CSI 3131

Operating Systems

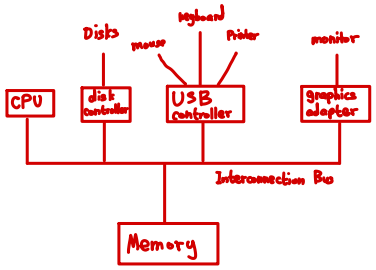
Study Guide

Summer 2024

Organization

Computer Hardware Consists of

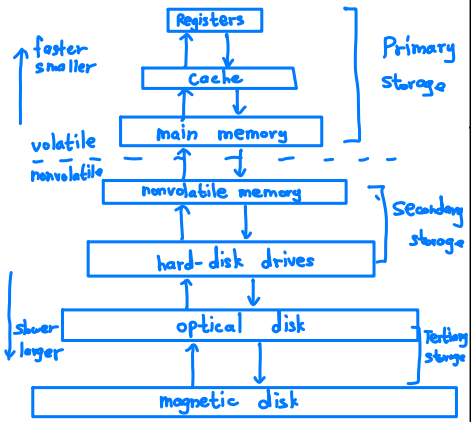
- one or more CPUs
- A main RAM memory for program
- I/O Device controllers
  - Local I/O ports
  - Special-purpose registers for moving data between peripheral devices
  - OS has device driver for each device controller that manages I/O, and provides uniform interface between controller and kernel (OS)
- Interconnection Bus



Storage Structure

- Register and cache
  - Implemented in static random-access memory
  - Volatile
- Main memory
  - Implemented in dynamic random-access memory
  - Only large storage media that the CPU can access directly
  - Volatile
- Secondary Storage
  - Extension of main memory
  - Large, nonvolatile storage capacity
  - Example: Solid-state disks
    - faster than hard disks
    - nonvolatile
    - Popular for light-weight and no mechanical or moving components.

The Storage Hierarchy



Interrupts

- Alert CPU events that require attention
- Interrupts used by OS to handle asynchronous events
- Trap: software interrupt
  - Caused by error or system call
- To start an I/O operation, the device driver loads the appropriate registers in the device controller to control the data flow.
  - Controller starts transfer of data from device to its local buffer
  - Once done, device controller informs device driver it has finished its operation using interrupt
  - Interrupt signaled to CPU requesting to be serviced

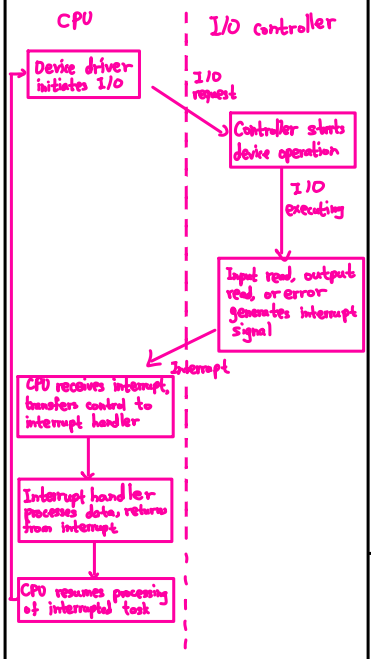
Interrupt Handling

- CPU stops what it is doing
  - Push CPU register contents to a stack
  - Save address of interrupted instruction
- Then interrupt transfers control to interrupt service routine through interrupt vector
- After finishing execution of ISR, the system must return from interrupt
  - Pull CPU contents back from the stack and resume execution from next instruction of interrupted program
- An operating system is interrupt-driven

I/O Interrupt Timeline

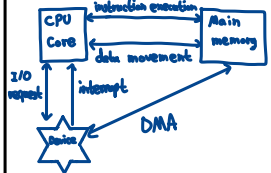
1. User program runs
2. I/O device receives I/O request
3. I/O device transfers data, signals interrupt
4. CPU receives interrupt, halts execution of user program.
5. Execution resumes
6. Repeat

Interrupt Cycle



Direct Memory Access (DMA)

- Used for high-speed I/O devices able to transmit information at close to memory speeds
- The form of interrupt-driven I/O described in Section Interrupts is fine for moving small amounts of data but can produce high overhead when used for bulk data movements
- To solve this problem, DMA is used
  - After setting up buffers, pointers, and counters for the I/O device, the device controller transfers an entire block of data directly to or from the device and main memory, with no intervention by the CPU.
  - Only one interrupt is generated per block, to tell the device driver that the operation has completed, rather than the one interrupt per byte generated for low-speed devices.
  - While the device controller is performing these operations, the CPU is available to accomplish other work



Interrupt-Handling Features

- Maskable interrupt can be temporarily disabled. Important when we want to defer interrupt handling during critical processing. Used by device controllers to request service.
- Nonmaskable interrupt cannot be disabled and must be served immediately. Reserved for events such as unrecoverable memory errors, or system reset.
- Interrupt mechanism also implements a system of interrupt priority levels
  - CPU defers handling of low-priority interrupts without masking all interrupts and makes it possible for a high-priority interrupt to preempt the execution of a low-priority interrupt.

Computer System Architecture

- Single Processor
  - Some small systems still use a single processor
  - They can also have some other special-purpose processors as well
- Multiprocessors
  - Growing in use and importance
  - Also known as parallel systems, tightly-coupled systems
  - Advantages include:
    - Increased throughput
    - Economy of scale
    - Increased reliability
  - Two Types
    - Asymmetric Multiprocessing: each processor is assigned a specific task
    - Symmetric Multiprocessing: each processor performs all tasks
- Clustered Systems
  - Loosely coupled multiple CPUs
  - Usually used to provide high-availability service

What Operating Systems Do?

- OS is a program that acts as an intermediary between a user of a computer and the hardware to
  - abstract and manage a computer's hardware resources
  - Use the computer hardware in an efficient manner
  - Provides a basis and control the execution of programs
- The OS is a resource allocator
  - Resources include CPU time, memory space, storage space, I/O devices, etc.
  - Hardware resources are shared between programs. The OS decides how to allocate them to specific programs and users in an efficient and fair way.
- The OS is a control program
  - Manages execution of user programs to prevent errors and improper use of computer.

Computer System Structure

- Can be divided into 4 components: hardware, operating system, application programs, and user.
- Hardware: provides basic computing resources for the system.
- Operating System: controls hardware and coordinates its use among the various application programs (processes) for the various users.
- Application Programs: Define the ways in which these resources are used to solve users' computing problems
- User: People, machines, other computers

Kernel

- The kernel is the fundamental part of an OS. It is a piece of software responsible for providing computer programs with secure access to the hardware.
- Many processes can run in parallel, and access to the limited hardware should be shared, the kernel decides when and how long a process should be able to make use of a piece of hardware.
- Kernels implement a set of abstractions over the hardware. These abstractions hide the hardware complexity and provide a clean and uniform interface to the underlying hardware, which makes application programs more portable and easier to develop.

System Programs

- Some services are provided outside of the kernel by system programs.
- System programs are anything not in the kernel but shipped with the OS.
- System programs are loaded into memory at boot time to become system daemons.
  - System daemons run the entire time the kernel is running.
- System programs are also called utility programs that provides some services like:
  - File management
  - Status information
  - Editing files
  - Programming language support
  - Program loading and execution
  - Communications
  - Application programs

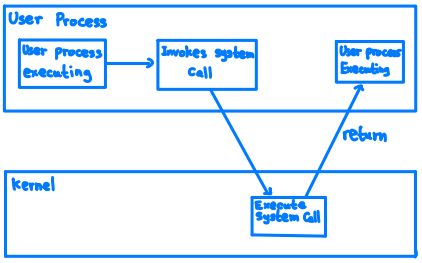
Dual Mode

- OS is interrupt driven
  - Hardware interrupt by external devices
  - Software interrupt (trap): caused either by an error or by a system call
- Some operations will have to be done only by reliable programs
- A solution is an operation in dual mode
- Dual mode allows the OS to protect itself and other system components
  - User mode (unprotected)
  - Kernel mode (protected)
- Mode bit: a bit added to hardware to indicate the current mode
  - 0 for kernel
  - 1 for user
- Some instructions are designated as privileged (may cause harm if badly implemented), only executable in kernel mode.
  - If an attempt is made to execute a privileged instruction in user mode, the hardware does not execute the instruction but rather treats it as illegal and traps it to the OS
- System call to OS changes mode bit to kernel mode, return from call sets it to user mode.

Timer

- A timer is used to prevent processes from getting stuck and never return control to the OS.
  - Before turning over control to the user, the OS ensures that the timer is set to interrupt.
  - A timer can be set to interrupt the computer after a specified period.
    - Keep a counter that is decremented by the physical clock. When it hits zero an interrupt is raised for an action.
    - If the timer interrupts, then the control transfers automatically to the OS, which may treat the interrupt as a fatal error or may give the program some more time.
    - Clearly, instructions that modify the content of the timer are privileged

Transition from User to Kernel mode



Resource Management

- Process Management
  - A process is an instance of program in execution.
  - OS manage resources needed by a process to accomplish its task
  - OS monitor and manage process activities like creation, termination, communication between Processes, process scheduling
- Main Memory Management
  - OS determines which process and when it occupies the main memory to optimize CPU usage and the computer's response to users
- Storage and File-System Management
  - The OS provides a uniform, logical view of the information (files) stored in secondary memory
- I/O subsystem
  - One of the purposes of the OS is to hide the peculiarities of specific hardware devices from the user

Virtualization

- Allows applications of different OS's to run on the same machine at the same time
- Allows different OS's to run on the same machine at the same time
- Allows OS's to run as applications with other OS's
- Emulation used when source CPU type is different from target type
- Virtual Machine Manager (VMM): runs the guest OS's, manages their resource use, and protects each guest from the others
- A user of a Virtual Machine (VM) can switch among the various OS's in the same way a user can switch among the various processes running concurrently in a single operating system
- Advantages of Virtualization
  - Each VM can use a different OS
  - In theory, we can build VMs on VMs
  - Complete protection, because VMs are isolated from each other
  - A new OS can be developed on a VM without disturbing others

Operating System Services

- An OS provides an environment for the execution of programs
  - Makes certain services to programs and to the users of those programs
  - Differ from one OS to another
- Program Execution
  - System must be able to: load, execute, and end the program
- I/O Operations
  - A running program may require I/O, which may involve a file or an I/O device.
  - For efficiency and protection, this must be done in kernel mode
- File-System Manipulation
  - Programs may need to do some operations over files or directories:
    - read, write, delete, search, create
  - OS can manage ownership, permissions or access to files or directories
- Communications
  - One process may need to exchange information with another process
    - Such communication may occur between processes that are executing on the same computer or between processes that are executing on different computer systems
    - Can be implemented via shared memory or message passing
- Resource Allocation
  - Multiple processes running at the same time and to ensure the efficient operation, the limited hardware resources must be allocated to each of them by the OS
  - The OS manages many different types of resources
    - Some resources managed by a specific allocation code
    - Others may be managed by a general request and release code
- Accounting (Logging)
  - Statistics or record keeping for different purposes such as:
    - how much and what kinds of computer resources a program uses
    - accounting (so that users can be billed)
  - Usage statistics may be a valuable tool for system administrators who wish to reconfigure the system to improve computing services
- Error Detection
  - One of the OS tasks is to detect and correct errors constantly
  - OS should take appropriate action to ensure correct and consistent computing
- Protection and Security
  - To control the use of information stored in a multiuser or networked computer system
    - Manage access authentications of different users
    - Prevent unauthorized access to the system
    - Prevent unauthorized access to resources
- User Interface
  - Most commonly
    - Graphical user interface: mouse and a keyboard
    - Touch-screen interface: "fingers" as in mobile systems
    - Command-line interface: a keyboard for typing in commands for more professional use

Command-Line Interface

- The command interpreter is a program that reads commands typed by the user
  - Command interpreters also known as shells
  - The main function of the command interpreter is to get and execute a user command
- The commands can be implemented in two general ways
  - Direct execution by the interpreter
  - By programming "custom-made" commands through system programs

Graphical User Interface (GUI)

- Users employ a mouse-based window-and-menu system characterized by a desktop metaphor
- Icons on the screen represent programs, file, directories, and system functions.
- GUI first appeared in the early 1970s at Xerox PARC research facility
- GUI became more widespread with the advent of Apple MacIntosh computers in the 1980s

User and OS Interface on Major OS's

- Major OS systems include CLI and GUI interfaces
  - Microsoft Windows is GUI with a CLI
  - MacOS provides both an Aqua GUI and a CLI
  - KDE and GNOME GUI desktops run on Linux, Solaris, and various UNIX systems and are available under open-source licenses

Choice of Interface

- The choice of whether to use a command-line or GUI interface is mostly one of personal preference
  - GUI and Touch-Screen interface are most of the population choice... user friendly interfaces
  - System administrators and power users who have deep knowledge of a system frequently use the command-line interface.
  - In most cases, only a subset of system functions is available via the GUI, the most advanced tasks are command-line only!
  - CLI is more efficient, giving faster access to the activities need to perform.
  - CLI usually make repetitive tasks easier, in part because they have their own programmability
  - A set of command-line steps can be recorded into a file, and that file can be run like a program.

System Calls

- System calls provide an interface to the services made available by an OS
- Generally available as C functions written in C and C++ (sometimes assembly)
- System calls are generated by user programs
- At the end of the function, the mode change back to user mode and values are returned to the calling program

Application Programming Interface (API)

- Application developers design programs according to an API
- The API specifies a set of C functions that are available to an application programmer
- Three of the most common APIs
  - Windows API for Windows systems
  - POSIX API for POSIX-based system
  - Java API for Java Virtual Machine
- Behind the scenes, the functions that make up an API typically invoke the actual system calls on behalf of the application programmer.
  - Actual system calls abstracted from application programmer by the API function
- Application programmer have the choice to use system calls directly
- Advantages of API over system calls
  - Improve program portability: the program to compile and run on any system that supports the same API
  - API hides complicated details
    - Caller doesn't need to know about how system call is implemented or what it does during execution
    - Rather, caller need only obey the API and understand what the OS will do as a result of execution of system call.

Handling a System Call

- User application invokes the system call through the system call interface
- System uses CPU-specific method to transition from user mode to kernel mode and pass the system call information to the kernel
- Each system call has a number that is used as an index in the system call table to invoke the appropriate code for the system call
- The system call executes and returns once it completes (or indicates an error).
- The system transitions from kernel mode back to user mode

Types of System Calls

- System calls can be grouped into six major categories
  - Process Control
    - Create, terminate, load, execute, etc.
  - File Management
    - Create, delete, open, close, read, write, etc.
  - Device Management
    - Request, release, read, write, etc.
  - Information Management
    - Set/get time, date, and get/set, process, file, or device attributes
  - Communication
    - Create/delete communication connection, send/receive messages, etc.
  - Protection
    - Get/set file permissions

Parameter Passing in System Calls

- Three general methods are used to pass parameters to the OS
  - Pass the parameters in registers: number of parameters is very limited
  - Store the parameters to pass in a block, or table, in memory, and the address of the block is passed as a parameter in a register or as a pointer to the bloc in C programming
  - Parameters can be placed, or pushed, onto a stack by the program and popped off the stack by the OS
- Some other operating systems prefer the block or stack method because those approaches do not limit the number or length of parameters being passed

OS Design and Implementation

- At the highest level, the design of the system will be affected by the choice of hardware and the type of OS
- The requirements: user goals and system goals
  - A user wants a system to be convenient to use, easy to learn and to use, reliable, safe, and fast. These specifications are not particularly useful in the system design, since there is no general agreement on how to achieve them
  - The system should be easy to design, implement, and maintain; and it should be flexible, reliable, error free, and efficient. Again, these requirements are weak and may be interpreted in various ways
- Implementation
  - Today, especially in C and C++, with small sections in assembly. Java may be used for UIs
  - CPU registers and peripheral ports can only be accessed in assembly.

OS Structure

- Internal structure of different OS's can vary widely
- Monolithic Structure
  - Hardware resources, simple functionality
  - Simplest structure, kernel is one program file
  - Advantage:
    - OS in a single address space provides very efficient performance
  - Disadvantage:
    - Tightly coupled kernel
    - Difficult to implement and extend
- Layered Structure
  - OS broken down into a number of layers
  - Bottom layer is hardware, highest layer is UI
  - Advantages
    - More resources and functionalities, simple to debug
    - Lower layer abstract operation implementation details from higher layer

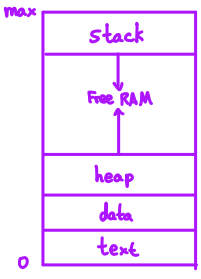
- The kernel is a loosely coupled system
- Disadvantages:
  - Appropriately defining the functionality of each layer
  - Poor overall performance
- Micro-kernel structure
  - Shrinking the kernel to minimum essential services
  - Moving all nonessential components from the kernel and implementing them as user-level programs
  - Advantages:
    - More resources and functionalities
    - Easily extendable and portable, security and reliability
  - Disadvantages:
    - Performance of microkernels can suffer due to increased system-function overhead
- Modular Structure
  - Flexibility and efficiency, services are implemented or removed dynamically
- Hybrid Systems
  - In practice very few operating systems adopt a single, strictly defined structure. Instead, they combine different structures, resulting in hybrid systems that address performance, security, and usability issues.

Processes

- A process is a program loaded into memory and executing (program in execution)
- To accomplish its task, a process will need certain resources such as
  - CPU time
  - Memory
  - Files
  - I/O devices
- A process is the unit of work in most systems
- Systems consist of a collection of processes
  - OS processes execute system code
  - User processes execute user code
- Programs and processes are different
  - A program stored on a HD is a passive entity
  - A process is an active entity, with a program counter specifying the next instruction to execute and a set of associated resources

Process in Memory

- Text section: executable code
- Data section: global variables
- Heap section: memory dynamically allocated during program run time
- Stack section: temporary data storage when invoking functions



Process States

- New: The process is being created
- Running: Instructions of process being executed
- Waiting: Process waiting for some event to occur
- Ready: Process waiting to be assigned to CPU
- Terminated: Process finished execution or forced to terminate

Process Control Block

- In multiprogramming, a process is running on the CPU intermittently
- Whenever a process takes over the CPU, it must resume from the state from where it was interrupted
- So, when a process execution is interrupted, PCB is used as the repository for all the data needed to start, or restart, a process, along with some accounting data.
- A PCB is a per-process data structure containing many pieces of information associated with the process.
- A PCB contains the following:
  - Process State: new, ready, running, waiting, terminated
  - Program Counter: indicates address of next instruction to be executed for this process. Must be saved to allow the process to be continued correctly when it runs again.
  - Other CPU registers: vary depending on architecture.
  - CPU scheduling information: process priority, scheduling queue pointers, other scheduling parameters
  - Memory-management information: value of base and limit registers and page tables, or segment tables, depending on memory system used by the OS
  - Accounting information: Amount of CPU and real time used, time limits, account numbers, job or process numbers
  - I/O status information: This information includes the list of I/O devices allocated to the process a list of open files, and so on.
  - Pointer to next PCB in a linked list

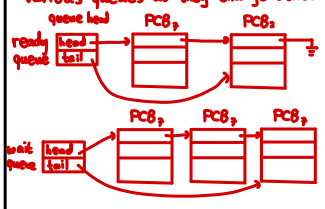
Process State
Process Number
Program Counter
Registers
Memory limits
List of open files
. .

Process Scheduling

- The objective of multiprogramming is to have some process running at all times so as to maximize CPU utilization
- The objective of time sharing is to switch a CPU core among processes so frequently - users perceive as all programs are running in parallel
- Process scheduler selects a process from a set of available processes for execution on a core
- For a system with a single CPU core, there will never be more than one process running at a time
- Multicore system can run multiple processes at one time. But we still need scheduling as if there are more processes than cores, excess processes will have to reschedule. The number of processes currently in memory is known as the degree of multiprogramming

Process Scheduling Queues

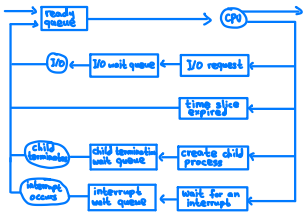
- As processes enter a system, they are put into a ready queue
  - where they are ready and waiting to execute on a CPU's core
  - This queue is generally stored as a linked list
  - Each PCB includes a pointer field that points to the next PCB in the ready queue
- The system includes other queues
- A running process on a CPU core will have to eventually terminate, interrupt, or wait
- Suppose the process makes an I/O request to a device such as a disk
  - A disk runs significantly than processes, the process will have to wait for the I/O to become available
  - Processes that are waiting for a certain event to occur are placed in the wait queue
- Processes can migrate between the various queues as they change states



- When a process migrate between the various queues, they do not physically move into memory
- The corresponding PCB's pointers are modified to point to a different queue

CPU Scheduling (short-term)

- The role of the CPU scheduler is to select from among the processes that are in the ready queue and allocate a CPU core to one of them
  - CPU scheduling decides which of the ready processes should run next on the CPU
- The CPU scheduler must select a new process for the CPU frequently
  - An I/O-bound process may execute for only a few milliseconds before waiting for an I/O request
  - A CPU-bound process will require a CPU core for longer durations, the scheduler is likely to remove the CPU from it and schedule another process to run
  - Therefore, the CPU scheduler executes at least once every 100 milliseconds, or much more frequently
- There are 2 types of queues present in the scheduling process



- The diagram above is the queueing diagram for scheduling
  - Circles represent resources that serve the queues
  - Arrows indicate flow of processes
- When a process terminates, it is removed from all queues and has its PCB and resources deallocated

Swapping (Intermediate Scheduling)

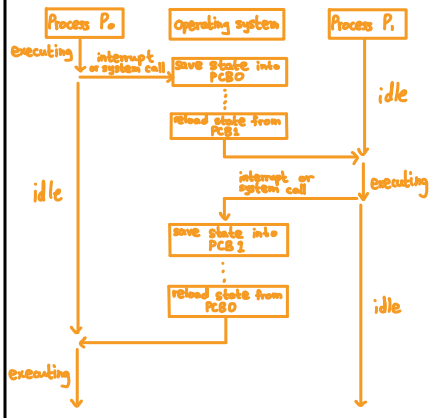
- Some operating systems have an intermediate form of scheduling, known as swapping
- Can be called if degree of multiprogramming needs to decrease by removing a process from memory to a disk storage
- Later, the process can be reintroduced into memory, to resume its execution (swapping)
- A swapping is
  - A process can be "swapped out" from memory to disk and its current status is saved
  - Later "swapped in" from disk back to memory, where its status is restored
- Swapping is typically only necessary when memory has been overcommitted and must be freed up

Long-term Scheduling

- Long-term scheduling decides when a process should enter the ready state and start competing for the CPU
  - Processes are created at unpredictable times and enter the system with the process state new
  - Long-term scheduling decides which new processes are moved to the ready queue to compete for the CPU
  - Processes are also subject to long-term scheduling when suspended and later reactivated by the OS.
- Long-term scheduling controls the degree of multiprogramming to achieve optimal performance
- Long-term scheduling takes place less frequently than short-term scheduling
  - Occurs only at process creation and when the OS suspends the process

Context Switch

- Context Switch is when the CPU moves from executing one process, say process 0, to another process, say process 1
- Context Switch occurs when the CPU is interrupted during the execution of process 0
- Save the running process (0) current context to PCB0 (state save)
  - Essentially suspending the process
  - Context: The state of its execution, including the contents of registers, its PC, and its memory content
- Finds and accesses the PCB1 of process 1, that was previously saved
- Perform context restore from PCB1
  - Essentially the opposite of context save to run the previously suspended process 1
- Then when process 1 is done, the above steps can be repeated to suspend process 1 and to run process 0 again



Process Creation

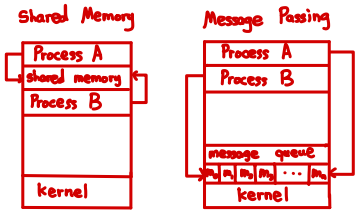
- During execution, a process (Parent) can create one child process
  - In turn, a child process can also have children processes - forming a tree of processes
- Generally, a process is identified and managed via a process identifier (pid), which is typically an integer number
- Usually, several properties can be specified at child creation time:
  - Resource sharing options
    - Share all resources
    - Share a subset of parent's resources
    - No sharing
  - When a parent creates a new process, two possibilities for execution exist:
    - Parent and child execute concurrently
    - Parent waits until children terminate
  - There are two address-space possibilities for the new process:
    - Child duplicate of parent
    - Child has a new program loaded into it
- We may need a child process because we need to fulfil a need for a program to perform more than one function simultaneously
- When a parent process creates a child process, it passes some data or instructions to the child process. The child process is an independent entity that can execute a different program or perform a different task from the parent process
- In UNIX, a new process is created by fork() system call
  - The new process consists of a copy of the address space of the parent process
    - The parent and the child continue execution at the instruction after the fork()
    - fork() returns: 0 if child executing, PID of child if parent executing
  - Parent may call wait() to wait until child terminates
  - exec...) system call, used after a fork() to replace the process' memory with a new program
  - When child process completes parent resumes from call to wait() until it completes
- n fork, $2^n - 1$ child processes

Process Termination

- Process executes last statement and asks the OS to delete it by exit() system call
  - Return status data from child to parent via wait()
  - Process's resources deallocated by OS
- Abnormal termination can occur because of errors
- Parent may terminate the execution of children processes using the abort() system call
- Some operating systems do not allow a child to exist if its parent has terminated. If a process terminates, then all its children must also be terminated
- The parent process may wait for termination of a child process by using the wait() system call. The call returns status information and the pid of the terminated process
- A child process that has terminated but whose parent has not invoked wait(), is known as a zombie process
  - Zombie processes exist only briefly until the parent calls wait(), then the zombie process identifier and its entry in the process table are released
- If the parent terminates without invoking wait(), the child process is an orphan

Interprocess Communication (IPC)

- Processes executing concurrently in the OS may be independent or cooperating
  - A process is independent if it does not share data with any other processes executing in the system
  - A process is cooperating if it can affect or be affected by the other processes executing in the system
- Reasons for cooperating processes:
  - Information sharing
  - Communication speedup
  - Modularity
- Cooperating processes requires interprocess communication (IPC)
- Two models of IPC:
  - Shared memory: processes can read/write data by a shared memory region
  - Message passing: cooperating processes communicate by message exchange
- Cooperating processes need IPC mechanism to exchange data and to synchronize their actions
  - Shared memory: typically faster than message passing - initial system call only to establish the shared memory segment, afterward it can be accessed in user mode
  - Message passing: all communications use system calls
    - Easier to implement



IPC - Shared Memory

- Normally the OS prevent one process from accessing another process's memory
- Shared memory requires that two or more processes agree to remove this restriction
  - One process makes a system call to create a shared memory region
  - Other processes make system call to attach a shared memory region to their address space
  - The data and the location are determined by these processes and are not under the operating system's control
- Major issue is to provide mechanism that will allow the user processes to synchronize their actions when they access shared memory
  - The processes are responsible for ensuring that they are not writing to the same location simultaneously
  - Producer-consumer problem, common paradigm for cooperating processes
  - Producer produces information and the consumer consumes it

IPC - Message Passing

- Message passing provides a mechanism to allow processes to communicate and to synchronize their actions without sharing the same address space
- Communication link is needed
  - Logical implementation: several methods, and notably the send()/receive() operations:
    - Direct or indirect communication
    - Synchronous or asynchronous communication
    - Automatic or explicit buffering
  - Hardware implementation: bus, or network

Message Passing - Direct Communication

- Under direct communication, processes must name each other explicitly:
  - send (P, message) - send message to process P
  - receive (Q, message) - receive message from process Q
- Properties of communication link:
  - Links are established automatically
  - A link is associated with exactly one pair of communicating processes
  - Between each pair there exists exactly one link
  - The link may be unidirectional, but is usually bi-directional
- This scheme exhibits symmetry in addressing
  - Both sender and receiver processes must name the other to communicate
- A variant of Direct communication employs asymmetry in addressing
  - Only sender names recipient, recipient not required to name sender
- Primitives are defined as follows:
  - send (P, message) - send a message to process P
  - receive (id, message) - receive message from any process
  - variable id set to name of the process with which communication has taken place
- Limitations:
  - Process definitions limited modularity of the resulting process definitions
  - Changing the id of a process may require all other process definitions to update them with the new id

Message Passing - Indirect Communication

- Messages are sent to and received from mailboxes or ports
  - A mailbox can be viewed abstractly as an object into which messages can be placed or removed by processes
  - Each mailbox has unique identification
  - Two processes can communicate only if they have a shared mailbox
- Primitives are defined as follows:
  - send (A, message) - send message to mailbox A
  - receive (A, message) - receive message from mailbox A
- Operations
  - create a new mailbox
  - send and receive messages through mailbox
  - destroy a mailbox
- Mailbox sharing
  - Processes P1, P2, P3 all share mailbox A
  - P1 sends to A while P2 and P3 receive
  - Which process will receive?
- Depends on the chosen method:
  - Allow a link to be associated with two processes at most
  - Allow at most one process at a time to execute a receive() operation
  - Allow the system to select arbitrarily the receiver. The system may identify the receiver to the sender

Message Passing - Synchronization

- Message passing may be either blocking or non-blocking
- Blocking - also known as synchronous message passing
  - Blocking send. The sending process is blocked until the message is received by the receiving process or by the mailbox
  - Blocking receive. The receiver blocks until a message is available
- Non-blocking is considered asynchronous
  - Non-blocking send - sender sends the message and return before the delivery of message
  - Non-blocking receive - receiver receives a valid message, or a null
- Different combinations possible
  - If both are blocking: rendezvous

Message Passing - Buffering

Whether communication is direct or indirect, messages exchanged by communicating processes reside in a temporary queue.

- Zero capacity:
  - no queue exist
  - no messages waiting
  - sender must block until the recipient receives the message
- Bounded capacity:
  - queue has finite length n
  - at most n messages can reside in it
  - if the queue is not full when a new message is sent, the message is placed in the queue, and the sender can continue execution without waiting
  - if link is full, the sender must block until space is available in the queue
- Unbounded capacity:
  - The queue's length is potentially infinite, thus, any number of messages can wait in it. The sender never blocks

Pipes

- Acts as a conduit allowing two processes to communicate
- Were one of the first IPC mechanisms in early UNIX systems
- They typically provide one of the simpler ways for processes to communicate with one another
- In implementing a pipe, four issues must be considered:
  - Does the pipe allow bidirectional communication, or is communication unidirectional?
  - If bidirectional communication is allowed, then is it half-duplex or full duplex?
  - Must a relationship exist between the communicating processes?
  - Can the pipes be used over a network, or must be on the same machine?
- Two common types:
  - Ordinary pipes - cannot be accessed from outside the process that created it. Typically, a parent process creates a pipe and uses it to communicate with a child process that it created
  - Named pipes - can be accessed without a parent-child relationship

Ordinary Pipes

- Ordinary pipes allow communication in standard producer-consumer style
  - Producer writes to one end (write-end)
  - Consumer reads from other end (read-end)
  - As a result, ordinary pipes are unidirectional
  - For two-way, two pipes must be used
  - Require parent-child relationship between communicating processes
- Ordinary pipes on UNIX is constructed by the function: Pipe (int fd[])
- On Windows they are called anonymous pipes
- The function pipe(int fd[]) creates a pipe that is accessed through the int fd[] file descriptors:
  - fd[0] read end
  - fd[1] write end
- Pipes can be accessed using ordinary read() and write() system calls
- Typically, a parent process creates a pipe and uses it to communicate with a child process that it creates via fork()
- The child inherits the pipe from its parent process
- Relationship of the file descriptors in the fd array to the parent and child processes
- Limitations
  - Exist only while the processes are communicating with one another, once the processes terminate they cease to exist
  - Require a parent-child relationship between the communicating processes. This means they can be used only for communication between processes on the same machine
- Each pipe is implemented using a fixed-size buffer

Named Pipes

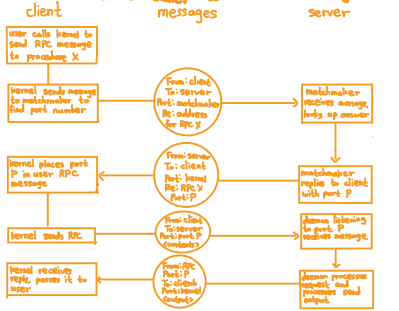
- Provides a much powerful communication tools than the ordinary pipes
- Communication can be bidirectional, and no parent-child relationship is needed
- Several processes can use the named pipe for communication
- Continue to exist after communicating processes have finished
- Provided on both UNIX and Windows systems
- Refened as FIFOs on UNIX systems
  - Created with mkfifo() system call
  - Once created, they appear as typical files in the file system
  - Can be manipulated with ordinary open(), read(), write(), and close() system calls
  - Continue to exist until it is explicitly deleted from file system
  - Bidirectional but only in half-duplex
  - Communicating processes must reside on the same machine
- Windows
  - Full-duplex communication is allowed
  - Communicating processes may reside on either the same or different machines
  - Only byte-oriented data may be transmitted across a UNIX FIFO, whereas Windows systems allow either byte- or message-oriented data
  - Named pipes created with CreateNamedPipe()
  - A client can connect to a named pipe using ConnectNamedPipe()
  - Communication over the named pipe can be accomplished using the ReadFile() and WriteFile() functions

Sockets

- A socket is defined as an endpoint for communication
  - A pair of processes communicating over a network employs a pair of sockets
  - A socket is identified by an IP address concatenated with a port number
  - The socket 161.25.19.8:1625 refers to port 1625 on host 161.25.19.8
  - Communication link corresponds to a pair of sockets
  - Port 80 reserved for HTTP server
- If the client process initiates a connection request, it is assigned a port by its host computer
  - This port has some arbitrary number greater than 1024
  - This connection will consist of a pair of sockets: on host X and on the web server
  - The packets travelling between the hosts are delivered to the appropriate process based on the destination port number
  - All connections must be unique

Remote Procedure Calls (RPC)

- A message-based communication scheme to provide remote service
- It is similar in many respects to IPC mechanisms, but processes are executing on separate systems
- The parameters and return values need to be somehow transferred between the computers
- Support for locating the server/procedure needed
- Stubs: side proxies implementing the needed communication
  - The client-side stub locates the server and marshals the parameters
  - Then the stub transmits a message to the server using message passing
  - The server-side stub receives this message and invokes the procedure on the server
  - If necessary, return values are passed back to the client using the same technique
- Client can find the port numbers on the server by:
  - An RPC call has a fixed port number associated with it. Once a program is compiled, the server cannot change the port number of the requested service
  - Dynamically by OS provided matchmaker: Function that matches a caller to a service being called

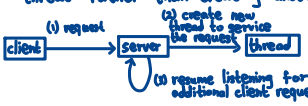


Threads

- A thread is a basic unit of CPU utilization
  - It comprises a thread ID, a program counter, a register set, and a stack
  - Threads belonging to the same process share code section, data section, and other operating-system resources
- A process with multiple threads of control, can perform more than one task at a time

Multithread Server Architecture

- A busy web server receive thousands of client service request
  - Each client request is concurrently serviced
  - A single-thread process, can service only one client at a time!
  - One solution is to create one process per received service request
  - It is generally more efficient to use one process that contains multiple threads
  - A multithreaded serve allows to create a separate thread rather than creating another process



Benefits of Threads

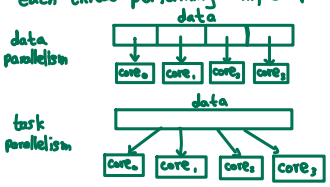
- Responsiveness: may allow continued execution if part of a process is blocked, especially for user interfaces
- Resource Sharing: threads share resources of process, easier than shared memory or message passing between processes
- Economy: cheaper than process creation, thread switching lower overhead than context switching between process
- Scalability: process can take advantages of multiprocessor architectures

Concurrency vs. Parallelism

- Multicore or multiprocessor is to place multiple computing cores on single processing chip where each core appears as a separate CPU to the OS
  - Multithreaded programming improves concurrency in multicores
- Parallelism implies a system can perform more than one task simultaneously
- Concurrency supports more than one task making progress

Types of parallelism

- Data parallelism: distributes subsets of the same data across multiple cores, Same operation on each
- Type parallelism: distributing threads across cores, each thread performing unique operation



Amdahl's Law

- Identifies performance gains from adding additional cores to an application that has both serial and parallel components
- S is serial portion
- N processing cores

$$\text{speedup} \leq \frac{1}{S + \frac{(1-S)}{N}}$$

User Threads and Kernel Threads

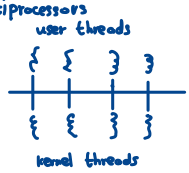
- User threads - management done by user-level thread library
  - Supported above the kernel and are managed without kernel support
- Kernel threads - Supported by the kernel
  - Supported and managed directly by the OS
  - Virtually all current OS's

Many-to-One Model

- Many user-level threads mapped to single kernel thread
- One thread blocking causes all to block
- Multiple threads may not run in parallel on multicore systems because only one may be in kernel at a time
- Few systems currently use this model

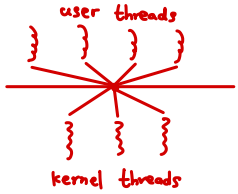
One-to-One Model

- Each user-level thread maps to kernel thread
  - Creating a user-level thread creates a kernel thread
  - A 1-2-1 model drawback: each user thread requires a kernel thread. Large number of kernel threads can burden performance
  - So, number of threads per process sometimes restricted due to overhead
  - More concurrency than many-to-one by allowing another thread to run when a thread makes a blocking system call
  - Allows multiple threads to run in parallel on multiprocessors



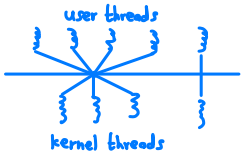
Many-to-Many Model

- Allows many user level threads to be mapped to a smaller or equal number of kernel threads
- Allows the operating system to create a sufficient number of kernel threads



Two-Level Model

- Variation of many-to-many model
  - Still multiplexes many user-level threads to a smaller or equal number of kernel threads
  - but also allow a user-level thread to be bound to a kernel thread



Thread Libraries

- Thread library provides the programmer with Application Programming Interface for creating and managing threads
- Two primary ways of implementing
  - Library entirely in user space -user controlled
    - Invoking a function in the library results in a local function call in user space and not a system call
    - Efficient as thread operations do not request system calls
    - Disadvantage: the kernel cannot schedule a thread of a process. Blocking a thread implies blocking a process
  - kernel-level library supported by OS
    - Code and data structures for the library exist in kernel space
    - The kernel is able to directly manage the states of the threads
    - Invoking a function in the API for the library results in a system call to the kernel

POSIX Threads

- POSIX Pthreads, provided as either a user-level or a kernel-level library
- Portable Operating System Interface (POSIX) standard API for thread creation and synchronization
- Common in UNIX operating systems
- Must include the pthreads.h header file when using the Pthreads API
- Data sharing for Pthreads threading, is done by the mean of global variable (in C)
  - variables declared outside of any function are visible and can be accessed/shared by all threads belonging to the same process

Windows Threads

- Windows thread library is a kernel-level library available on Windows systems
- The technique for creating threads is similar to the Pthreads technique in several ways
- Must include the windows.h header file when using the Windows API
- Data sharing for Windows threading is done by the mean of global variable (in C)
  - Variable declared outside of any function are visible and can be accessed/shared by all threads belonging to the same process

Java Threads

- Java thread API allows threads to be created and managed directly in Java programs
  - JVM runs on top of a host OS
    - generally implemented using a thread library available on the host system
      - Windows: Windows API
      - UNIX: Pthreads
- Java has no equivalent notion of global data
  - access to shared data must be explicitly arranged between threads
- Two techniques for explicitly creating threads in a Java program
  - Method 1: Create a new class that is derived from the Thread class and override its run() method
  - Method 2: Define a class that implements the Runnable interface, that defines a single abstract method with the signature public void run()
- Thread creation involves:
  - creating a Thread object and passing it an instance of a class that implements Runnable
  - followed by invoking the start() method on the Thread object
- Invoking the start() method for the new Thread object does two things
  - It allocates memory and initializes a new Thread in the JVM
  - It calls the run() method, making the thread eligible to be run by the JVM
- join() method can be used to force the parent thread to wait for the children threads to finish before proceeding

Java Executor Framework

- Beginning with version 1.5 and its API, Java introduced several new concurrency features
  - provide developers with much greater control over thread creation and communication
  - available in java.util.concurrent
  - Rather than explicitly creating Thread objects, thread creation is instead organized around the Executor interface:

```
public interface Executor{
    void execute(Runnable command);
}
```

  - Classes implementing this interface must define the execute() method, which is passed a Runnable object
  - This means using the Executor rather than creating a separate Thread object and invoking its start() method
- The Executor framework is based on the producer-consumer model
  - tasks implementing the Runnable interface are produced
  - and the threads that execute these tasks consume them
  - advantage of this approach, divides thread creation from execution and provides a mechanism for communication between concurrent tasks
- java.util.concurrent package defines the Callable interface
  - Callable behaves similarly to Runnable except that a result can be returned
  - Results returned from Callable tasks are known as Future objects that can be retrieved from the get() method defined in the Future interface

Callable vs. Runnable in Java

- Callable and Runnable interfaces in Java are both used to represent tasks that can be executed by another thread
  - They encapsulate functions that are supposed to be completed by another thread
  - Are widely used in multithreaded programming to perform tasks concurrently
- The main advantage of using Callable over Runnable is that Callable tasks can return a result and throw exceptions, while Runnable tasks cannot

Asynchronous and Synchronous Threading

- Asynchronous threading: once the parent creates a child thread, the parent resumes its execution
  - The parent and child execute concurrently and independently of one another
  - There is typically little data sharing between parent and child
  - Commonly used for designing responsive user interfaces
- Synchronous threading: parent thread must wait for all of its children to terminate before it resumes
  - Threads created by the parent perform work concurrently, but the parent cannot continue until this work has been completed
  - Once each thread has finished its work, it terminates and joins with its parent
  - Only after all of the children have joined can the parent resume execution
  - Typically, synchronous threading involves significant data sharing among threads

Implict Thread

- Growing in popularity as number of threads increase program correctness more difficult with explicit thread
- Creation and management of threads done by compilers and run-time libraries rather than programmers

Thread Pools

- A number of threads created at process startup and placed in a pool, where they sit and wait for work
- Server submit a request to the thread pool and resumes waiting for additional requests
- If there is an available thread in the pool, it is awakened, and the request is serviced immediately
- If the pool contains no available thread, the task is queued until one becomes free
- Once a thread completes its service, it returns to the pool and awaits more work (it is not terminated)
- Advantages:
  - Faster: Usually slightly faster to service a request with an existing thread than create a new thread
  - Bounded: Allows the number of threads in the application(s) to be bound to the size of the pool
  - Separating task to be performing from mechanics of creating task allows different strategies for running task

Semantics of fork() and exec()

- The semantics of the fork() and exec() system calls change in a multithreaded program
- fork() sometimes have two versions
  - Duplicates all threads
  - Duplicates only the thread that invoked the fork()
- exec() replaces the running process address spaces and this includes all threads
- Which of the two versions fork() to use?
  - If depends on the application:
    - if exec() is called immediately after forking, then duplicating all threads is unecessary
    - if exec() is not called after forking, the separate process should duplicate all threads

Thread Cancellation

- Terminating a thread before it has finished
- Two general cancellation approaches:
  - Asynchronous cancellation terminates the target thread immediately
  - Potential problems:
    - OS may not reclaim all the cancelled thread resources
    - May leave some share data in an inconsistent state

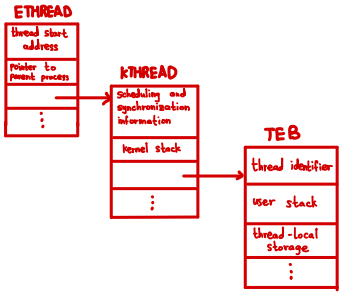
- Deferred cancellation allow the target thread to periodically check if it should be cancelled
  - One thread indicates that a target thread is to be cancelled
  - but cancellation occurs only after the target thread has checked a flag to determine wheter or not it should be cancelled
  - The thread can only perform this check at a point at which it can be cancelled safely

Thread-Local Storage

- Threads belonging to a process share the data of the process
- But in some circumstances, each thread might need its own copy of certain data
- Thread-local storage (TLS) allows each thread to have its own copy of data
  - Useful when you do not have control over the thread creation process
  - Another example, in a transaction-processing system, transaction in a separate thread - each thread should have its unique transaction identifier in their TLS
- TLS vs. local variables
  - Local variables visible only during single function invocation (local scope)
  - TLS visible across function invocations
  - TLS unique to each thread

Windows Threads

- One-to-one model
- General components of a thread:
  - Thread ID uniquely identifying the thread
  - Register set representing status of processor
  - Program counter
  - User stack, employed when thread is running in user mode
  - Kernel stack, employed when thread is running in kernel mode
  - Private data storage memory area
- Register set, stacks, and private storage area are known as the context of the thread
- The primary data structures of a thread include
  - ETHREAD (executive thread block): includes pointer to process to which thread belongs and to kTHREAD, in kernel space
  - KTHREAD (kernel thread block): scheduling and synchronization info, kernel-mode stack, pointer to TEB, in kernel space
  - TEB (thread environment block): thread id, user-mode stack, thread-local storage, in user space



Linux Threads

- Linux refers to them as tasks rather than threads
- Thread creation is done through clone() system call
- clone() allows a child task to share the address space of the planned task
  - Flags control behaviour

Flag	Meaning
CLONE_FS	File-system information is shared
CLONE_VM	The same memory space is shared
CLONE_SIGHAND	Signal Handlers are shared
CLONE_FILES	The set of open files is shared

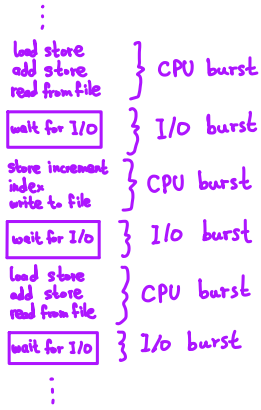
- If no flags is set when clone() is invoked, no sharing takes place, resulting in functionality similar to fork()

CPU Scheduling Motivation

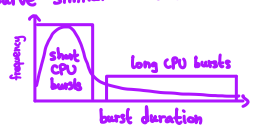
- The motivation behind multiprogramming is to have some process running at all times, to maximize CPU utilization.
  - When for example if one process wait for an I/O, another process can execute on the core.
  - This pattern continues - every time one process has to wait, another process can take over the CPU.
  - On a multicore system, this concept of keeping the CPU busy is extended to all processing cores on the system.
  - Scheduling of this kind is a fundamental OS function.
  - Almost all computer resources are scheduled before use
- The CPU is one of the primary computer resources. Thus, CPU scheduling is central to OS design.

CPU-I/O Burst Cycle

- CPU scheduling success depends on an observed process property:
  - Process execution consists of a cycle of CPU execution and I/O wait- Phases alternate between these two states.
  - Process execution begins with a CPU burst, followed by an I/O burst, then followed by CPU burst, and so on.
  - Eventually, the final CPU burst ends with a system request to terminate execution.
  - CPU burst distribution of main concern.



- The durations of CPU bursts have been measured extensively:
  - They vary greatly from process to process and from computer to computer
  - They tend to have a frequency curve similar to this:



  - The curve is generally characterized as exponential or hyperexponential, with a large number of short CPU bursts and a small number of long CPU bursts.
  - An I/O-bound program typically has many short CPU bursts
  - A CPU-bound program might have a few long CPU bursts
  - This distribution can be important when implementing a CPU-scheduling algorithm.

CPU Scheduler

- Short-term scheduler selects from among the processes in the ready queue, and allocates the CPU to one of them
  - Queue may be ordered in various ways
- CPU scheduling decisions may take place when a process:
  1. Switches from running to waiting state (I/O request)
  2. Switches from running to ready state (interrupt occurs)
  3. Switches from waiting to ready (I/O operation completed)
  4. Terminates
- Scheduling under 1 and 4 is nonpreemptive (cooperative)
  - Running process keeps the CPU until it releases it
- Scheduling under 2 and 3 is preemptive
  - Can result in race conditions when data are shared by several processes
    - When two processes that share data. While one process is updating the data, it is preempted so that the second process can run. The second process then tries to read the data, which are in an inconsistent state.

Dispatcher

- Dispatcher module gives control of the CPU to the process selected by the short-term scheduler; this involves:
  - Context switching from one process to another
  - switching to user mode
  - jumping to the proper location in the user program to restart that program
- Dispatch latency - time it takes for the dispatcher to stop one process and start another running
  - Should be as fast as possible, since it is invoked during every context switch

Scheduling Criteria

- Different algorithms may favor one class of processes over another
- A particular algorithm may favor a partiular situation
- We must consider the properties and criteria of the various algorithms:
  - Throughput: a measure of work - the number of processes that are completed per time unit
    - For long processes, this rate may be one process over several seconds
    - For short transactions, it may be tens of processes per second
  - Turnaround time: For a particular process, how long it takes to execute that process
    - Is the interval from the time of submission of a process to the time of completion
    - Is the sum of the periods spent waiting in the ready queue, executing on the CPU, and doing I/O
  - Waiting time: Measure only the amount of time that a process spends waiting in the ready queue
    - Is the sum of the periods spent waiting in the ready queue
  - Response time: time from the submission of a request until the first response is produced
    - Is the time it takes to start responding, not the time it takes to output the response
- Ideally, we want:
  - maximize CPU utilization, throughput
  - minimize turnaround, waiting, and response time

First-Come, First-Served (FCFS) Scheduling

- Implementation is easily managed with a FIFO queue
  - When a process enters the ready queue, its PCB is linked onto the tail of the queue
  - The process at the head of the queue will run next on the CPU
  - Each process is associated with a burst time
  - When a process runs, it will run for the duration of its burst
  - FCFS scheduling algorithm is nonpreemptive
    - A running process releases the CPU, either
      - by terminating
      - by requesting I/O
    - The FCFS algorithm is thus particularly troublesome for interactive systems, where it is important that each process get a share of the CPU at regular intervals
    - It would be disastrous to allow one process to keep the CPU for an extended period
- Assume one CPU-bound process holds the CPU, and many I/O-bound processes
  - During this time, all the other I/O-bound processes finish their I/O and move into the ready queue, waiting for the CPU
  - While the processes wait in the ready queue, the I/O devices are idle
  - Eventually, the CPU-bound process finishes its CPU burst and moves to an I/O device
  - All the I/O-bound processes, which have short CPU bursts, execute quickly and move back to the I/O queues
  - At this point, the CPU sits idle
  - The CPU bound process will then move back to the ready queue and be allocated the CPU
  - Again, all the I/O processes end up waiting in the ready queue until the CPU-bound process is done
  - There is a convoy effect as all the other processes wait for the one big process to get off the CPU
  - Convoy effect results in lower CPU and device utilization

Discussion of FCFS

- Simple and easy to program
- Costs little time to make scheduling decision
- Waiting time can be quite long
- Convoy effect affects CPU utilization

Shortest-Job-First (SJF) Scheduling

- Scheduling depends on the length of the next CPU burst of a process, rather than total length
  - Associate with each process the length of its next CPU burst
  - The shortest process burst will run first
- Optimal in principle from the point of view of average waiting time
- The difficulty is knowing in advance the length of the process's next CPU burst
- Can be either preemptive or nonpreemptive
- Choice arises when a new process arrives at the ready queue while a previous process is still executing
- The next CPU burst of the newly arrived process may be shorter than what is left of the currently executing process
  - nonpreemptive - will allow the current running process to finish its CPU burst
  - preemptive - will preempt the currently executing process
    - Sometimes called Shortest-Remaining-Time-First
    - Optimal: minimum average waiting time for a given set of processes

Discussion of SJF

- Low average waiting time
- Can have long response time because if there is a steady stream of short CPU bursts, the longer bursts will not be scheduled (suffer from starvation)
  - Starvation: occurs when a process waits for an indefinite time to get the resource it requires. Always overtaken by other processes

SJF - CPU Next Burst Prediction

- Can only estimate the length of a burst - should be like last ones
  - Then pick process with shortest predicted next CPU burst
- Can be done by using the length of previous CPU bursts for this process, using exponential averaging
  - t_n = actual length of n^{th} CPU burst
  - τ_{n+1} = predicted value for next CPU burst
  - $\alpha, 0 \leq \alpha \leq 1$
  - $\tau_{n+1} = \alpha t_n + (1-\alpha)\tau_n$
- Commonly, $\alpha = \frac{1}{2}$

Round Robin Scheduling (RR)

- Each process gets a small unit of CPU time slice called time quantum q, usually 10-100 milliseconds
- After q time has elapsed (before any other interruption), the process is preempted (by the q timer interrupt)
  - The RR scheduling algorithm is thus preemptive
- Interrupted process is added to the end of the ready queue
- The performance of the RR algorithm depends heavily on the size of the time quantum
- If there are n processes in the ready queue and the time quantum is q, then each process gets $1/n$ of the CPU time in chunks of at most q time units at once
- No process waits more than $(n-1)q$ time units

Timer interrupts every quantum to schedule next process

- q large $\Rightarrow$ FIFO
- q small $\Rightarrow$ q must be large with respect to context switch, otherwise overhead is too high
- Typically, higher average turnaround than SJF, but better response time

- If the time quantum q is extremely large, RR degenerates to FCFS policy
- If the time quantum is extremely small, the RR approach can result in a large number of context switches
- Thus, we want the time quantum to be large with respect to the context-switch time, but not too large

Priority Scheduling

- A priority number (integer) is associated with each process
- The CPU is allocated to the ready process with the highest priority (with preemption or with no preemption)

Equal-priority processes are scheduled in FCFS order

- Problem: Starvation - low priority processes may never execute
- Solution: Aging - as time progress increase the priority of the process
- Some systems use lower numbers for lower priority; others use it for high priority. This difference can lead to confusion
- In this text, we assume that low numbers represent high priority

Multilevel Queue Scheduling

- Partition processes into several separate queues based on priority or process type
  - foreground (interactive processes): high-priority
  - background (batch processes): low-priority
- Entering the system, a process permanently assigned to a given queue
  - low scheduling overhead, but it is inflexible
- Each queue has its own scheduling algorithm
- How must scheduling must be done from among the queues:
  - Fixed priority preemptive scheduling
    - i.e. the interactive queue may have absolute priority over the background queue
    - serve all foreground processes first then move to serve background processes
    - Possibility of background processes starvation
  - Time slice
    - Each queue gets a certain portion of the CPU time which it can then schedule among its various processes
    - Not necessarily optimal

Multilevel Feedback Queue Algorithm

- A process can move between the various queues
  - An aging process can be promoted to a higher priority queue to prevent starvation
  - A "gourmand" process using too much CPU time can be moved down to a lower priority queue
  - Short CPU bursts processes are left in the higher-priority queues
- Multilevel-feedback queue scheduler defined by the following parameters:
  - number of queues
  - Scheduling algorithms for each queue
  - method used to determine when to promote a process
  - method used to determine when to demote a process
  - method used to determine which queue a process will enter when that process needs service
- Adaptable to specific systems
- But most complex to implement

Multiple-Processor Scheduling

- Scheduling multiple CPUs is more complex than a single CPU
- Therefore, OS must deal with efficient load sharing and time management among the available multiple CPUs
- Result: Parallel execution
  - Load sharing - when multiple processes may run in parallel
  - OS overheads shared among different cores
- All processors are identical - Homogeneous - in terms of their functionality
- Two approaches to multiprocessor scheduling

Asymmetric multiprocessing - only one core accesses the system data structures, reducing the need for data sharing

- Symmetric multiprocessing - each CPU is self-scheduling
  - The standard approach in modern computing OS's to support multiprocessors
  - Two possible strategies for organizing the scheduling
    - (a) All processes in common ready queue
    - (b) Each has its own private queue of ready processes

Symmetric Multiprocessing Complication

- Load Balancing - it is important to keep the workload balanced among all CPUs to fully benefits of having more than one CPU
  - Required when each CPU has its own ready queue
  - Push migration: a task runs periodically to evenly distribute load among CPUs (moving task from overloaded to an idle or a less-busy CPU)
  - Pull migration: an idle CPU pulls a waiting task from a busy CPU
  - Linux OS supports both Push and Pull techniques

Can counteract the benefits of processor affinity, since it moves processes from one CPU to another

- Processor affinity - process has affinity for processor on which it is currently running
  - When a process runs on a physical CPU, cache memory is updated with content of the process
  - If the process is moved to another CPU, benefits of caching is lost
  - SMP systems try to keep processes running on the same physical CPU, known as processor affinity

Scheduling Algorithm Evaluation

- First, identify the selection criteria
- Next, evaluate the algorithms under consideration using various methods:
  - Deterministic modelling
  - Queuing models
  - Simulations

Deterministic Modeling

- A type of analytic evaluation
- Takes a particular predetermined workload and defines the performance of each algorithm for that workload

Queuing Models

- Analytical method based on probability theory
- Describes the arrival of CPU and I/O bursts with probability theory
  - Commonly exponential, described by mean
  - Computes average throughput, utilization, waiting time, etc
- Computer system described as network of servers, each with queue of waiting processes (queuing-network analysis)
  - Knowing arrival rates and service rates
  - Computes utilization, average queue length, average wait time, etc.
- Simplified model: OS times ignored

Little's Formula

- n = average queue length
- W = average waiting time in queue
- λ = average arrival rate into queue

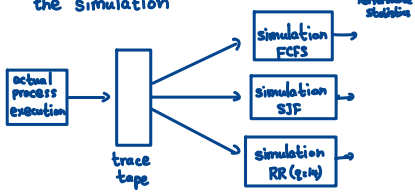
Little's Law: in steady state, processes leaving queue must equal processes arriving, thus:

$$n = \lambda \times W$$

- Valid for any scheduling algorithm and arrival distribution

Evaluation by Simulations

- Build a simulator and run different scheduling algorithms and evaluate results
- Assign a duration of time to each event
- Run the model for this sequence to get algorithm performance statistics
- How to feed data about CPU and I/O bursts?
  - 2 ways
    1. Analytically: a random number generator that is programmed to generate processes, CPU burst times, arrivals, departures, and so on, according to probability distributions. The distributions can be defined mathematically.
    2. Empirically: feed in data from a real system under study, and record the sequence to trace files, then use this sequence to drive the simulation



Race Condition

- Concurrent threads often share user data (files or common memory) and resources (cooperative tasks)
- Race condition occurs where several tasks access and manipulate the same data concurrently
- A race condition exists when access to shared data is not controlled, possibly resulting in corrupt data values (outcome of execution depends on the particular order in which the access takes place)

Critical Section Problem

- When multiple threads execute in parallel, we cannot make assumptions about the execution speed of the threads, nor their interlacing
- May be different each time the program is run
- Critical section is part of a task whose execution must not interlace with other tasks' critical sections
  - Once a task enters, it must be allowed to complete this section without allowing other tasks to manipulate on the same data
- Critical-section problem is to design a protocol that the threads can use to synchronize their activity so as to cooperatively share data
  - The result of their actions does not depend on the interlacing order of execution
- The execution of critical sections must be mutually exclusive: at any time, only one thread can execute a critical section for a given data
- This can be achieved by placing special instructions at the beginning and end of the critical section
- Once a task enters the critical section, it must complete it as an atomic bloc (no other tasks are allowed to mess with the same data)
- The critical section must be locked to become indivisible (atomic)

Program Structure

```
while (true) {
    entry section
        critical section
    exit section
        remainder section
}
```

Criteria for Valid Solutions to CSP

1. Mutual Exclusion
   - At any time, at most one thread can be in a critical section
2. Progress
   - Ensures programs will cooperatively determine what task will next enter its critical section
   - A critical section will only be given to a task that is waiting to enter it
   - Whenever a CS becomes available, if there are threads/tasks waiting for it, one of them must be able to enter it
3. Bounded Waiting
   - Limits the amount of time a program will wait before it can enter its critical section

- A thread waiting to enter a critical section will finally be able to enter (alternation and no starvation)
  - No thread can be forever excluded from the critical section because of other threads monopolizing it

Some Critical Section Problem Solutions

- Software based solutions
  - algorithms that do not use special instructions
  - Peterson's algorithm
- Hardware solutions
  - rely on the existence of certain special instructions
  - test_and_set(), compare_and_swap()
- Higher-level software tools solution
  - Provides certain system calls to the programmer
  - Mutex, Semaphores, monitor
- All solutions are based on the atomic access to central memory: a memory address can only be assigned by one instruction at a time, therefore by one thread at a time
- In general, all solutions are based on the existence of atomic instructions, which function as basic critical sections

Software Solution 1

- Have T_i tasks and a shared variable turn indicating whose turn it is now
  - Turn is initialized to a valid task number
- T_i may enter the critical section if and only if turn = i
- After exiting the critical section, turn is assigned next i task number, so it gains access to its critical section next
- T_i can be in a busy wait if T_j is in its CS
- Mutual exclusion and bounded waiting satisfied
  - Only one thread can enter the critical section at any moment (Mutual exclusion)
  - Tasks alternate very well and no starvation (bounded waiting)
- But assuming we have 1000 threads and only a handful are active:
  - Each time, before a thread can enter the critical section, it must wait until all the others have had this chance
  - This is a contradiction with the Progress requirement

Software Solution 2

- Gives the critical section only to threads that want it (active threads)
- However, we cannot allow a task to systematically give itself the critical section
  - This will cause starvation for others
  - Each process that wants to enter must give others a chance before entering
- Use a boolean variable per thread: flag[0] and flag[1]
- T_i signals that it wants to execute its CS by setting flag[i] = true
- But T_i does not enter if another thread also set its flag to enter
- Mutual Exclusion is satisfied
- Progress is not satisfied
  - T_0: flag[0] = true
  - T_1: flag[1] = true
  - Each thread will wait indefinitely to execute, resulting in a deadlock
- This algorithm allows only active threads to enter the critical section, but it may result in a deadlock when multiple threads want to enter at the same time

Software Solution 3: Peterson's Solution

- Provides a good algorithmic description of solving the critical-section problem
- Illustrates some of the complexities involved in designing software that addresses the requirements of:
  - mutual exclusion, progress, bounded waiting
- No guarantees that it will work correctly on modern computer architectures
- Restricted to 2 processes/tasks that alternate
- Combines ideas from previous solutions
  - flag[i] = intention to enter
  - turn = whose turn
- Initialization:
  - flag[0] = flag[1] = false
  - turn = i or j
- If we want to run the critical section, it indicated by flag[i] = true
- Put flag[i] = false on exit
- Thread T_i should wait if the other wants to enter and it's the other's turn
  - flag[j] == true and turn == j
- Thread T_i can enter if the other doesn't want to enter or it's their turn
  - flag[j] == false or turn == i
- T_i uses the boolean flag[i] to indicate its desire to enter its CS
- It also uses turn to give T_j the priority to enter its CS
- T_i can enter the critical section only when flag[j] == false or turn == i
- To enter the critical section, a task T_i first sets flag[i] to be true and then sets turn to the value j
  - thereby asserting that if T_j wishes to enter its critical section, it can do so
- If both tasks try to enter at the same time, turn will be set by both tasks roughly the same time:
  - But turn is shared by both, so only the latest of these assignments will hold
  - The eventual value of turn determines which of the two tasks is allowed to enter the critical section first
- Mutual Exclusion is preserved
  - A task enters its critical section only if it is its turn when both want in
- Progress requirement is satisfied
  - A task will enter its critical section if and only if it is its turn and the other task does not want to enter its critical section
  - If both wants to enter, it is not possible as turn can hold only 1 value that allow only 1 task to enter CS

Bounded-waiting requirement is met

- An executing task will set its flag to false before reaching its remainder section, this will unlock the other task from its busy wait and allows it to execute its critical section
- If a solution satisfies the requirements of mutual exclusion and progress, it provides robustness against the thread failure in its non critical section
- If a thread fails in its critical section, it does not send a signal to the other threads, which results in them being blocked
  - Timeout is a solution: a thread that has CS after a certain time is interrupted by the OS
- Peterson's algorithm can be generalized to more than 2 tasks

Peterson's Solution Possible Failure

- May not work on modern computer
- Processors and/or compilers may reorder read and write operations that have no dependencies
- For a multithread application with shared data, the reordering of instructions may render inconsistent or unexpected results
- This can cause two threads to be active in their critical sections at the same time

$P_0 \rightarrow$ turn = 1 $\longrightarrow$ flag[0] = true $\rightarrow$ CS

$P_1 \longrightarrow$ turn = 0, flag[1] = true $\rightarrow$ CS

Software Based Solution Discussion

In order for threads with shared variable to succeed, it is necessary that all involved threads use the same coordination algorithm

- Software solutions are difficult to program or understand
  - Threads that desire entry into their CS are busy waiting, which consumes CPU time
  - For long critical sections, it is preferable to completely block threads that must wait, then wake them up when they can enter critical section

Hardware Support: Memory Barriers

- A multicore system may reorder instructions, leading to unreliable data states
- Memory barriers
  - Force propagate any memory changes to all threads running on different cores
  - Ensures that all load and store operations are completed before additional load and store operations are performed

Hardware Support: Instructions

- Modern computer systems provide special hardware instructions that:
  - Test and modify the content of a word
  - Automatically swap the contents of two words atomically - as one uninterruptible unit
- We can use these special instructions to solve the critical-selection problem in a relatively simple manner

test_and_set() instruction

- Executed atomically
- If two test_and_set instructions are executed simultaneously, they will be executed sequentially in some arbitrary order
- Mutual exclusion can be implemented by declaring a boolean variable lock, initialized to false

```
// Instruction definition
boolean test_and_set(boolean *target){
    boolean rv = *target;
    *target = true;
    return rv;
}
```

The structure of process T_i is

```
while (true){
  while (test_and_set(&lock));
    /* critical section */
  lock = false;
    /* remainder section */
}
```

Some disadvantages:

- Still using busy waiting
- When T_i leaves its critical section, the selection of T_j to enter its CS is arbitrary: no bounded waiting → starvation is possible

compare_and_swap() instruction

- Very similar to test_and_set() instruction atomically
- Mechanism is based on the swapping of two words
- Operates on three operands: lock(value), expected, and new_value
- Definition of instruction:

```
int compare_and_swap (int *value, int expected, int new_value){
    int temp = *value;
    if (*value == expected)
        *value = new_value;
    return temp;
}
```

Some disadvantages:

- Still using busy waiting
- It does not satisfy the bounded-waiting requirement

- Mutual exclusion can be implemented by declaring a boolean variable lock, initialized to false or 0.
- The first process that invokes compare and swap will set lock to 1
- It will then enter its critical section, because the original value of lock was equal to the expected value of 0
- Subsequent calls to compare and swap will not succeed, because lock now is not equal to the expected value of 0
- When a program exits its critical section, it sets lock back to 0, which allows another process to enter its critical section

```
while (true){
  while(compare_and_swap(&lock,0,1)!=0);
    /* critical section */
  lock = 0;
    /* remainder section */
}
```

- On intel x86 architecture, the assembly language statement on intel x86 is used to implement the compare_and_swap() instruction
- The general form of this instruction appears as

  lock cmpxchg <destination operand>, <source operand>

- To enforce atomic execution, the lock prefix is used to lock the bus while the destination operand is being updated
- Interchanges the contents of source operand and destination operand atomically

compare_and_swap() with waiting

- An algorithm using compare and swap that satisfies all the critical-section requirements
- The common data structures are:

```
boolean waiting[n]; //initialized to false
int lock; //initialized to 0
```

- Task T_i can enter its critical section only if either:
  - waiting[i] == false
  - key == 0
- The value of key can become 0 only if the compare_and_swap() is executed; all other tasks must wait
- The variable waiting[i] can become false only if another process leaves its critical section
- Only one waiting[i] is set to false, maintaining the mutual-exclusion requirement
- Mutual exclusion maintained:
  - A task exiting the CS either sets the lock to 0 or waiting[i] to false - both allow a waiting task to enter CS

- Bounded-waiting requirement fulfilled
  - when a task leaves its critical section, it scans the waiting[i] in the cyclic ordering (i+1, i+2, ..., n-1, 0, ..., i-1)
  - It designates the first task in this ordering that is in the entry section (waiting[j]==true) as the next one to enter the critical section
  - Any task waiting to enter its critical section will thus do so within n-1 turns

Program Structure

```
while (true) {
    waiting[i] = true;
    key = 1;
    while (waiting[i] && key == 1)
        key = compare_and_swap(&lock, 0, 1);
    waiting[i] = false;

    /* critical section */

    j = (i+1) % n;
    while ((j!=i) && !waiting[j])
        j = (j+1) % n;

    if (j == i)
        lock = 0;
    else
        waiting[j] = false;

    /* remainder section */
}
```

Atomic Variables

- Atomic variables are a tool for solving the critical-section problem
- Provides atomic operations on basic data types such as Int and bool
- Atomic variables ensure mutual exclusion on a shared variable
- Special atomic data types and functions for accessing and manipulating atomic variables exist only on supported operating systems
- Limitation: their use is often limited to single updates of shared data such as counters and sequence generators
- They do not entirely solve race conditions in all circumstances

Mutex Locks (spinlocks)

- Mutex: short for mutual exclusion
- Simplest of high-level software synchronization tools
- Mutex lock protects critical sections and thus prevents race conditions
- A task must acquire the lock before entering a critical section; it releases the lock when it exits the critical section
  - acquire() function acquires the lock
  - release() function releases the lock
- On multicore systems, spinlocks can be the preferable choice for locking, if a lock is to be held for a short duration
  - One thread can "spin" on one core while another thread performs its critical section on another core
- Definition of acquire() and release():

```
acquire() {
    while(!available);
    available = false;
}

release() {
    available = true;
}
```

- boolean variable available is true only if the lock is available, otherwise it is false
- A task calling acquire() can enter critical section, only if the lock if available
- If not available, then the calling task is blocked until the lock is released
- Disadvantage:
  - requires busy waiting
  - Other tasks not in the critical section must loop continuously in the call to acquire()
- Not appropriate to implement on single-processor systems
- The condition that would break a task out of the spinlock can be obtained only by executing a different task
- If the task is not relinquishing the processor, other tasks do not get the opportunity to set the program condition required for the first task to make progress
- In a multiprocessor system, other tasks execute on other processors and therefore can modify the program state in order to release the first task from the spinlock

Semaphores

- Similar to a mutex lock, but can also provide more sophisticated ways for tasks to synchronize their activities
- A semaphore S is an integer variable is accessed only through two standard atomic operations
  - wait() and signal() with definitions

```
wait(S) {
    while (S<=0);
    S--;
}

signal(S) {
    S++;
}
```

- The integer S in wait() and signal() operations must be executed atomically
  - no other task can simultaneously modify that same semaphore S value
- Testing of (S≤0) and its possible modification (S--) must not be interrupted

Binary Semaphore

- The value of a binary semaphore S can take only 0 or 1
- Thus, it behaves similarly to mutex locks
- In fact, a binary semaphore is a counting semaphore with S is restricted to 0 and 1
- Binary semaphores can be used for mutual exclusion instead of mutex locks on systems that do not provide mutex locks
- Binary semaphores can be used to implement mutual exclusion among n tasks

Counting Semaphore

- Counting semaphores control access to a finite number of instances
  - S can range over an unrestricted domain
- S initialized to the number of resources available
- Each task that wishes to use a resource performs a wait() operation on S
- When a process releases a resource, it performs a signal() operation
- When the count for S goes to 0, all resources are being used
- After that, processes that wish to use a resource will block until the count becomes greater than 0
- When S≥0:
  - The number of threads that can run wait(S) without busy waiting is S
    - S threads can enter the critical section
    - In solutions where S>1 it will be necessary to have a 2nd semaphore to control threads entry to critical section one at a time (mutual exclusion)
  - When S becomes greater than one, the first thread to enter the critical section is the first to test S. This is a random choice, which may cause starvation

Semaphores with no busy waiting

Implementation without busy waiting

- The mutex and the previous semaphore all suffer from busy waiting
- To overcome the problem, we can modify the definition of wait() and signal() operations
- To overcome the busy waiting problem, the definition of wait is modified as follows:
  - Instead of busy waiting in wait(), the task can suspend itself
  - Suspend will place a task into a waiting queue associated with the semaphore and switches its state to waiting
  - Then control is transferred to the CPU scheduler, which selects another ready task to execute
- A suspended task, waiting on a semaphore S, should be restarted when some other task executes a signal() operation
  - The task is restarted by a wakeup() operation, which changes the task from the waiting state to the ready state.
  - The task is then placed in a ready queue
- To implement semaphores under this new definition, we define a semaphore as new type as follows:

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

- A semaphore typed variable has 2 members:
  - -int value
  - -list of processes
- When a task must wait on a Semaphore, it is added to the list of tasks
- A signal() operation removes one task from the list of waiting tasks and awakens that task
- Definition of wait():
  - S is a semaphore typed variable
  - *S is a pointer to S
  - S→value is a pointer to S member value
  - sleep() replaces previous busy wait

```
wait(semaphore *S){
    S->value--;
    if (S->value < 0){
        add process to S->list;
        sleep();
    }
}
```

- Definition of signal():
  - sleep() suspends the task that invokes it
  - wakeup(P) resumes the execution of a suspended task P
  - These two operations are provided by the OS as basic system calls

```
signal(semaphore *S){
    S->value++;
    if (S->value <= 0){
        remove a process from S->list
        wakeup(P)
    }
}
```

- Under this new definition, if a semaphore value is negative, its magnitude is the number of processes waiting on that semaphore
- The operations wait() and signal() must be executed atomically
  - In a single core, it can be solved by inhibiting interrupts when a task is performing these operations
  - In multi-core, interrupts also must be disabled on every processing core
- It is important to admit that we have not completely eliminated busy waiting, we have limited busy waiting to the critical sections of the wait() and signal() operations, and these sections are short
  - Thus, the critical section is almost never occupied, and busy waiting occurs rarely, and then for only a short time

Problems with Semaphores

- Incorrect use of semaphore operations:
  - signal(mutex) ... wait(mutex)
  - wait(mutex) ... wait(mutex)
  - Omitting of wait(mutex) or signal(mutex) (or both)
- Deadlock and starvation are possible
- Various types of errors can be generated easily when programmers use semaphores or mutex locks incorrectly to solve the critical-section problem
- One strategy for dealing with such errors is to incorporate simple synchronization tools as high-level language constructs

Monitors

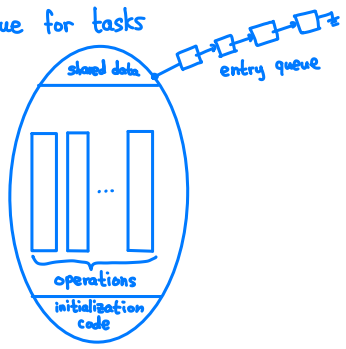
- A high-level abstraction that provides a convenient and effective mechanism for process synchronization
- Abstract data types, encapsulates:
  - internal variables and data with a set of functions (procedures) to operate on that data
  - initialization sequence

```
monitor monitor-name {
    /* shared variable declarations */
    function P1(...) {...}
    function P2(...) {...}
        ...
    function Pn(...) {...}
    initialization_code(...){...}
}
```

- Local (internal) variables are only accessible by code within encapsulated functions (procedures)
- A task enters the monitor by invoking one of its functions
- Ensures that only one task at a time can execute within the monitor at any moment; but more tasks can be waiting in the monitor.
- Ensures mutual exclusion without the need to explicitly program
- Shared data encapsulated and protected by the monitor
  - Shared data is locked when accessed by a task
- Task synchronization is provided by condition typed variables
  - They represent conditions after which a thread might wait before executing in the monitor
- Two versions
  1. Simple monitors
     - Essentially Java's synchronized methods
  2. Monitors with condition variables
     - Task synchronization is provided by condition-typed variables that are local to the monitor

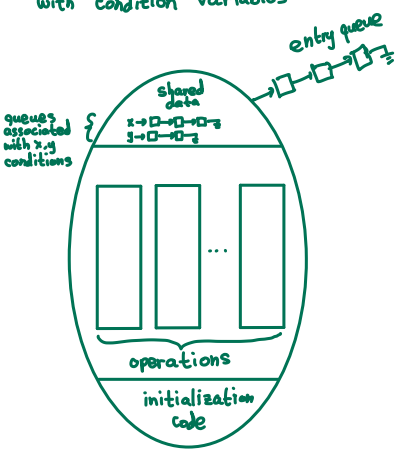
Simple Monitors

- Synchronized methods
- Only one task can enter at a time
- Queue for tasks



Condition Variables

- The simple monitor is not sufficiently powerful for modeling some synchronization schemes. So, we need to define additional synchronization mechanisms: condition variables
- Condition variables are accessible only within the monitor
- wait() and signal() are the only two operations that can be invoked on a condition variable
  - x.wait(): suspend the task invoking this operation on condition x until another process invokes x.signal()
  - x.signal() resumes exactly one suspended task on condition x
    - If no task suspended, do nothing
    - If more than one task are suspended, then choose one
- Schematic view of monitors with condition variables



- If a task executes x.signal() and a task Q is suspended in x.wait(), what should happen next?
  - Two tasks Q and P are not allowed to be active simultaneously within the monitor, then P must wait
- Two possibilities exist
  - Signal and wait: P either waits until Q leaves the monitor or waits for another condition
  - Signal and continue: Q either waits until P leaves the monitor or waits for another condition
- Language implementer can decide which of the 2 options to adopt

Bounded-Buffer Problem: Producer-Consumer

- A finite size array in memory is shared by a number for producer and consumer threads
- A classic problem in the study of communicating processes: a producer produces data for a consumer process
- A buffer is needed to store produced item
- If the buffer is of length 1, the producer and consumer must necessarily go at the same speed
- Longer length buffers allow some independence

Bounded Buffer

- A fundamental data structure in OS
- Bounded buffer is in the memory shared between producer and consumer
- When writing information to the buffer, the producer updates the in pointer
- When reading information in the buffer, the consumer updates the out pointer
- If the buffer is full, the producer will have to go to sleep (later be woken up by the consumer)
- The role of the consumer is symmetrical
- Bounded buffers are everywhere in computing, and everywhere in operating systems
- The queues used in operating systems are bounded buffers:
  - Pipes in Unix
  - queues for resources
  - communication protocols use bounded buffers
  - a client communicates with a server through bounded buffers

Difficulty concerning Buffers

- A buffer is shared between two or more processes
- We must make sure to synchronize these processes, otherwise we will easily fall into troubles
- Suppose a consumer process seeks to read data that a producer has not yet finished writing
- Or that two processes seek to update the indices simultaneously
- Since the producer and the consumer are independent tasks, problems could occur allowing concurrent buffer access
- Semaphores can solve this problem

Semaphore Solution to Bounded Buffer Problem

- Producer and consumer share the following data structures and initialization:

```
int N;
Semaphore mutex = 1;
Semaphore empty = N;
Semaphore full = 0;
```

- Assume that the pool consists of N buffers
  - each buffer capable of holding one item
- The mutex binary semaphore provides mutual exclusion for accesses to the buffer pool
  - mutex is initialized to the value 1
- The empty and full semaphores count the number of empty and full buffers
  - empty is initialized to the value N
  - full is initialized to the value 0
- Note the symmetry between the producer and the consumer
- We can interpret this code as the producer producing full buffers for the consumer or as the consumer producing empty buffers for the producer

```
Producer Process:
  while (true) {
    ...
    /* produce an item in next_produced */
    ...
    wait(empty);
    wait(mutex);
    ...
    /* add next_produced to the buffer */
    ...
    signal(mutex);
    signal(full);
  }

Consumer Process:
  while (true) {
    wait(full);
    wait(mutex);
    ...
    /* remove an item from buffer to next_consumed */
    ...
    signal(mutex);
    signal(empty);
    ...
    /* consume the item in next_consumed */
    ...
  }
```

Readers-Writers Problem

- Multiple threads can access a database
  - To read or write there
- Writers must be in sync with each other and with readers (only one writer at a time)
  - a thread should be prevented from reading during a write
  - two writers should be prevented from write simultaneously
  - if a writer and some other process access the database simultaneously, chaos may result
- Readers are allowed access to the database simultaneously
- Several variations are possible
  - The simplest one is the first readers-writers problem
    - No reader be kept waiting unless a writer has already obtained permission to use the shared object
  - Second readers-writers problem
    - A ready writer must write as soon as possible (a waiting writer must access the shared object before a new reader is ready)
  - A Solution to either problem may result in starvation

First Readers-Writers Problem

- The reader processes share the following data structures

```
semaphore rw_mutex = 1;
semaphore mutex = 1;
int read_count = 0;
```

- The binary semaphores mutex and rw_mutex are initialized to 1
- read_count is a counter representing # of active readers - initialized to 0
- The semaphore rw_mutex is common to both reader and writer processes
- The mutex semaphore is used to ensure mutual exclusion when the variable read_count is updated
- The read_count variable keeps track of how many processes are currently reading the object
- The semaphore rw_mutex functions as a mutual exclusion semaphore for the writers
  - It is also used by the first or last reader that enters or exits the critical sections
  - It is not used by readers that enter or exit while other readers are in their critical sections
- If a writer is in the critical section and n readers are waiting
  - n-1 readers are queued on mutex
  - one header is queued on rw_mutex
- When a writer executes signal(rw_mutex)
  - we may resume the execution of either the waiting readers or a single waiting writer
  - Selection decided by scheduler
- Reader process

```
while (true) {
  wait(mutex);
  read_count++;
  if (read_count == 1)
    wait(rw_mutex);
  signal(mutex);
  ...
  /* reading is performed */
  ...
  wait(mutex);
  read_count--;
  if (read_count == 0)
    signal(rw_mutex);
  signal(mutex);
}
```

- Writer process:

```
while (true) {
  wait(rw_mutex);
  /* writing is performed */
  signal(rw_mutex);
}
```

Dining Philosophers Problem

- Five philosophers think, eat, think, eat, think,...
- One philosopher on each chair
- In the center of the table is a bowl of rice
- Five chopsticks available (two needed to eat)
- Thinking philosophers don't interact with others
- Each philosopher need to pick up left and right chopsticks
- Philosophers cannot pick up a chopstick that is already in use
- Philosophers with both chopsticks can eat
- When finished eating, philosopher puts down both chopsticks and starts thinking
- Illustrates the difficulty of syncing and allocating resources among process without deadlock and starvation

Semaphore Solution to Dining Philosophers Problem

- Each philosopher is a thread
- One semaphore per chopstick
  - Two philosophers cannot grab the same chopstick simultaneously
  - semaphore chopstick[5]
  - chopstick[i] initialized to 1
- This solution guarantees that no two neighbors are eating simultaneously
- But suppose that all five philosophers become hungry at the same time and each philosopher grabs the chopstick to the left
  - All the elements of chopstick will now be equal to 0
  - Then, when they try to grab the right chopstick... never going to happen... forever
  - A deadlock
- Solution:

```
semaphore chopstick[5];
...
while (true) {
  wait(chopstick[i]);
  wait(chopstick[(i+1) % 5]);
  ...
  /* eat for a while */
  ...
  signal(chopstick[i]);
  signal(chopstick[(i+1)%5]);
  ...
  /* think for a while */
  ...
}
```

- Several possible remedies to the deadlock problem are the following:
  - Allow at most four philosophers to be sitting simultaneously at the table
  - Allow a philosopher to pick up chopsticks only if both chopsticks are available
  - Use an asymmetric solution - that is, an odd-numbered philosopher picks up first left and then right chopstick, whereas an even-numbered philosopher picks up right and then left chopstick
  - Monitor Solution
- However, a satisfactory solution must guard against the possibility that one of the philosophers will starve to death
- A deadlock-free solution does not necessarily eliminate the possibility of starvation
- One solution: admit only 4 philosophers at a time who can attempt to eat (0 to 3)

```
T=3
semaphore chopstick[5]
...
while (true) {
  wait(T)
  wait(chopstick[i]);
  wait(chopstick[(i+1)%5]);
  ...
  /* eat for a while */
  ...
  signal(chopstick[i]);
  signal(chopstick[(i+1)%5]);
  signal(T);
  ...
  /* think for a while */
  ...
}
```

- There will always be at least one philosopher who can eat
  - even if everyone takes 1 or 2 chopsticks
  - Added a semaphore T which limits the number of philosophers who can attempt to eat

Monitor Solution to Dining Philosophers Problem

- Deadlock free solution
- Imposes the restriction on a philosopher to pick up chopsticks only if both are available
- To code the solution, we need to distinguish among three states in which we may find a philosopher by the following data structure:

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

- A philosopher i can set the variable state[i]=EATING only if the two neighbours are not eating:

(state[(i+4) % 5] != EATING) and (state[(i+1)%5]!=EATING)

- We also need to declare: condition self[5]
- This allows philosopher i to wait on self[i] when it is hungry but is unable to obtain the two chopsticks
- Each philosopher, before starting to eat, must invoke the operation pickup()
  - This act may result in the suspension of the philosopher process
  - After the successful completion of the operation, the philosopher may eat
- Following this, the philosopher invokes the putdown() operation
- Thus, philosopher i must invoke the operations pickup() and putdown() in the following sequence

```
while (true){
    DiningPhilosophers.pickup(i);
        ...
        eat
        ...
    DiningPhilosophers.putdown(i);
}
```

- The distribution of the chopsticks is controlled by the monitor DiningPhilosophers
- Shared variables: each philosopher has its own State that can be: (thinking, hungry, eating)
  - Philosopher i can only have state[i]=eating if its neighbors are not eating
- Conditional variables: each philosopher has a condition self (delay eat with no available chopsticks)
- Four functions
  - pickup(i) - philosopher i wants to pick up chopsticks
  - putdown(i) - Philosopher I puts down the chopsticks
  - test(i) - test the state of philosopher i
  - initialization_code() - initialization
- Monitor definition

```
monitor DiningPhilosophers {
  enum {THINKING, HUNGRY, EATING} state[5];
  condition self[5]

  void pickup (int i){
    state[i] = HUNGRY;
    test(i);
    if (state[i] != EATING)
      self[i].wait();
  }
  void putdown (int i){
    state[i] = THINKING;
    test ((i+4) % 5);
    test ((i+1) % 5);
  }
  void test (int i){
    if((state[(i+4) % 5] != EATING &&
        state[i] == HUNGRY) &&
       (state[(i+1) % 5] != EATING)) {
      state[i] = EATING;
      self[i].signal();
    }
  }
  initialization_code() {
    for (int i = 0; i<5; i++)
      state[i] = THINKING;
  }
}
```

Liveness Failure vs. Deadlock vs. Livelock

Liveness Failure: Failure of a task to progress or terminate as when it got stuck in an infinite loop or in a deadlock

Deadlock: The state in which at least two tasks are stuck waiting for an event that can only be caused by one of the two tasks

Livelock: A condition in which a thread continuously attempts an action that fails

System Model

- A system has limited resources shared among some competing tasks
- A task may utilize a resource in the following sequence:
  - **Request:** if the request cannot be granted immediately, then wait until it can acquire the resource
  - **Use:** can operate on the resource
  - **Release:** the task releases the resource
- A set of threads is in a deadlocked state when every thread in the set is waiting for an event that can be caused only by another thread in the set
- Multithreaded application developers must pay careful attention to how locks are acquired and released. Otherwise, deadlocks can occur

Necessary Conditions for Deadlock

- **Mutual Exclusion:** At least one resource must be held in a nonsharable mode; that is, only one thread at a time can use the resource. If another thread requests that resource, the requesting thread must be delayed until the thread has been released
- **Hold and wait:** A thread must be holding at least one resource and waiting to acquire additional resources that are currently being held by other threads
- **No preemption:** Resources cannot be preempted; that is, a resource can be released only voluntarily by the thread holding it, after that thread has completed its task
- **Circular wait:** A set $\{T_0, T_1, \ldots, T_n\}$ of waiting threads must exist such that T_0 is waiting for a resource held by T_1, T_1 is waiting for a resource held by $T_2, \ldots, T_{n-1}$ is waiting for a resource held by T_n, and T_n is waiting for a resource held by T_0

Resource Allocation Graph

- Consists of a set of vertices V and a set of edges E
- V is partitioned into two different types of nodes
  - $T = \{T_1, T_2, \ldots, T_n\}$, the set consisting of all the active tasks in the system
  - $R = \{R_1, R_2, \ldots, R_m\}$, the set consisting of all resource types in the system
- **Request edge:** A directed edge from task T_i to resource type R_j ($T_i \rightarrow R_j$)
  - It signifies that task T_i has been requested an instance of resource type R_j and is currently waiting for that resource
- **Assignment edge:** A directed edge from resource R_j to task T_i ($R_j \rightarrow T_i$)
  - It signifies that an instance of resource type R_j has been allocated to T_i
- Pictorially, we represent each task T_i by a circle and each resource type R_j by a rectangle
  - Since resource type R_j may have more than one instance, we represent each such instance as a dot in the rectangle

Deadlocks and Resource Allocation Graphs

- If a resource-allocation graph does not have a cycle, then the system is not in a deadlocked state
- If there is a cycle, then the system may or may not be in a deadlocked state
  - If only one resource per type - deadlock
  - If several resources per type - possible deadlock

Termination Hypothesis

- A task that has all the resources it needs, it uses them for a finite amount of time, then it releases them
- We say that the task terminates, but it could also continue, it doesn't matter, the important thing is that it releases the resource
- There is no deadlock if all tasks can terminate, one at a time
- In practice, this detection method oversimplifies the tasks

Methods for Handling Deadlocks

- Deadlocks can be dealt with in one of the following ways:
  - Ignore the problem altogether and pretend that deadlocks never occur in the system
  - Use a protocol to prevent or avoid deadlocks, ensuring the system will never enter a deadlocked state
  - Allow the system to enter a deadlocked state, detect it, and recover
- **Deadlock Prevention:** Provides a set of methods to ensure that at least one of the necessary conditions cannot hold
- **Deadlock Avoidance:** OS must get in advance some information concerning resources needed by a thread execution. Then the OS can decide whether or not the thread should wait - decision based on resources current availability
- **Act after detection:** Use an algorithm to detect a deadlock - If so, then run another algorithm to recover from the deadlock
- **Don't care:** OS do not deal with deadlock; system may stop working, in worst case scenario a manual intervention to restart the system is needed

Deadlock Prevention

- Prevent at least one of the 4 necessary conditions
- **Mutual exclusion:** eliminate the use of shared resources and critical sections
  - Possible only in the case of completely independent processes
- **Hold and wait:** a process that requests new resources should not hold others
  - How to know?
- **No preemption:** if a process requests other resources and cannot have them, then it must release its resources then put to wait
  - Requires an intervention from OS
- **Circular wait:** impose an order on resources. Difficult
- Prevention is difficult in general

Deadlock Avoidance

- Manage resources in a way that avoid getting into a deadlock
  - The simplest and most useful model requires that each task must declare the maximum number of anticipated resources
  - An algorithm examine all possible execution sequences to see if a Circular wait is possible
  - The algorithm dynamically examines the resource-allocation state to ensure that a circular-wait condition can never exist
  - The resource-allocation state is defined by the number of available and allocated resources and the maximum demands of the tasks

Safe State

- A state is safe if the system can allocate resources to each task (up to its anticipated maximum) in some order and still avoid a deadlock
- More formally, a system is in a safe state only if there exists a safe sequence for all tasks
- No deadlock is possible if a system is in safe state
- A deadlock is possible when a system is in unsafe state
  - In an unsafe state, the OS cannot prevent tasks from requesting resources in such a way that a deadlock occurs
  - The behaviour of the tasks controls unsafe states
- Avoidance ensure that a system will never enter an unsafe state
  - Do not allocate a resource to a task if the resulting state is not safe
- A sequence of threads $\langle T_1, T_2, \ldots, T_n \rangle$ is a safe sequence for the current allocation state if, for each T_i, the resource requests that T_i can still make, can be satisfied by the currently available resources include the resources held by all T_j which precede them ($i<j$)
  - If the resources that T_i needs are not immediately available, then T_i can wait until T_j have finished
  - When they have finished, T_i can obtain all of its needed resources, complete its designated task, return its allocated resources, and terminate
  - When T_i terminates, T_{i+1} can obtain its needed resources, and so on. Therefore, a safe sequence is a sequence that allow to run all tasks to completion
- If no such sequence exists, then the system state is said to be unsafe

Resource Allocation Graph Algorithm

Consider a resource allocation graph with only one instance of each resource type

- In addition to the actual request and assignment edges, we introduce a claim edge represented in the graph by a dashed line
- A claim edge $T_i \rightarrow R_j$ indicates that T_i may request R_j at some time in the future
- Claim edge $T_i \rightarrow R_j$ is converted to request edge when a process requests a resource, then when R_j is released the assignment edge $R_j \rightarrow T_i$ is reconverted to a claim edge $T_i \rightarrow R_j$
- Resources must be claimed in advance in the system
- If T_i requests R_j, this can be granted only if converting the request edge $T_i \rightarrow R_j$ to an assignment edge $R_j \rightarrow T_i$ does not result in the formation of a cycle in the resource allocation graph
  - A cycle detection algorithm is used to detect this

Banker's Algorithm

- A new thread entering the system must declare the maximum number of instances of each resource type that it may need, and it may not exceed the total number of resources in the system
- When a user requests a set of resources, the system must determine whether the allocation of these resources will leave the system in a safe state
- If it will, the resources are allocated; otherwise, wait until available
- Several data structures must be maintained to implement the banker's algorithm
  - n is the number of threads in the system
  - m is the number of resource types
  - Available: a vector of length m indicates the number of available resources of each type. If Available[i] equals k, then k instances of resource type R_i are available

- Max: An n×m matrix defines the maximum demand of each thread. If Max[i][j] equals k, then thread T_i may request at most k instances of resource type R_j
- Allocation: An n×m matrix defines the number of resources of each type currently allocated to each thread. If Allocation[i][j] equals k, then thread T_i is currently allocated k instances of resource type R_j
- Need: An n×m matrix indicates the remaining resource need of each thread. If Need[i][j] equals k, then thread T_i may need k more instances of resource type R_j to complete its task.
  Note: Need[i][j] = Max[i][j] - Allocation[i][j]

- Safety Algorithm: determines if a system is in a safe state

1. Work: vector of length m
   Finish: vector of length n
   initialize Work = Available, Finish[i]=false for i=0,1,...,n-1
2. Find an index such that both
   a. Finish[i] = false
   b. Need[i] ≤ Work
   If no such i exists, go to step 4
3. Work = Work + Allocation[i]
   Finish[i] = true
   go to step 2
4. If Finish[i] == true for all i, then system is in safe state

- Resource-Request Algorithm: determines whether requests can be safely granted
  - Request[i] be the request vector for thread T_i. If Request[i][j]=k, then thread T_i wants k instances of resource type R_j

1. If Request[i] ≤ Need[i], go to step 2. Otherwise, raise error condition
2. If Request[i] ≤ Available, go to step 3. Otherwise, T_i must wait
3. Have the system pretend to have allocated the requested resources to thread T_i as follows:
   Available = Available - Request[i]
   Allocation[i] = Allocation[i] + Request[i]
   Need[i] = Need[i] - Request[i]

   If the resulting resource-allocation state is safe, the transaction is completed, and thread T_i is allocated its resources. However, if the new state is unsafe, then T_i must wait for Request[i], and the old resource-allocation state is restored

Deadlock Detection

- It is difficult to detect if there is actually a deadlock in a system
- We might see that a number of processes are waiting for resources
- To know that there is a deadlock, we must know that no process in a group has a chance of receiving the resource

Deadlock Detection: Single instance of Each Resource

- Construct a resource-allocation graph
- Then we can convert it into a wait-for graph
  - An edge from T_i to T_j in a wait-for graph implies that thread T_i is waiting for thread T_j to release a resource that T_i needs
  - $T_i \rightarrow T_j$ in a wait-for graph exists if and only if the corresponding resource-allocation graph contains $T_i \rightarrow R_q$ and $R_q \rightarrow T_j$ for some resource R_q
- Use cycle detection algorithms to check if there are cycles in the wait-for graph. If there's a cycle, then a deadlock exists

Deadlock Detection: Several Instances of Resource Type

- Uses similar method as banker's algorithm

1. Work = Available
   For i=0,1,...,n-1
   if Allocation[i] ≠ 0
   Finish[i]=false
   else
   Finish[i]=true
2. Find an index i such that both
   a. Finish[i] == false
   b. Request[i] ≤ Work
   if no such i exists, go to step 4
3. Work = Work + Allocation[i]
   Finish[i] = true
   Go to step 2
4. If Finish[i] == false for some i, $0 \le i < n$, then system is in a deadlocked state. Moreover, if Finish[i]==false, then thread T_i is deadlocked

Recovery From Deadlock

- When a detection algorithm determines that a deadlock exists, several alternatives are available
  - Inform the OS to deal with deadlock
  - Let system recover from deadlock
    - Process and thread termination: simply to abort one or more threads to break the circular wait
    - Resource preemption: Preempt some resources from one or more of the deadlocked threads

Process and Thread Termination

- Abort all deadlocked processes
  - It will break the deadlock cycle, but at great expense
    - The deadlocked processes may have computed for a long time, and the results of these partial computations must be discarded and probably will have to be recomputed later
- Abort one process at a time until the deadlock cycle is eliminated
  - Considerable overhead: after aborting a process a deadlock-detection algorithm must be invoked to determine if any processes are still deadlocked
- We need a policy:
  - What the priority of the process is?
  - How long the process has computed and how much longer the process will compute before completing its designated task?
  - How many and what types of resources the process has used?
  - How many more resources the process needs in order to complete?
  - How many processes will need to be determined?

Resource Preemption

- It successfully preempts some resources from processes and give these resources to other processes until the deadlock cycle is broken
- Three issues needs to be addressed
  - Selecting a victim: Determine the preemption order of to minimize cost
    - factors may include number of resources per deadlocked process, time cost, etc
  - Rollback: We must have a roll back mechanism for preempted process to some safe state and restart it from that state
    - In most cases abort process and restart it
  - Starvation: Possible if same process is always picked as victim
    - Solution: Include number of rollbacks in the cost factor

Memory Management

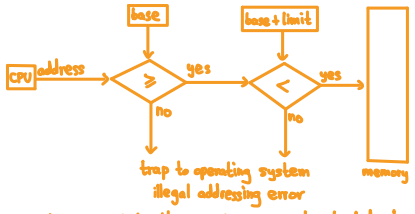
- The main purpose of a computer system is to execute programs
- Modern computer systems maintain several processes in memory during system execution
- Many memory-management schemes exist, reflecting various approaches, and the effectiveness of each algorithm varies with the situation
- Most memory-management algorithms require some form of hardware support
- Memory can be managed in various ways
- The memory-management algorithms vary from a primitive bare-machine approach to a strategy that uses paging
- Each approach has its own advantages and disadvantages
- Selection of a memory-management method for a specific system depends on many factors especially on the system hardware design
- Most algorithms require hardware support, leading many systems to have closely integrated hardware and OS memory management

Memory Background

- Memory is central to the operation of a modern computer system
  - Consists of a large array of bytes, each with its own address
- A process in execution is a program loaded into memory
  - As it executes, it accesses instructions and data from memory
  - The CPU fetches instructions from memory pointed to by PC
  - Fetched instruction will get decoded and executed and may cause operands to be loaded/stored from/to memory addresses
    Eventually, the process terminates, and its memory is reclaimed
- The memory unit provide access to memory data by addressing
  - It ignores source of the request
  - Accordingly, we can ignore how a program generates a memory address
  - We are interested only in the memory address sequence generated by a running program
- Several issues are pertinent to managing memory
  - Basic hardware
  - The binding of symbolic memory addresses to actual physical addresses
  - The distinction between logical and physical addresses
  - Dynamic linking and shared libraries

Memory Space Protection

- Main memory and CPU registers are the only general-purpose storage that the CPU can access directly
  - Instructions and data must be loaded from a secondary storage to main memory before the CPU can operate on them
- The hardware needs to provide memory access protection
  - Protect the OS from access by user processes
  - Protect user processes from one another
- Each process should have a separate memory space
  - This is fundamental for concurrent execution
- To separate memory spaces, we need the ability to determine the range of legal addresses that a process may access
  - Two registers needed
    - Base register holds smallest legal physical memory address
    - Limit register: specifies the size of the range
- CPU compares every address generated in user mode with the registers
- Any attempt by a program executing in user mode to access OS memory or other users' memory results in a trap to the OS
  - which treats the attempt as a fatal error
  - This prevents a user program from modifying the code or data structures of either the OS or other users



- The base and limit registers can be loaded only by the OS by a special privileged instruction
- OS, executing in kernel mode, is given unrestricted access to both OS memory and users' memory
  - This allows the OS to load users' programs into users' memory
  - To dump out these programs in case of errors
  - To access and modify parameters of system calls
  - To perform I/O to and from user memory
  - To provide many other services

Address Binding

- A user process may reside in any part of the physical memory
- A user program goes through several steps before being executed and addresses may be represented in different ways
  - A source program code has symbolic names
  - A compiler typically binds these symbolic addresses to relocatable addresses
  - The linker or loader in turn binds the relocatable addresses to absolute addresses
  - Each binding is a mapping from one address space to another
- Instructions/data binding to memory is done at any step along the way:
  - At compile time: if the process space in memory is known, then absolute code can be generated from the address and up - must recompile if memory location change
  - At load time: if at compile time the process space in memory is not known, then the compiler must generate relocatable code and final absolute binding is generated at load time
    - If starting address changes, then only reload the code to incorporate this changed value
  - At execution time: binding is done during execution time (dynamic binding)
    - Load, relocate system library during run-time
    - Special hardware is needed
    - Most operating systems use this method

Logical vs. Physical Address Space

- An address generated by the CPU is referred to as a logical or virtual address to specify a location in the program
- A physical address or absolute is asserted on the address bus to decode a physical location in the system
- Binding addresses at either compile or load time generates identical logical and physical addresses
- Binding addresses at execution time results in differing logical and physical addresses
  - The set of all logical addresses generated by a program is a logical address space
  - The set of all physical addresses corresponding to these logical addresses is a physical address space
- The run-time mapping from virtual to physical addresses is done by a hardware device called the memory-management unit (MMU)

- A simple MMU:
  - base-register value is added to every address generated by a user process at the time the address is sent to memory (Dynamic allocation)
- Real physical addresses are abstracted from the user program that deals with logical addresses only
- The memory-mapping hardware converts logical addresses into physical addresses
- We now have two different types of addresses: logical addresses (in the range 0 to max) and physical addresses (in the range R+0 to R+max for a base value R).
- The concept of a logical address space that is bound to a separate physical address space is central to proper memory management

Dynamic Loading

- By default, a routine is not loaded until it is called for the first time by a running process
- To load a routine, the relocatable linking loader is called to load the desired routine into memory and to update the program's address tables. Then, control is passed to the newly loaded routine.
- Implemented through program design, no special support from the OS is required. However, operating systems may provide library routines to implement dynamic loading

Dynamically Linked Libraries (DLL)

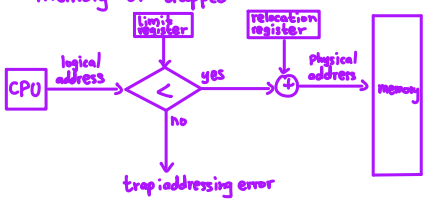
- System libraries linked to running user programs
- When a program references a routine that is a dynamic library, the loader locates the DLL and load it into memory if necessary
- Dynamic linking generally require help from OS
  - OS needs to check and to allow sharing of the same routine by multiple processes

Contiguous Memory Allocation

- Main memory must accomodate both the OS and the various user processes - in the most efficient way possible
- Main memory divided into partitions - one for the OS and one for the user processes
  - OS kernel can be placed at low memory together with the interrupt vector, or at high memory
  - Each process is contained in a single contiguous section of physical memory

Contiguous Memory Allocation: Memory Protection

- Prevent a process from accessing memory that it does not own
- Use relocation register (base register) together with a limit register
  - The relocation register contains the value of the smallest physical address; the limit register contains the range of logical addresses
  - Each logical address must fall within the range specified by the limit register
  - The MMU maps the logical address dynamically by adding the value in the relocation register
  - This mapped physical address is sent to memory or trapped if violation is found



Variable Partition

- Variably sized partitions that may contain exactly one process
- OS keeps a table of available/occupied memory
  - Initially, all memory is available for user processes
  - But eventually, memory contains a set of holes of various sizes
- The general dynamic storage-allocation problem concerns how to satisfy a request of size n from a list of free holes
- There are many solutions to this problem - most commonly used to select a free hole from the set of available holes:
  - first fit: Allocate the first hole that is big enough
    - searching either from the beginning of holes or from where the previous first-fit search ended
    - stop searching as soon as a free hole that is large enough is found
  - best fit: Allocate the smallest hole that is big enough
    - Search the entire list
    - This strategy produces the smallest leftover hole
  - worst fit: Allocate the largest hole
    - Search the entire list
    - This strategy produces the largest leftover hole, which may be more useful than the smaller leftover hole from a best-fit approach

External Fragmentation

- Available memory contains holes that together have enough free space to satisfy a request, but the available spaces are not contiguous to fit the request
  - Storage is fragmented into a large number of small holes
  - If all these small pieces of memory were in one big free block instead, we might be able to run several more processes
- First-fit and Best-fit strategies both suffer from external fragmentation

Compaction

- It is one solution to the external fragmentation problem
- Shuffle the memory contents so as to place all free memory holes together in one large block
  - It is possible only if relocation is dynamic and is done at execution time
  - Requires moving the process and data and then changing the base register to reflect the new base address
- When compaction is possible, we must determine its cost
- The simplest compaction algorithm is to move all processes toward one end of memory, producing one large hole of available memory
- Compaction can be expensive

Internal Fragmentation

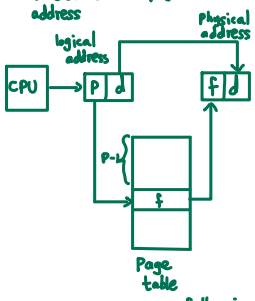
- Fragmentation that is internal to a partition
  - Consider a memory hole of 18,464 bytes and we want to fit a 18,462 bytes process
  - If we allocate exactly the requested block, we are left with a small external hole of 2 bytes only
  - The overhead to keep track of this hole will be substantially larger than the hole itself
  - The general approach to avoid this problem is to break the physical memory into fixed-sized blocks and allocate memory in units based on block size
  - Then the memory allocated to a process may be slightly larger than the requested memory
  - The difference between these two numbers is internal fragmentation - unused memory that is internal to a partition
  - Internal "hole" is reclaimed only when the process terminates

Paging

- A memory management scheme that permits a process's physical address space to be noncontiguous
- To avoid external fragmentation and the associated need for compaction
- Used for most operating systems
- Implemented through cooperation between the OS and the computer hardware

Basic Paging Method

- Break physical memory into fixed-sized blocks called frames
- Break logical memory into blocks of the same size called pages
- A process's logical pages are loaded into any available memory frames
- Every address space is now separate from the physical address space
- Every address generated by the CPU is divided into two parts: a page number (p) and a page offset (d)
  - The page number is used as an index into a per-process page table
  - The page table contains the base address of each frame in physical memory, and the offset is the location in the frame being referenced
  - Thus, the base address of the frame is combined with the page offset to define the physical memory address



- The MMU takes the following steps to translate a logical address generated by the CPU to a physical address
  - Extract the page number p and use it as an index into the page table
  - Extract the corresponding frame number f from the page table
  - Replace the page number p in the logical address with the frame number f
  - As the offset d does not change, it is not replaced, and the frame number and offset now comprise the physical address
- The page size is defined by the hardware
  - The size of a page is a power of 2, typically varying between 4kB and 1GB per page
  - If the size of the logical address space is 2^m, and the page size is 2^n bytes, then the high-order m-n bits of the logical address designate its page number and the n low-order bits designate the page offset
- The OS must maintain a page table for each process
- A list of free frames is also maintained
- When a process arrives in the system to be executed, its size is examined
- Each page of the process needs one frame

Paging Observations

- No external fragmentation
- We may have some internal fragmentation
  - Frames are allocated as units
  - If the memory requirements of a process do not happen to coincide with page boundaries, the last frame may not be completely full (internal fragmentation)
- In the worst case, a process would need n pages plus 1 byte. It would be allocated n+1 frames, resulting in internal fragmentation of almost an entire frame
- Internal fragmentation averages one-half page per process
- This consideration suggests that small page sizes are desirable
- However, overhead is involved in each page-table entry, and this overhead is reduced as the size of the pages increases
- Generally, page sizes have grown over time as processes, data sets, and main memory have become larger
- Today, pages are typically either 4kB or 8kB in size, and some systems support even larger page sizes
- Some CPUs and operating systems even support multiple page sizes
- Runtime address translation is easily accomplished by hardware:
  - A logical address (p,d) is translated into a physical address (f,d) by indexing the page table and appending the same offset d to the number of the frame f
- A program can be run on different hardware using different page sizes
  - What changes is the interpretation of the bits by the addressing mechanism
- Paging provide a clear separation between the programmer's view of memory and the actual physical memory
- The programmer views memory as one single space, containing only this one program
- In fact, the user program is scattered throughout physical memory, which also holds other programs
- Mapping (translation of logical to physical address) is hidden from the programmer and is controlled by the OS
- User program cannot access memory address outside of its page table, and the table includes only those pages that the process owns
- The OS manage physical memory and is aware of the allocation details
  - Which frames are allocated
  - Which frames are available
  - How many total frames there are, and so on
- This information is generally kept in a single, system-wide data structure called a frame table
  - One entry for each physical page frame

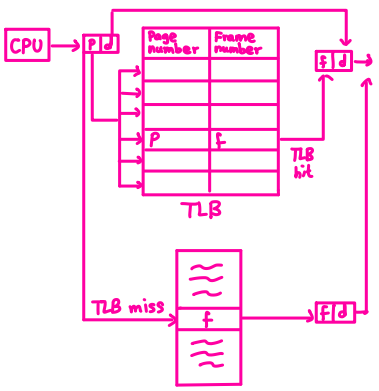
Hardware Support for Paging

- Page address translation is performed by hardware mechanisms
- However, if the page table is in the main memory, each logical address causes at least two references to memory
  - One for the page table entry
  - The other for the actual data access
- Thus, memory access is slowed by a factor of two - intolerable delay
- If the page table is moved to CPU registers, we gain in speed but lose in space
- We can have a mixed solution:
  - keep the page tables in main memory
  - Move most used addresses to CPU registers

Translation Look-Aside Buffer

- TLB is a small, fast lookup hardware cache - associative, high-speed memory
- Each entry in the TLB consists of 2 parts:
  - A key (or tag) and a value
    - key is page number
    - value is frame
  - When the associative memory is presented with an item, the item is compared with all keys simultaneously
    - However, the TLB must be kept small. It is typically between 32 and 1024 entries in size
  - If the item is found, the corresponding value field is returned
- The TLB contains only a few of the page-table entries
  - A logical address is generated by the CPU

    The MMU first checks if its page number is present in the TLB
  - If it is found (TLB hit), its frame number is immediately available and is used to (quickly) access memory
  - If the page number is not in the TLB (TLB miss), proceed according to the basic method
    - When the frame number is obtained, we can use it to access memory
    - Then the page and frame numbers are added to the TLB to replace another entry



- Some TLBs support address-space identifiers (ASIDs) in each TLB entry
  - ASID is used to allow the TLB to contain entries for several different processes simultaneously and to identify each process for protection purpose
  - Each page number must be matched to the ASID to running process - if no match, then it is treated as TLB miss
- If the TLB does not support separate ASIDs, then every time a new page table is selected, the TLB must be flushed
  - This ensure that the next executing process does not use the wrong translation information
  - Otherwise, the TLB could include old entries that contain valid virtual addresses but have incorrect or invalid physical addresses left over from the previous process

Effective Memory Access Time

- The percentage of times that the page number of interest is found in the TLB is called the hit ratio
- To find the effective memory-access time, we weight the case by its probability

EMAT = Hit Ratio * TLB hit memory access time + (1-Hit Ratio) * TLB miss memory access time

Paging Protection

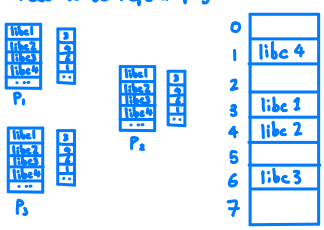
- Protection bits can be associated with each frame in the page table
- This approach can be easily expanded to provide a finer level of protection
  - A hardware can be implemented to provide read-only, read-write, or execute-only protection

We can use a valid-invalid bit to check for access to the process memory:

- Valid bit = the associated page is in the process's logical address space
- Invalid bit: the associated page is not in the process's logical address space
- OS can set this bit for each page to allow or disallow access to the page, then trap any illegal addresses
- This may result in internal fragmentation
- Rarely does a process use all its address range
  - Many processes use only a small fraction of the address space available to them
  - It would be wasteful in these cases to create a page table with entries for every page in the address range
  - Most of the table would be unused but would take up valuable memory space
  - Solution: Some systems provide hardware-page-table length register (PTLR), to indicate the size of the page table. This value is checked against every logical address to verify that the address is in the valid range for the process. Failure of this test causes an error trap to the OS

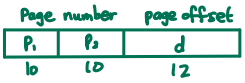
Shared Pages

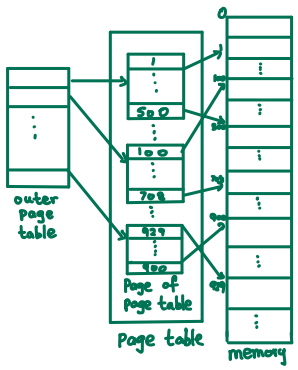
- An advantage of paging is the possibility of sharing common code
- Shared code
  - One copy of read-only code shared among processes
- Private code and data
  - Each process keeps a separate copy of private code and data
- The diagram below shows three processes sharing the pages for the standard C library libc
  - Reentrant code is non-self-modifying code: it never changes during execution Thus, two or more processes can execute the same code at the same time
  - Only one copy of the standard C library need to be kept in physical memory



Two-Level Paging

- Page itself is also paged
- Outer page table entries point to the pages of the real page table
- Consider a system with a 32-bit logical address and page size 4kB
  - A page number consisting of 20 bits and a page offset of 12 bits
  - Since we page the page table, the page number is further divided into two 10-bit each

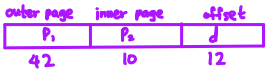




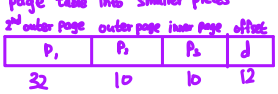
- This shows the address-translation method for this architecture
- Because address translation works from the outer page table inward, this scheme is also known as a forward-mapped page table
- In the case of the two-level paging, the use of the TLB becomes even more important to reduce the multiple memory accesses to calculate the physical address
- In computers with large logical address space, multi-level paging system is needed
- TLB is searched first

Multi-Level Paging

- For a system with 64-bit logical address space, a two-level paging scheme is no longer appropriate
  - Assume we maintain a page size at 4kB then the page table consists of up to 2^{52} entries
  - Making it two-level with inner page tables = 2^{10} 4-byte entries, then the outer = 2^{42} entries of 4-byte



- The obvious way to avoid such a large table is also divide the outer page table into smaller pieces



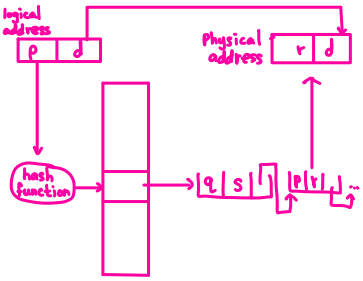
- The outer page table is still large
- The next step would be a four-level paging scheme, where the second-level outer page table itself is also paged, and so forth

Hashed Page Tables

- For handling address spaces larger than 32 bits
  - Hash value being virtual page number
  - Each entry in the hash table contains a linked list of elements that hash to the same location
  - Each element consists of 3 fields:
    - virtual page number
    - value of mapped page frame
    - pointer to next element
- Virtual page numbers are compared in this chain searching for a match

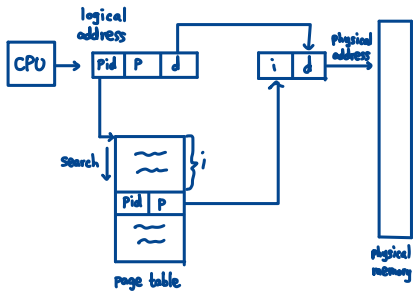
Hashed Page Tables Algorithm

- The virtual page number in the virtual address is hashed into the hash table
- The virtual page number is compared with field 1 in the field element in the linked list
- If there is a match, the corresponding page frame (field 2) is used to form the desired physical address
- If there is no match, subsequent entries in the linked list are searched for a matching virtual page number



Inverted Page Table

- Usually, each process has an associated page table that has one entry for each page that the process is using
  - A drawback is that each page table may consist of millions of entries that may consume large amounts of memory just to keep track of how memory is being used
- Inverted page tables have only one entry for each physical frame of memory
  - Each entry consists of the virtual address of the page stored in that real memory location, with information about the process that owns the page
  - Only one page table is in the system, and it has only one entry for each page of physical memory
  - But how do we translate from page number to frame number?
    - Search the inverted page table until we find a match for the page number and process ID
- Inverted page tables often require that an address space identifier be stored in each entry of the page table
- Storing the address-space identifier ensures that a logical page for a particular process is mapped to the corresponding physical page frame



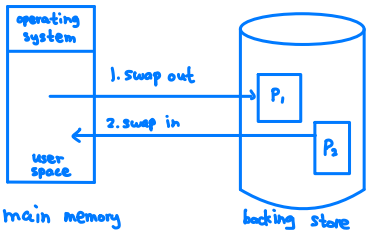
- This scheme decreases the amount of memory needed to store each page table
- But it increases the amount of time needed to search the table when a page reference occurs
  - Because the inverted page table is sorted by physical address, but lookups occur on virtual addresses, the whole table might need to be searched before a match is found - This would take far too long
  - To alleviate this problem, we use a hash table, to limit the search to one, or at most a few page table entries
    - Each access to the hash table adds a memory reference to the procedure - one virtual memory reference requires at least two real memory loads
    - TLB searched first

Swapping

- Used to increase the degree of multiprogramming in a system
  - So, the total physical address space of all processes can exceed the real physical memory of the system
  - A process, or a portion of a process, can be swapped temporarily out of memory to a backing store (secondary storage area for process swapping) and then brought back into memory for continued execution

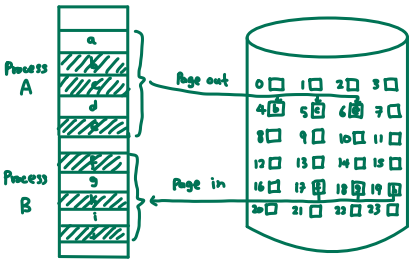
Standard Swapping

- Standard swapping involves moving entire processes between main memory and a backing store
- For a multithreaded process, all per-thread data structures must be swapped as well
- The OS must also maintain metadata for processes that have been swapped out, so they can be restored when they are swapped back into memory
- The advantage of standard swapping is that it allows physical memory to be oversubscribed, so that the system can accomodate more processes than there is actual physical memory to store them
- Idle or mostly idle processes are good candidates for swapping; any memory that has been allocated to these inactive processes can then be dedicated to active processes



Swapping with Paging

- Standard swapping is generally no longer used in contemporary operating systems
  - The amount of time required to move entire processes between memory and the backing store is prohibitive
- Paging only swap some pages of a process - rather than an entire process
  - Still allows physical memory to be oversubscribed but does not incur the cost of swapping entire processes, as presumably only a small number of pages will be involved in swapping
  - A page out operation moves a page from memory to the backing store; the reverse process is known as a page in



Swapping on Mobile Systems

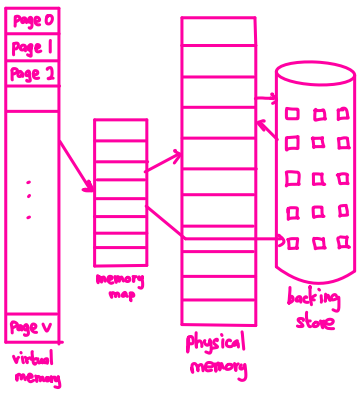
- They typically do not support swapping in any form
- Mobile devices generally use flash memory for nonvolatile storage - space constraint is one reason to avoid swapping
- Other reasons include the limited number of writes that flash memory can tolerate before it becomes unreliable and the poor throughput between main memory and flash memory in these devices
- Instead of using swapping, when free memory falls below a certain threshold:
  - Ask applications to optimize the use of memory
  - Applications that fail to free up sufficient memory may be terminated by the OS
  - However, before terminating a process, some OS writes its application state to flash memory so that it can be quickly restored

Virtual Memory

- A technique that allows the execution of processes that are not completely in memory
- Virtual memory abstracts main memory into an extremely large, uniform array of storage - it frees programmers from the concerns of memory-storage limitations
- Virtual memory allows processes to share files and libraries, and to implement shared memory
- Provides efficient mechanism for process creation
- Not easy to implement and may substantially decrease performance if used carelessly
- Instructions to be executed must be in physical memory
  - One approach is to place the entire logical address space in physical memory
  - Dynamic linking can help to ease this restriction but requires special precautions and extra work by the programmer
  - In many cases, the entire program is not needed in main memory
    - Programs with code to handle error conditions - in practice almost never executed
    - Arrays, lists, and tables allocated more memory than needed
    - Certain options and features of a program may be used rarely
- Motivation: virtual memory has the ability to execute a program that is only partially in memory. It would offer many benefits:
  - Possibility to run programs larger than the main memory
  - Less physical memory to each program

Logical/Physical Memory Separation

- Virtual memory involves the separation of logical memory as perceived by developers from physical memory - allows an extremely large virtual memory to programmers when physical memory is relatively small



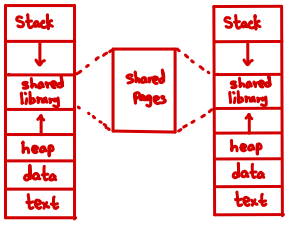
Virtual Address Space

A process virtual address space refers to the logical view of how a process is stored in memory - say address 0 - and exists in contiguous memory

- It is up to memory-management unit (MMU) to map logical pages to physical page frames in memory
- The heap grows upward in memory as it is used for dynamic memory allocation
- The stack grows downward in memory through successive function calls
- The hole in the middle is part of the VAS but will require actual physical pages only if the heap or stack grows. VAS that include holes are known as sparse address spaces, the holes can be filled by growing stack/heap or dynamically linked libraries

Virtual Memory Sharing

- Virtual memory allows files and memory sharing between processes
- The actual frames in physical memory are shared by all the resources
- Virtual memory allows one process to create a region of memory that it can share with another process - each process consider it part of their VAS



Demand Paging

- Demand paging: In memory management, bringing in pages from storage as needed
- Locality of reference: The tendency of processes to reference memory in patterns rather than randomly
- Page fault: In virtual memory, a fault resulting from a reference to a non-memory-resident page
- Reference string: A string of memory references
- While a process executes, some pages are in main memory and the rest are in secondary storage - hardware support is needed to distinguish between the two:
  - Use valid-invalid bit scheme
  - When the bit = valid, the associated page is both legal and in main memory
  - If the bit = invalid, the page either is not valid or is valid but is currently in secondary storage
  - Marking a page invalid will have no effect if the process never attempts to access that page

Handling Page Fault

- The valid-invalid bit is initialized to 0 for all pages
- Access to a page marked invalid is trapped by the operating system, causing a page fault
- The OS would then check if the reference is legal or not. If it is illegal, the process is terminated
- If the reference is legal, then the kernel finds a free frame in physical memory and schedules a secondary storage operation to read the desired page into the newly allocated frame. Then the frame number is loaded into the page table entry
- Then restart the instruction that was interrupted by the trap

Demand Paging Performance

- Pure demand paging: never bring a page into memory until it is required
  - In worst case, a process starts with zero pages in memory
  - It immediately faults from the page, then it is brought into main memory
  - The process continues to execute, faulting as necessary until every page that it needs is in memory. At that point, it can execute with no more faults
- Some processes could access several new pages causing multiple page faults per instruction - unacceptable performance
- Secondary memory should be a high-speed disk or NVM device. It is known as the swap device, and the section of storage used for this purpose is known as swap space

Effective Access Time

- Let p be the probability of a page fault ($0 \le p \le 1$). We should expect p to be close to zero - that is, we would expect to have only a few page faults. The effective access time is then

  effective access time = $(1-p) \times ma + p \times$ page fault time

- The effective access time is directly proportional to the page-fault rate.
- It is important to keep the page-fault rate low in a demand-paging system. Otherwise, the effective access time increases, slowing process execution dramatically

Page Replacement

- In a situation where all memory is in use, but an executing process needs a page from the secondary storage (swap space)
- The OS has several options at this point
  - Terminate the process (not the best choice)
  - Use standard swapping to reduce multiprogramming level - it is no longer used by most OS due to the overhead of swapping entire processes
  - Combine swapping pages with page replacement
- If there are no free frames, we find one that is not currently being used and free it by:
  - Moving it to swap space
  - We can now use the freed frame to hold the page for which the process faulted
- Modify the page-fault routine to include page replacement:
  1. Find the location of the desired page on secondary storage
  2. Find a free frame
     a. If there is a free frame, use it
     b. If there is no free frame, use a page-replacement algorithm to select a victim frame
     c. Write the victim frame to secondary storage (if necessary); change the page and frame tables accordingly
  3. Read the desired page into the newly freed frame; change the page and frame tables
  4. Continue the process from where the page fault occurred

Dirty Bit

- If no frames are free in the main memory, two page transfers (page-out and page-in) are required - page-fault service time doubled and effective access time increased accordingly
- To reduce this overload, use a modify bit (or dirty bit)
  - Associate a dirty bit to each page or frame
  - A page dirty bit is set by the hardware whenever any byte in the page is written into, indicating that the page has been modified - when selected for replacement
    - if dirty bit is set, it means that the page has been modified (updated) since it was read in from secondary storage - must write it to storage
    - if dirty bit is not set, the page has not been modified since it was read into memory - no need to write it to storage
  - This technique also applies to read-only pages
  - Can significantly reduce the time required to service a page fault - reduces I/O time by one-half

Algorithm Selection Criteria

- We want to select a page-replacement algorithm with the lowest page-fault rate
- As the number of available frames in main memory increases, the number of page faults drops to some minimal level
  - Adding physical memory increases the number of available frames

FIFO Page-Replacement Algorithm

- Simplest algorithm - associates time-in to main memory to each page
- When a page must be replaced, the oldest page is chosen
- FIFO queue holds all pages in main memory - replace the page at the head - insert brought-in page (to main memory) at the tail
- The algorithm is easy to understand and program - but its performance is not always good
- A replaced page could contain a heavily used variable that was initialized early and is in constant use - a fault occurs almost immediately to retrieve this page
  - Thus, a bad replacement choice increases the page-fault rate - slows execution

Belady's Anomaly

- Belady's Anomaly is when increasing the number of available frames actually increases the number of page fault
- As a result, the assumption of improving a process performance by giving it more memory is not always true
- For some page-replacement algorithms, the page-fault rate may increase as the number of allocated frames increases

Optimal Page Replacement Algorithm

- Never suffer from Belady's anomaly
- Replaces the page that will not be used for the longest period of time
- Guarantees lowest possible page-fault rate
- Hard to implement

LRU Page Replacement Algorithm

- An approximation of optimal replacement algorithm
  - use recent past as an approximation of the near future
- Associates last use of each page when a page must be replaced
- Replaces the page that has not been used for the longest period of time
  - Not necessarily the same as FIFO's "oldest page"
  - For LRU it is in terms of last page reference
- By the principle of locality, this should be the page least likely to be referenced in the near future
- Performs nearly as well as optimal algorithm
- Often used as a page-replacement algorithm and considered to be good
- Major problem: how to implement?
  - Require substantial hardware assistance
  - Problem is to determine an order for the frames defined by the time of last use
- Two implementations are feasible
  - Counters
  - Stack

LRU - Counters Algorithm

- Associate a time-of-use field to each page-table entry
  - updated for every memory reference - always have the "time" of the last reference to each page
  - Replace the page with the smallest value
- Requires a search of the page table to find the LRU page and a write to memory for each memory access
- The times must also be maintained when page tables are changed
- Overflow of the clock must be considered

LRU - Stack Algorithm

- keep a stack of page numbers - whenever a page is referenced, it is removed from the stack
  - The most recently used page is always at the top of the stack
  - The least recently used page is always at the bottom
- Requires removing elements from the middle of the stack - a doubly linked list with a head pointer and a tail pointer
- Requires changing six pointers at worst to maintain the stack
- Each update is a little more expensive, but there is no search for a replacement
- This approach is particularly appropriate for software or microcode implementations of LRU replacement

LRU Approximation Page Replacement

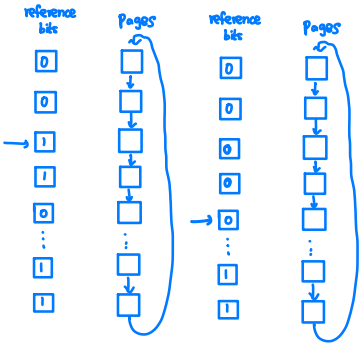
- Most practical - implemented by most operating systems

LRU approximation page replacement - associate a reference bit to each entry in the page table - initialized to 0 - then set to 1 with each page reference. After some time, we can determine which is not being used - order of use not maintained

- Additional-reference-bits algorithm - similar but adding more bits to help maintaining the order

Second-Chance (Clock) Algorithm

- Is a FIFO with a reference bit, if the reference bit is 1 then give the page a second chance (reset bit = 0) and move on to select the next FIFO page
- Implementation: As a circular queue with pointer indicates which page is to be replaced next:
  - When a frame is needed, the pointer advances until it finds a page with a 0-reference bit, then is replaced with a new page in the circular queue in that position
  - As the pointer advances, it clears the reference bits - in the worst case, when all bits are found to be 1, the pointer cycles through the whole queue, giving each page a second chance
- Second-chance replacement degenerates to FIFO replacement if all bits are set



- Each bloc of memory has a reference bit
- When the page has been referenced to the bit is set to 1 by the hardware
- The OS can examine this bit
  - If 0, page can be replaced
  - If 1, change to 0

Enhanced Second-Chance Algorithm

- Considering the reference bit and the modify (dirty) bit as an ordered pair - 4 possible classes:
  - (0,0) neither recently used nor modified - best victim page to replace
  - (0,1) not recently used but modified - not quite as good, because the page will need to be written out before replacement
  - (1,0) recently used but clean - probably will be used again soon
  - (1,1) recently used and modified - probably will be used again soon, and the page will need to be written out to secondary storage before it can be replaced
- At page fault - examine the class - replace first encountered page in the lowest nonempty class
- May have to scan the circular queue several times before picking a victim
- The major difference between this algorithm and the simpler clock:
  - We give preference to pages that haven't been modified
  - reduce I/Os required

Counting-Based Page Replacement

- keep a reference number counter - made to each page and develop the following two schemes
  - Least Frequently Used (LFU) - an actively used page have a large reference count - replace the page with the smallest count
    - Problem: A page heavily used for an initial phase has a large count - but then is never used again - no longer needed but persist in memory
    - Solution: Shift counts right by 1 bit at regular intervals (binary division), forming an exponentially decaying average usage count
  - Most frequently used (MFU) - the smallest count page was probably just brought in and has yet to be used
- Neither MFU nor LFU replacement is common
- The implementation of these algorithms is expensive, and they do not approximate OPT replacement well

Page-Buffering Algorithms

- Not a page-replacement by itself - but a procedure that can be added to a specific page-replacement algorithm - pages to be replaced are kept in main memory for a while to guard against poorly performing algorithms such as FIFO
  - keep a pool of free frames
  - At page fault, a victim frame is chosen - not written out yet
  - The requested page is read into a free frame from the pool
  - The process can restart ASAP
  - When later the victim is written out, its frame is added to the free-frame pool
- One variation is to maintain a list of modified pages (victims) - write a page to secondary storage whenever the paging device is idle and reset its modify bit to 0
  - This scheme increases the probability that a frame will be free when it is selected for replacement
- Another variation is to keep a pool of free frames but to remember which page was in each frame
- When a frame is written to secondary storage - actually it is copied out - so the old page can be reused directly from the free-frame pool if it is needed before that frame is reused
  - When a page fault occurs, we first check whether the desired page is in the free-frame pool
- Some versions of the UNIX system use this method in conjunction with the second-chance algorithm
- Can be a useful augmentation to any page-replacement algorithm, to reduce the penalty incurred if the wrong victim page is selected

Allocation of Frames

- To execute, a process needs a minimal number of memory frames
- It is easy to see that when a process receives few frames, it will generate an excessive number of page faults and be slowed considerably
- How to ensure that a process is allocated its minimum
  - Equal allocation: each process has an equal portion of physical memory
  - Proportional allocation: each process is allocated according to its size
- The criteria should be more related to the pages needed

Global vs. Local Allocation

- The way frames are allocated to the various processes is page replacement
- With multiple processes competing for frames, we can classify page-replacement algorithms into 2 broad categories:
  - Global replacement: allows a process to select a replacement frame from all frames
  - Local replacement: Each process select from only its own set of allocated frames

Thrashing

- Paging memory at a high rate - insufficient physical memory to meet virtual memory demand
- A process is thrashing if it is spending more time paging (waiting in I/O queues) than executing - it no longer can complete any useful work
- A process needs a minimum number of pages to run efficiently
- In multiprogramming
  - Number of pages needed by a running process hit a point where it exceeds the number of available physical memory frames
  - It starts faulting and taking frames away from other processes
  - So they also fault
  - Heavy page swap in and out
  - CPU utilization decreases as many processes are waiting in I/O queues
  - CPU scheduler seeks to increase the degree of multiprogramming
    - introduce new processes in
    - taking frames away from already "steady" processes
    - causes more faulting
    - more new processes introduced
  - Thrashing occurs

Limiting the Effects of Thrashing

- Implement a local replacement algorithm - a process select from only its own set of allocated frames
  - If the process fault - select from only its own set of frames for replacement
  - Then it thrashes it cannot spread to others by stealing from their frames
  - Thus, thrashing is localized to the thrashing process
- However, the problem is "localized" but not entirely solved
- The affected process will stay longer in I/O queue - page fault average service time will increase for other processes that are not thrashing

Locality Model

- To prevent thrashing, the OS must provide a process with as many frames as it needs - but how to know it "needs"?
- One strategy starts by looking at how many frames a process is actually using - the locality model of process execution
- States: as a process executes, it moves from locality to locality - may overlap
- A locality is a set of pages that are actively used together
- All programs will exhibit this basic patterned memory reference structure
- Allocate enough frames to a process to accomodate its current locality - it will fault until all locality pages are in main memory; then, it will not fault again until it changes localities
- Enough frames must accomodate the size of the current locality - if not - the process will thrash

Working-Set Model

- Based on the assumption of locality - an approximation of the program's locality
- Uses a parameter, Δ, to define the working-set window (window of time)
  - Examine the most recent Δ page references
  - The set of pages in the most recent Δ page references is the working set
  - If a page is in active use, it will be in the working set
  - If it is no longer being used - it will drop from the working set Δ time units after its last reference
- The accuracy of the working set depends on its size (the selection of Δ)
  - if too small, it will not encompass the entire locality
  - if too large, it may overlap several localities
- If WSS_i is the working-set size for each process in the system, the total demand for frames is

$$D = \sum WSS_i$$

- So a process i needs WSS, frames, and each process is actively using the pages in its working set
- If the total demand is greater than the total number of available frames (D>m) - thrashing will occur
- Once Δ has been selected, use of the working-set model is simple
- OS monitors the working set of each process - allocates enough frames to its working-set size
- If there are enough extra frames, another process can be initiated
- If the sum of the working-set sizes exceeds the total available frames - selects a process to suspend (swap it out and reallocate its frames to other processes). The suspended process can be restarted later
- This working-set strategy prevents thrashing while keeping the degree of multiprogramming as high as possible - it optimizes CPU utilization
- Page-fault rate peaks at as new locality begin demand-paging - once in memory then it will drop
- Page-fault rate rises toward a peak once again when the process moves to a new working set - returning to a lower rate once the new working set is landed into memory
- The span of time between the start of one peak and the start of the next peak represents the transition from one working set to another

- The difficulty in keeping track of the working set is that at each memory reference:
  - a new reference appears at one end
  - the oldest reference drops off the other end
  - a page is in the working set if it is referenced anywhere in the working-set window

Page-Fault Frequency

- The specific problem is how to prevent thrashing - we know it has a high page-fault rate - so, let's control the page-fault rate
  - When it is too high, we know that the process needs more frames
  - When it is too low, then we know that the process may have too many frames
  - So, establish upper and lower bounds on the desired page-fault rate
  - If the actual page-fault rate exceeds the upper limit - allocate the process another frame
  - If the page-fault rate falls below the lower limit - remove a frame from the process
  - Thus, we can directly measure and control the page-fault rate to prevent thrashing
- As with the working-set strategy, we may have to swap out a process
- If the page-fault rate increases and no free frames are available, we must select some process and swap it out to backing store
- The freed frames are then distributed to processes with high page-fault rates

File System

- A file is a collection of related information defined by its creator
- Files are mapped by the OS onto a nonvolatile mass-storage devices
- A file system describes how files are mapped onto physical devices, and how they are accessed/manipulated by users/programs
- File system must provide efficient access to relatively slow physical storages
- File system is also required to provide files support for: sharing, remote access, etc.

File Concept

- A text file is a sequence of characters organized into lines
- A source file is a sequence of functions, each of which is further organized as declarations followed by executable statements
- An executable file is a series of code sections (binary) that the loader can bring into memory and execute

File Attributes

- A file's attributes vary from one operating system to another but typically consist of:
  - Name: human-readable form information
  - Identifier: File identification by the file system
  - Type: needed for systems that support different types of files
  - Location: a pointer to a device and to the file location on that device
  - Size: of the file and possibly the maximum allowed size are included in this attribute
  - Protection: determine who can read, write, execute, and so on
  - Timestamps and user identification: creation, last modification, and last use - can be useful for protection, security, and usage monitoring
  - Some newer file systems also support extended file attributes
- The information about all files are kept in the directory structure, which resides on the same device as the files themselves
- In general, for every file there are two data structures
  - One to store information related to a file
  - The second to store the actual file data
  - The directory have the file name and a number (pointer to inode blocks)
  - The inode block has references to the data blocks that contain the actual contents of the file

File Operations

- Seven basic file operations
  - Create file: Two steps
    - Allocate space
    - Add entry in a directory for the new file
  - Open file: sequential access pointer
    - OS evaluate name, check access permissions
    - open() system call required by all operations except create and delete
  - Write: maintain a write pointer in the file location where the next write is to take place
  - Read: maintain a read pointer in the file location where the next read is to take place
  - Reposition within a file: the current file position pointer of the open file is repositioned to a given value
  - Delete file: release all file space, so that it can be reused by other files
  - Truncate: erase the contents of a file but keep its attributes - all attributes remain unchanged - except for file length
- Some other operations
  - Appending new information to the end of an existing file
  - Renaming an existing file
- These primitive operations can be combined to perform other file operations

File Types

- Windows use the file name extension to identify the type
- Unix:
  - Use magic number (optional) binary file or Text magic number for text file - at the start of files to indicate the type
  - File type extension meant to aid users in determining file type
- Mac-OS:
  - Each file has a type and a creator attribute containing the name of the program that created it
  - For instance, a file "B" produced by a word processor "X" has "X" as its creator. When the user opens "B", "X" is invoked automatically to load the file "B"

File Structure

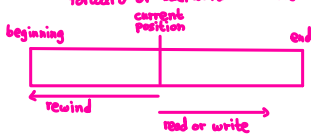
- The type of a file can be used to indicate its internal structure
  - File structures must match the expectations of the programs that read them
  - Certain files must conform to a required structure that is understood by the OS
  - Some operating systems has a set of system-supported file structures - disadvantages large and cumbersome OS - but simplifies the application
- Some operating systems impose (and support) a minimal number of file structures
- However, all operating systems must support at least one structure - that of an executable file - so that the system is able to load and run programs

Access Methods

- To access a file-stored information - it must be read into computer main memory
- This information can be accessed in several methods - choosing the right one for a particular application is a major design problem

Sequential Access

- The simplest: information in the file is processed in order, one record after the other - tape model
  - Read operation: read_next() - reads the next file portion and advances a file pointer to the next record location
  - Write operation: write_next() - appends to the file end and advances to the end of the newly written material
    - can also rewind to the beginning
    - jump to a specific location - skip forward or backward n records



Direct Access

- A file structure - fixed-length logical records - read and write records in no particular order
- A disk model direct access (random access to any file block)
  - The file is viewed as a numbered sequence of blocks or records
- It is great use for immediate access to large amounts of information
- A relative logical block number is an index relative to the beginning of the file - a contiguous 0 to N seen by the programmer
  - The OS get the relative block numbers from the user then decides where the file should be placed
  - Some systems start their relative logical block numbers at 0, others start at 1
- File operations include read(n) and write(n), where n is the logical block number
- An alternative approach is (from tape model perspective) is: to use position_file(n), where n is the logical block number, then either use read_next() or write_next() operation

Simulation of sequential access on direct-access file

- Not all operating systems support both sequential and direct access to files
- Some systems require that a file be defined as sequential or direct when it is created. Such a file can be accessed only in a manner consistent with its declaration
- We can easily simulate sequential access on a direct-access file by simply keeping a variable cp that defines our current position

sequential access	implementation for direct access
reset	cp=0;
read_next	read cp; cp=cp+1;
write_next	write cp; cp=cp+1;

Other Access Methods

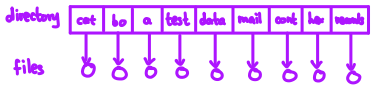
- Use a small main index (in memory) that points to second level index (disk blocks on disk) that in turn point to the location of the file data blocks
  - To find a particular item, we first make a binary search of the main index, which provides the block number of the secondary index
  - This secondary block is again binary searched to find the block containing the desired record
  - Finally, this block is searched sequentially to access the actual data

Directory Structure

- The directory can be viewed as a symbol table that translates file names into their file control blocks - it can be organized in many ways that must allow:
  - Insert entries
  - Delete entries
  - Search for a named entry
  - List all entries in the directory
- When considering a particular directory structure, we need to keep in mind the operations that are to be performed on a directory
  - Search for a file: to find a particular file - or find all files whose names match a particular pattern
  - Create a file: new files need to be created and added to the directory
  - Delete a file: note a delete leaves a hole in the directory structure and the file system may have a method to defragment the directory structure
  - List a directory: list the files in a directory and the contents of the directory entry for each file in the list
  - Rename a file: renaming a file may also allow its position within the directory structure to be changed
  - Traverse the file system: access every directory and every file within a directory structure

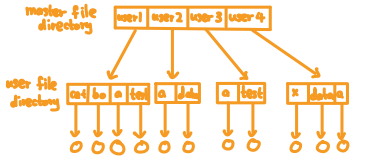
Single-Level Directory

- The simplest structure - all files are contained in the same directory which is easy to support and understand
  - Has significant limitations
    - when the number of files increases - must each have a unique name
    - if system has many users - naming conflicts - 1 directory for all users
  - Even a single user on a single-level directory may find it difficult to remember the names of all the files as the number of files increases
- Primitive - all files present in the same directory



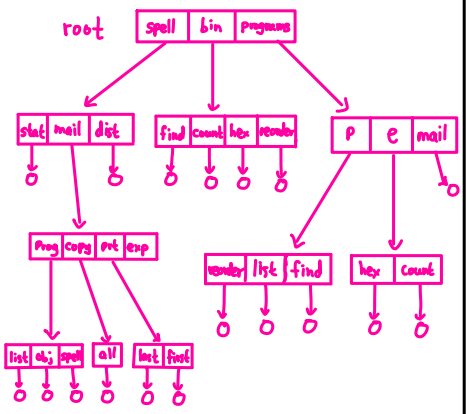
Two-Level Directory

- Each user has their own directory - user file directory (UFD)
- There is main file directory (MFD) (master node) that has a separate directory for each user
  - When a user job starts or a user logs in, the MFD is searched
  - The MFD is indexed by username or account number, and each entry points to the UFD for that user - users may have same file name within their respective UFDs
- Each user is allocated one directory (UFD) - better than a single-level directory structure but still not very efficient



Tree-Structured Directories

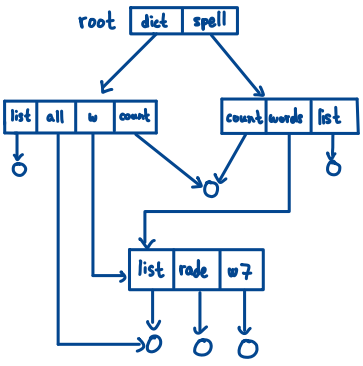
- Most common - allows sub-directories in a directory
- Has root directory
  - allows users to create subdirectories and to organize their files accordingly
  - every file in the system has a unique path name
- Efficient searching
- Grouping capability



- In normal use, each process has a current directory - it should contain most of the files that are of current interest to the process
  - When reference is made to a file, the current directory is searched
  - If a file is needed that is not in the current directory, then the user usually must either specify a path name or change the current directory to be the directory holding that file
- A path can be absolute or relative
  - An absolute path name begins at the root and follows a path down to the specified file
  - A relative path name defines a path from current directory

Acyclic Graph Directories

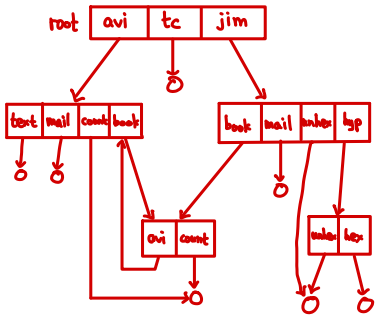
- Allows sharing subdirectories and files - allows access a file or a subdirectory from multiple directories
  - Cycles are not allowed
  - Symbolic links are used to point from multiple directories to a particular directory or file
  - Similar to tree + links for sharing



- Several problems must be considered carefully
  - A file may now have multiple absolute path names - distinct file names may refer to the same file
  - Deletion problem - shared file by symbolic links space allocation - if a user deletes the shared file - this will leave dangling pointers to the now-nonexistent file and possibly to actual disk addresses - Possibly into other files in the reused space
- UNIX OS uses the following approach for hard links - keep the number of references count - adding a new link increments the count. If count > 0, then delete only the link and decrements the count - when the count is 0, then the file is deleted

General Graph Directory

- Similar to acyclic-graph directory - cycles allowed inside a directory - offers more flexibility



- As cycles are allowed - poorly designed algorithm might result in an infinite loop continually searching through the cycle and never terminating
  - When crossing the graph, it is necessary to know if we land on a node already visited
  - Algorithms exist to deal with these case; however they are complicated and have significant execution times, which means that they are not always used
- A similar problem exists when we are trying to determine when a file can be deleted
  - Acyclic-graph used reference count = 0 to delete the file - This do not work here due to cycles where count may not be 0 even when no more links refer to a file and it can be deleted
  - Garbage collection solution is needed - requires two traversing passes to the entire file system - extremely time consuming

Types of Access

- File owner/creator should be able to control:
  - what can be done to the file and by whom
- Types of access:
  - Read: read from file
  - Write: write or rewrite the file
  - Execute: load the file into memory and execute it
  - Append: write new information at the end of the file
  - Delete: delete the file and free its space for possible reuse
  - List: list the name and attributes of the file
  - Attribute change: changing the attributes of the file
  - Other operations, such as renaming, copying, and editing the files, may also be considered

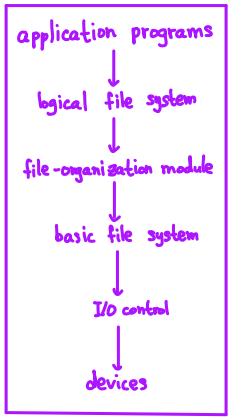
Access Control

- Different users may need different types of access to a file or directory
- Identity-dependent scheme access-associate an access-control list (ACL) with each file and directory
  - Each entry specifies: user names and the types of access allowed
    - Checked by OS at each access to allow or deny access accordingly
  - Advantage: enabling complex access methodologies
  - Problem: lengthy list
- Condensed version of the access list:
  - Recognize three classifications of users in connection with each file
- Owner: the user who created the file is the owner
- Group: a set of users who are sharing the file and need similar access is a group
- Other: all other users in the system
- In UNIX, a three field - owner, group, and universe - each consisting of the three bits rwx to control read access, write access, and execution
  - a user can list the content of a subdirectory only if the r bit is set in the appropriate field
  - a user can current directory to another current directory only if the x bit associated with the subdirectory is set

File-System Structure

- To improve I/O efficiency
  - I/O transfers between memory and mass storage are performed in units of blocks
- Each block on a hard disk drive has one or more sectors
  - Sector size is usually 512 bytes or 4096 bytes
  - NVM devices usually have blocks of 4096 bytes, and the transfer methods used are similar to those used by disk drives
  - All disk blocks have fixed size, but tape blocks are variable
- Files are allocated in units of blocks. The last block is therefore rarely filled with data - Internal Fragmentation
- The file system resides in secondary storage - provide access to data on storage device as follows:
  - Storing, locating, retrieving data
- It is generally composed of many different levels
  - an example of a layered design is shown
  - each level in the design uses the features of lower levels to create new features for use by higher levels
- I/O control level: consists of device drivers and interrupt handlers to transfer information between main memory and the disk system - a translator
  - Its input consists of high-level commands
  - Its output of low-level, hardware specific instructions to interfaces the I/O device to the rest of the system
- Basic file system: issues some commands based on logical block addresses to the appropriate device driver to read and write blocks on the storage device
  - I/O request scheduling
  - Manages the memory buffers (mass data transfer) and caches that hold various file systems, directory, and data blocks
- File-organization module: knows about files and their logical blocks. Each files logical blocks are numbered from 0 or 1 through N
  - Includes the free-space manager, which tracks unallocated blocks and provides these blocks to the file-organization module when requested
- Logical file system: manages metadata information that includes all of the file-system structure except the actual data (or contents of the files)
  - Manages the directory structure to provide the file-organization module with the information the latter needs, given a symbolic file name
  - Maintains file structure via file-control blocks. A file-control block (FCB) (an inode in UNIX file system)
    - Inode contains information about the file, including ownership, permissions, and location of the file contents
  - Responsible for protection

Layered File-System Structure



A Typical File-Control Block

To create a new file, a process calls the logical file system that allocates a new FCB (inode)

- Update the new file name and FCB ID into the appropriate directory
- A typical FCB as follows

file permissions
file dates
file owner, group, ACL
file size
file data blocks or pointers