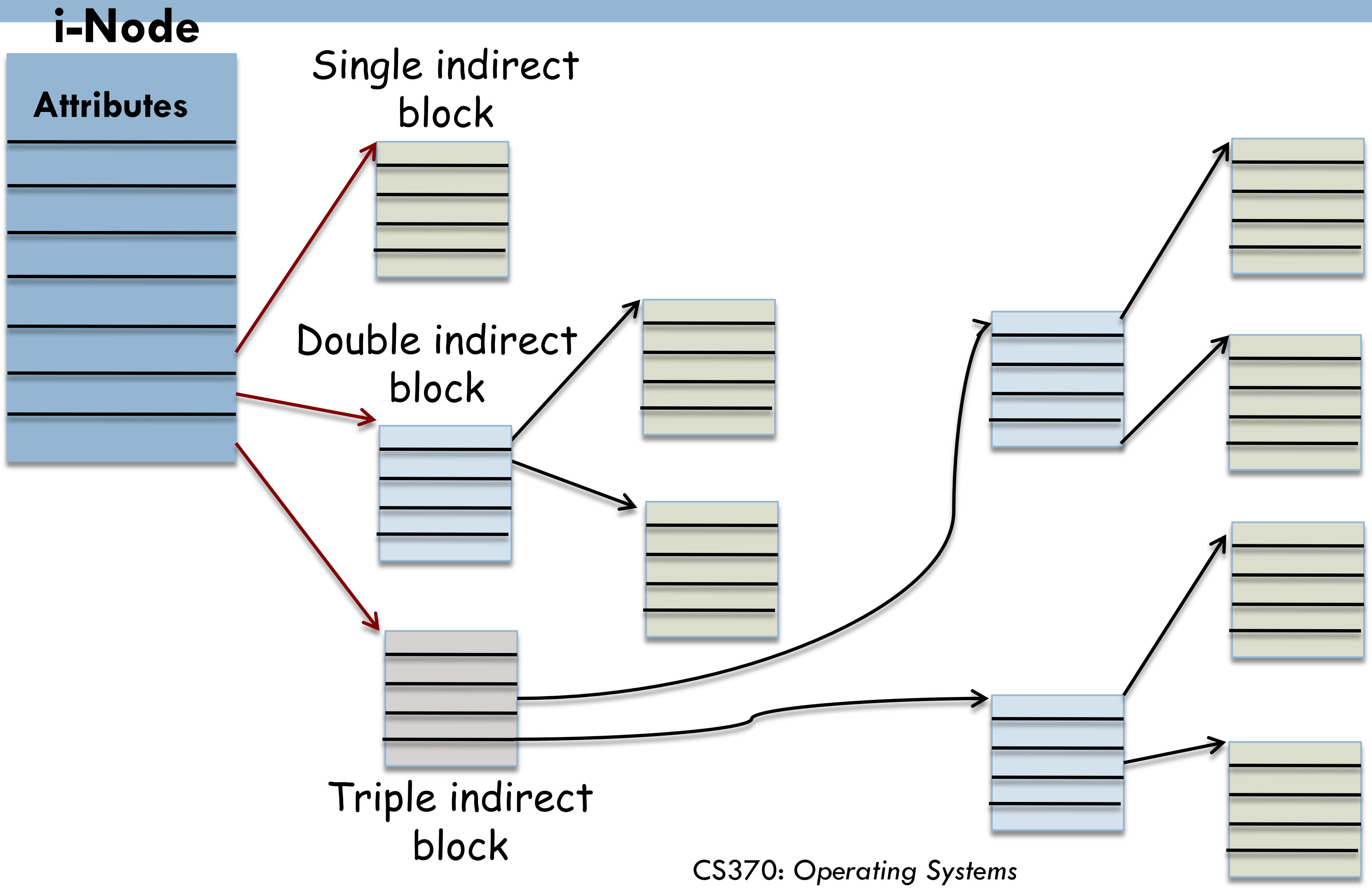
Managing information about data blocks in the inode

- First few data blocks of the file stored in the inode
- If the file is large: **Indirect** pointer
  - To a block of pointers that point to additional data blocks
- If the file is larger: **Double indirect** pointer
  - Pointer to a block of indirect pointers
- If the file is huge: **Triple indirect** pointer
  - Pointer to a block of double-indirect pointers

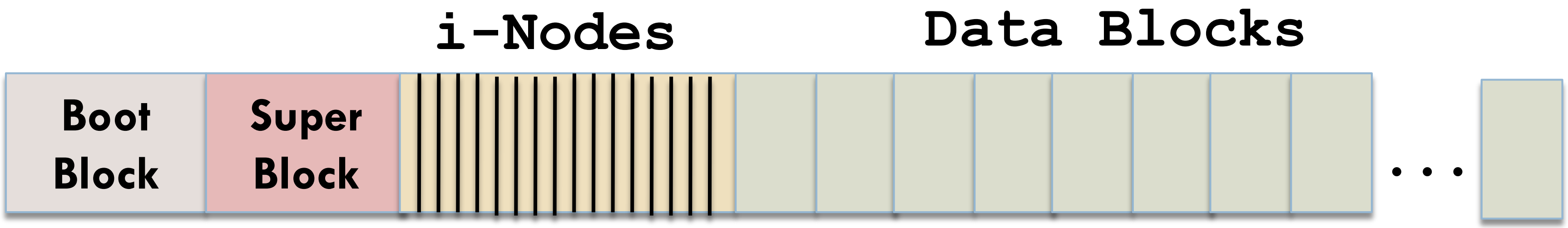
Schematic structure of the inode



i-Node: How the pointers to the file blocks are organized



Disk Layout in traditional UNIX systems



An integral number of inodes fit in a single data block

Super Block describes the state of the file system

- Total size of partition
- Block size and number of disk blocks
- Number of inodes
- List of free blocks
- inode number of the root directory

- Destruction of super block?
  - Will render file system unreadable

A linear array of inodes follows the data block

- inodes are numbered from **1** to some **`max`**
- Each inode is identified by its inode number
  - inode number contains info needed to **locate** inode on the disk
  - Users think of files as filenames
  - UNIX thinks of files in terms of inodes

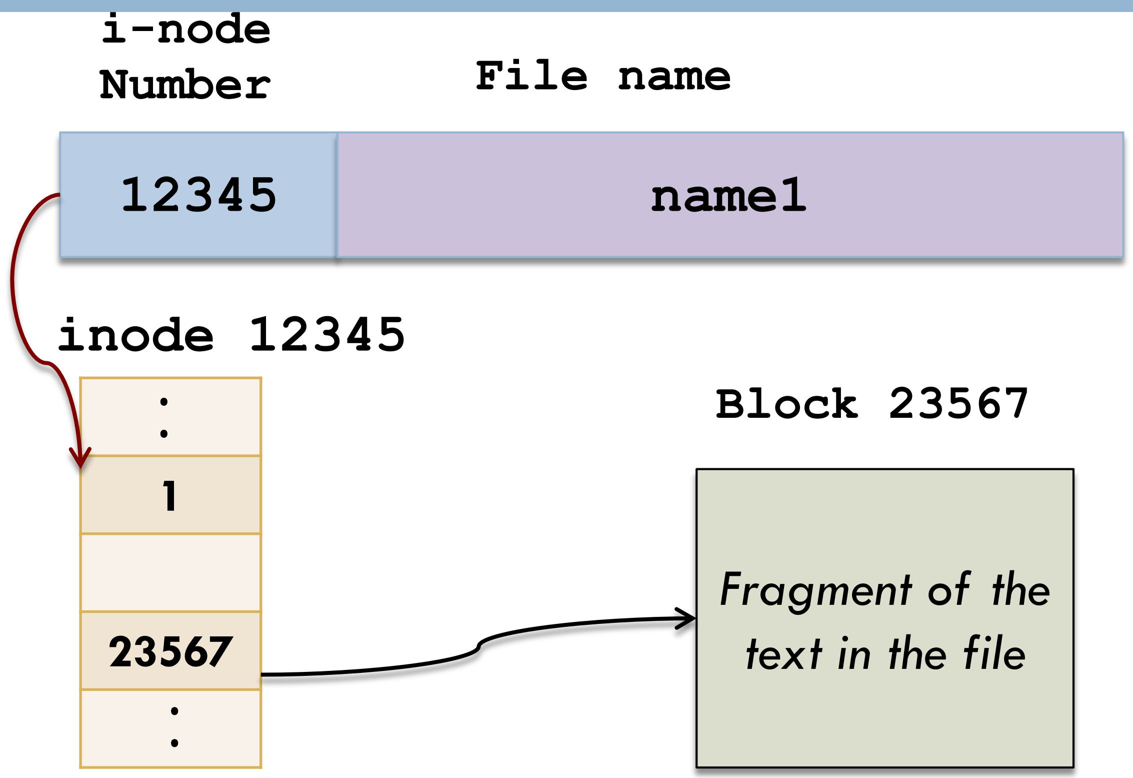
UNIX directory structure

- Contains only file names and the corresponding inode numbers

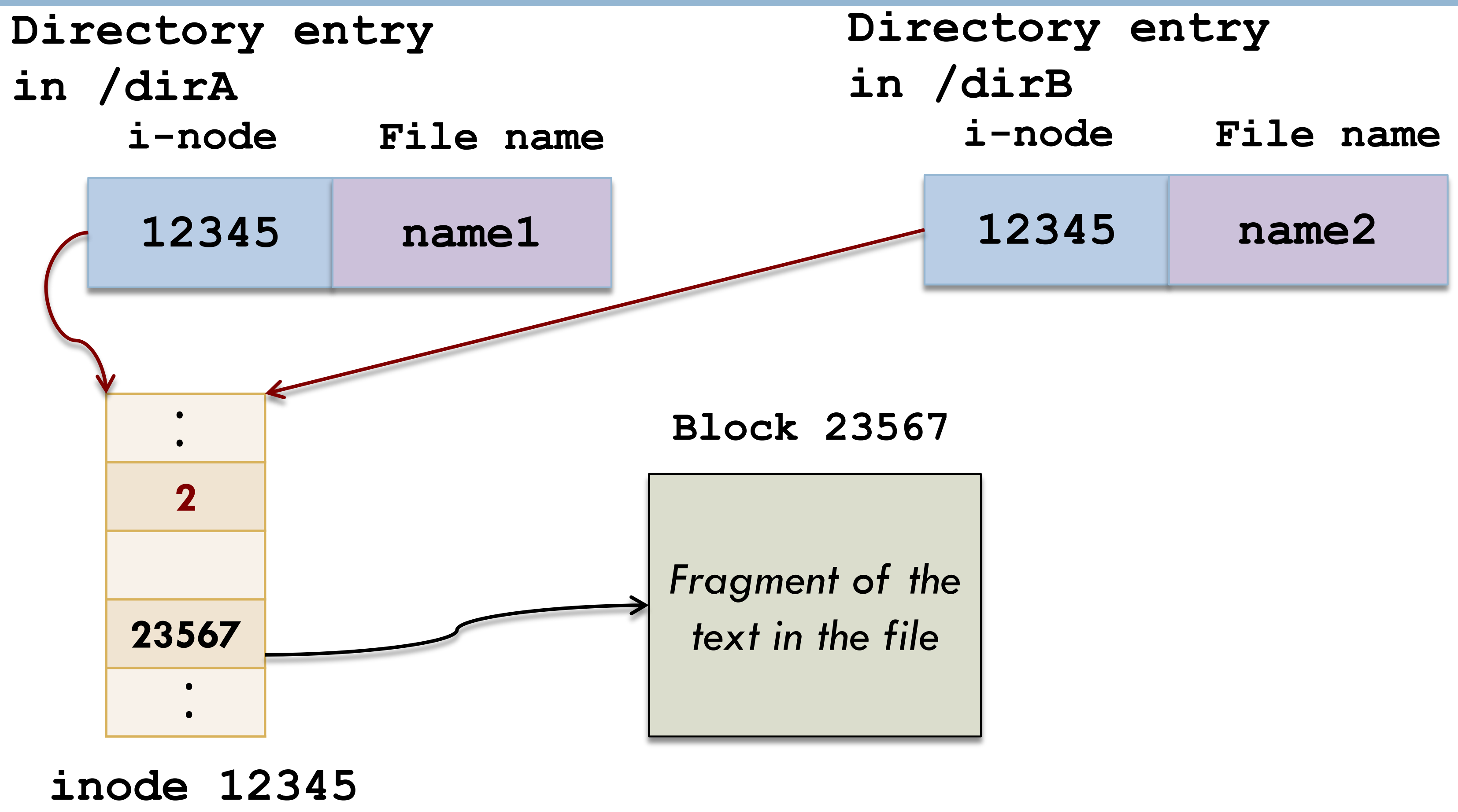
i-node Number	File name

- Use `ls -i` to retrieve inode numbers of the files in the directory

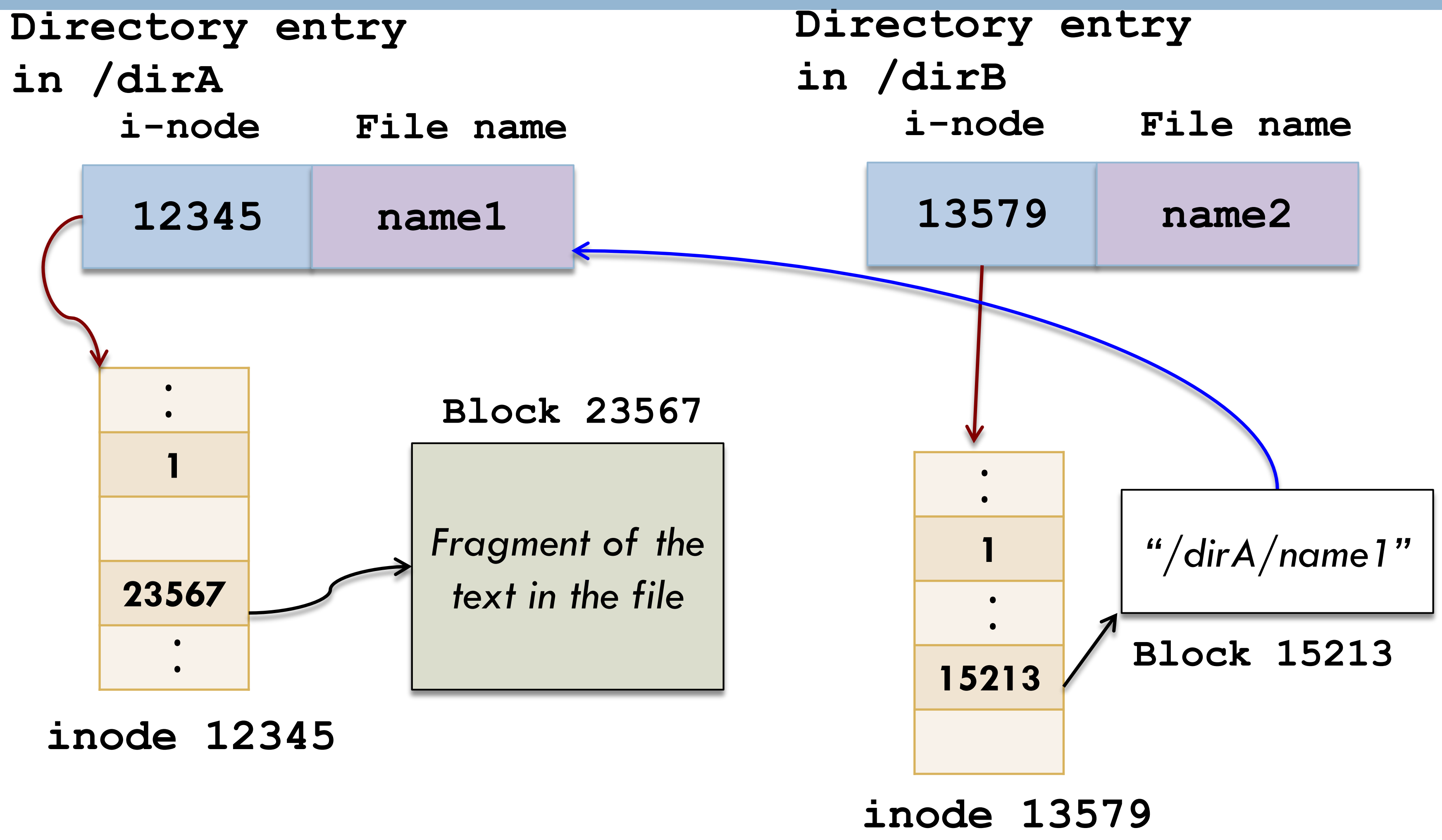
Directory entry, inode and data block for a simple file



Two hard links to the same file



File with a symbolic link



Limitations of a file system based on inodes

- File **must fit** in a single disk partition
- Partition size and number of files are **fixed** when system is set up

Memory mapped files

- `open()`, `read()`, `write()`
  - Requires system calls and disk access
- Allow part of the virtual address space to be logically associated with the file
  - **Memory mapping**

Memory-mapping maps a disk block to a page (or pages) in memory

- Manipulate files through memory
  - Multiple processes may **map** file concurrently
    - Enables data sharing
  - Since JVM 1.4, Java supports memory-mapped files
    - FileChannel
- Writes to files in memory are not necessarily immediate