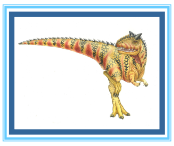
Chapter 2: Operating-System Structures



Chapter 2: Operating-System Structures

- Operating System Services
- User and Operating System Interfaces
- System Calls
- Operating system examples
- System Programs
- Linkers and Loaders
- Operating System Design and Implementation
- Operating System Structure

Objectives

- Identify services provided by an operating system
- Illustrate how system calls are used to provide operating system services
- Compare and contrast monolithic, layered, microkernel, modular, and hybrid strategies for designing operating systems

Operating System Services

- OS provides an environment for
  - Execution of programs
  - Services to programs and users
- One set of OS services - OS functions that are helpful to the user:
  - User interface - Almost all operating systems have a user interface (**UI**) - Command-Line (CLI), Graphics User Interface (GUI), touch-screen,
  - Program execution - The system must be able to load a program into memory and to run that program, end execution, either normally or abnormally (indicating error)
  - I/O operations - A running program may require I/O, which may involve a file or an I/O device

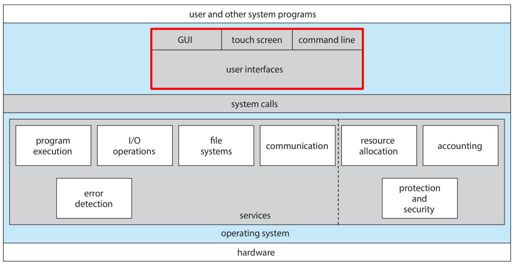
Operating System Services (Cont.)

- One set of OS services - OS functions that are helpful to the user:
  - File-system manipulation - The file system is of particular interest. Programs need to read and write files and directories, search, create and delete them, list file Information, permission management.
  - Communications – Processes may exchange information, on the same computer or between computers over a network
    - Communications may be via **shared memory** or through **message passing** (packets moved by the OS)
  - Error detection – OS needs to be constantly aware of possible errors
    - May occur in the CPU and memory, in I/O devices, in user programs
    - For each type of error, OS must take appropriate actions to ensure correct and consistent computing
    - Debugging facilities can greatly enhance the user's and programmer's abilities to efficiently use the system

Operating System Services (Cont.)

- Another set of OS services – OS functions for ensuring the *efficient* operation of the system itself via resource sharing
  - Resource allocation - When multiple users or multiple jobs run concurrently, resources must be allocated to each of them
    - Many types of resources - CPU cycles, memory, file storage, I/O devices.
  - Logging - To keep track of which users use how much and what kinds of computer resources
  - Protection and security - The owners of information stored in a multiuser or networked system may want to control the use of that information, concurrent processes should not interfere with each other
    - Protection involves ensuring that all access to system resources is controlled
    - Security of the system from outsiders requires user authentication, extends to defending external I/O devices from invalid access attempts

A View of Operating System Services



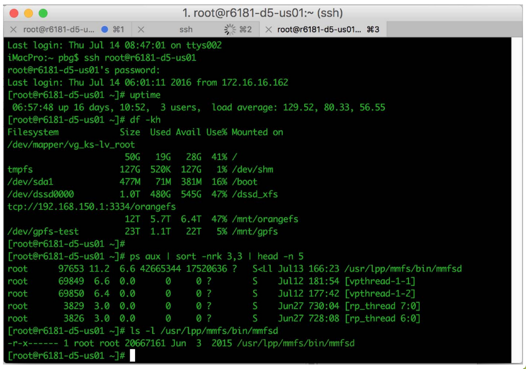
User Operating System Interface - CLI

- There are generally three approaches. One provides a command-line interface (CLI), or command interpreter, that allows users to directly enter commands to be performed by the operating system. The other two allow users to interface with the OS via a graphical user interface, or GUI.

CLI or command interpreter allows direct command entry

- Sometimes implemented in kernel, sometimes by system programs
- Sometimes multiple flavors implemented – **shells** in Unix or Linux
- The primary functionality is to fetch a command from user, interprets it and executes it
- UNIX and Linux systems provide different shells, such as C shell, Bourne-Again shell, Korn shell, and others

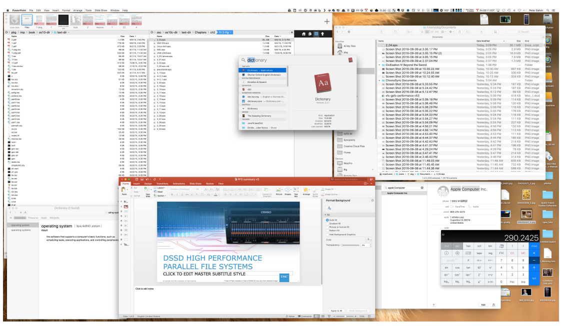
Bourne Shell Command Interpreter



User Operating System Interface - GUI

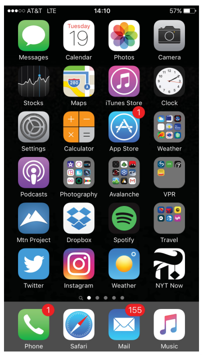
- User-friendly desktop metaphor interface
  - Usually mouse, keyboard, and monitor
  - Icons represent files, programs, directories, and system functions
  - Various mouse buttons over objects in the interface cause various actions (provide information, options, execute function, open directory (known as a folder)
  - Invented at Xerox PARC earlier 1970s, first widely use in Apple Macintosh
- Many systems now provide both CLI and GUI interfaces
  - Microsoft Windows is GUI with CLI "command" shell
  - Apple Mac OS X is "Aqua" GUI interface with UNIX kernel underneath and shells available
  - Unix and Linux have CLI with optional GUI interfaces (KDE, GNOME)

The Mac OS X GUI

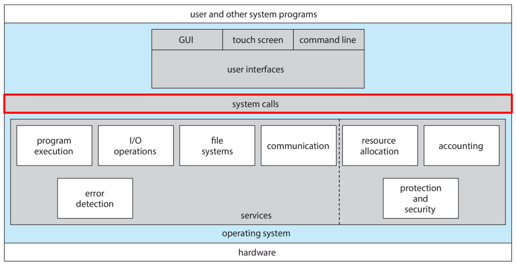


Touchscreen Interfaces

- Touchscreen devices require new interfaces
  - Mouse not feasible or not desired
  - Actions and selection based on gestures
  - Virtual keyboard for text
- Voice command
  - iPhone Siri

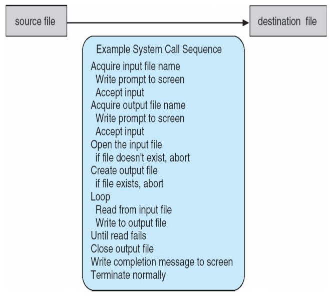


System Calls



System Calls (cont.)

- Programming interface to the services provided by the OS
- The system calls are generally available as functions written in a high-level language (C/C++), certain low-level tasks are written in assembly languages (accessing hardware)
- An example: cp in.txt out.txt – a sequence of system calls



Copying one file to another

System Calls - API

- Application Program Interface (API) specifies a set of functions that are available for application programmers to use, including the parameters passed to the function and return values it may expect
- The functions that make up an API typically invoke the actual system calls on behalf of the application programmer
  - For example, the Windows function CreateProcess() actually invokes the NTCreateProcess() system call in the Windows kernel
- A programmer access APIs via a library of codes provided by the OS
  - In the case of UNIX and Linux for programs written in the C language, the library is called **libc**
- Three most common APIs – for programming
  - Win32 API for Windows systems
  - POSIX API for POSIX-based systems (including virtually all versions of UNIX, Linux, and Mac OS X)
  - Java API for the Java virtual machine (JVM)

Example of Standard API

Library header file provided by Linux

```
#include <unistd.h>

ssize_t    read(int fd, void *buf, size_t count)
```

return value — function name — parameters

Parameters
- `int fd` – the file descriptor to be read
- `void *buf` – a buffer where the data will be read into
- `size_t count` – the maximum number of bytes to be read into the buffer

Return value
- 0 indicates end of file
- -1 indicates an error has occurred

System Calls – API (cont.)

Advantages - why use APIs rather than directly invoking system calls?

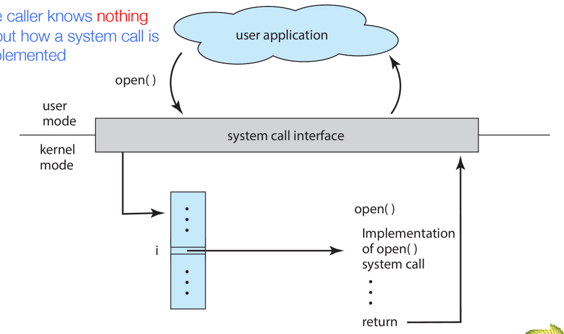
- Program portability – a programmer designing a program using an API can expect the program to compile and run on any system that supports the same API
- Hide the complex details of the system call from users
  - The actual system calls can often be more detailed and difficult to work with than the API available for an application programmer
  - A caller of an API need know nothing about how the system call is implemented or what it does during execution. Rather, the caller need only obey the API (format) and understand what the operating system will do as a result of the execution of that system call

System Call Implementation

- For most programming languages, the run-time environment (RTE) (a set of functions built into libraries) provide a system call interface that serves as the link to system calls made available by the operating system
  - An identity number is associated with each system call
  - The system-call interface maintains a table indexed according to these numbers
- The system call interface - functions
  - intercepts function calls in the API
  - invokes the necessary system call within the OS, and
  - returns status of the system call and return value(s), if any

API – System Call – OS Relationship

The caller knows nothing about how a system call is implemented

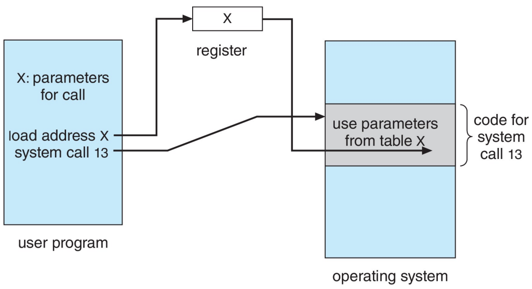


System Call Parameter Passing

- Often, more information is required than the identity of desired system call
  - Exact type and amount of information vary according to OS and call
- Three general methods used to pass parameters to the OS
  - Simplest – pass the parameters in registers
    - In some cases, may be more parameters than registers
  - Block method– parameters stored in a block, or table, in memory, and address of block passed as a parameter in a register
  - Stack method– parameters placed, or pushed, onto the stack by the program and popped off the stack by the OS

Block and stack methods do not limit the number or length of parameters being passed

Parameter Passing via Table



Types of System Calls

- Process control
  - create process, terminate process
  - end, abort
  - load, execute
  - get process attributes, set process attributes
  - wait for time
  - wait event, signal event
  - allocate and free memory
  - Dump memory if error
  - Debugger for determining bugs, single step execution
  - Locks for managing access to shared data between processes

Types of System Calls (cont.)

- File management
  - create file, delete file
  - open, close file
  - read, write, reposition
  - get and set file attributes
- Device management
  - request device, release device
  - read, write, reposition
  - get device attributes, set device attributes
  - logically attach or detach devices

Types of System Calls (Cont.)

- Information maintenance
  - get time or date, set time or date
  - get system data, set system data
  - get and set process, file, or device attributes
- Communications
  - create, delete communication connection
  - send, receive messages if message passing model to host name or process name
  - Shared-memory model create and gain access to memory regions
  - transfer status information
  - attach and detach remote devices
- Protection
  - Control access to resources, get and set permissions
  - Allow and deny user access

Examples of Windows and Unix System Calls

EXAMPLES OF WINDOWS AND UNIX SYSTEM CALLS

The following illustrates various equivalent system calls for Windows and UNIX operating systems.

	Windows	Unix

Process control	`CreateProcess()`
	`ExitProcess()`
	`WaitForSingleObject()`
		`fork()`
		`exit()`
		`wait()`

File management	`CreateFile()`
	`ReadFile()`
	`WriteFile()`
	`CloseHandle()`
		`open()`
		`read()`
		`write()`
		`close()`

Device management	`SetConsoleMode()`
	`ReadConsole()`
	`WriteConsole()`
		`ioctl()`
		`read()`
		`write()`

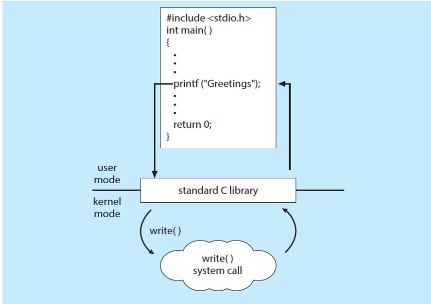
Information maintenance	`GetCurrentProcessID()`
	`SetTimer()`
	`Sleep()`
		`getpid()`
		`alarm()`
		`sleep()`

Communications	`CreatePipe()`
	`CreateFileMapping()`
	`MapViewOfFile()`
		`pipe()`
		`shm_open()`
		`mmap()`

Protection	`SetFileSecurity()`
	`InitlializeSecurityDescriptor()`
	`SetSecurityDescriptorGroup()`
		`chmod()`
		`umask()`
		`chown()`

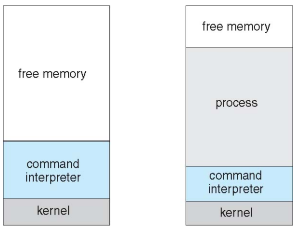
Standard C Library Example

- C program invoking `printf()` library call, which calls `write()` system call



Example: MS-DOS

- Single-tasking
- Shell invoked when system booted
- Simple method to run program
  - No process created
- Single memory space
- Loads program into memory, overwriting all but the kernel
- Program exit -> shell reloaded



(a) (b)

At system startup running a program

System Programs

- Another aspect of a modern system is its collection of system services
- System services, or system programs, or system utilities, provide a convenient environment for program development and execution
  - Some of them are simply user interfaces to system calls; others are considerably more complex
- The view of the operating system seen by most users is defined by the application and system programs, not the actual system calls
  - Considering a GUI featuring a mouse-and-windows interface, and a command line UNIX shell. Both use the same set of system calls, but the system calls appear different and act in different ways

System Programs (cont.)

- File management
  - Create, delete, copy, rename, print, dump, list, and generally manipulate files and directories
- Status information
  - Some ask the system for the date, time, amount of available memory, disk space, number of users
  - Others provide detailed performance, logging, and debugging information
- File modification
  - Text editors to create and modify files
  - Special commands to search file contents or perform transformations of the text

System Programs (Cont.)

- Programming-language support
  - Compilers, assemblers, debuggers, and interpreters for common programming languages (such as C, C++, Java, and Python) are often provided
- Program loading and execution
  - Absolute loaders, relocatable loaders, linkage editors, and overlay-loaders, debugging systems for higher-level and machine language
- Communications - provide the mechanism for creating virtual connections among processes, users, and computer systems
  - Allow users to send messages to one another's screens, browse web pages, send electronic-mail messages, log in remotely, transfer files from one machine to another

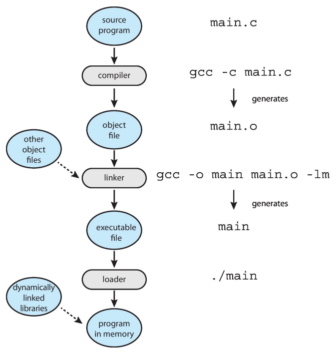
System Programs (Cont.)

- Background services
  - Launch at boot time
    - Some of these processes terminate after completing their tasks
    - Some continue to run until the system is halted, often known as services, subsystems, or daemons
  - Provide facilities like disk checking, process scheduling, error logging
- Application programs
  - Not part of the operating system
  - Launched by command line, mouse click, finger poke
  - Examples include web browsers, word processors, text formatters, spreadsheets, database systems, and games.

Linkers and Loaders

- Source codes are compiled into object files designed to be loaded into any physical memory location – relocatable object files
- **Linker** combines these object files into single binary executable file, along with libraries if needed
- Program resides on the secondary storage as binary executable, which must be brought into memory by **loader** to be executed
  - Relocation assigns final addresses to program parts and adjusts code and data in program to match those addresses
- Modern general-purpose systems don't link libraries into executables
  - Rather, dynamically linked libraries (in Windows, DLLs) are loaded as needed, shared by all programs that use the same version of that same library (loaded only once)
- Object files, executable files have standard formats(machine codes and symbolic tables), so operating system knows how to load and start them

The Role of the Linker and Loader



Protection

- Protection is an internal problem, security, in contrast, must consider both the system and the environment— within which the system is used.
- OS must protect itself from user programs
  - Reliability: compromising the OS generally causes it to crash
  - Security: limit the scope of what processes can do
  - Privacy: limit each process to the data it is permitted to access
  - Fairness: each should be limited to its appropriate share of system resources
- System protection features are guided by the principle of need-to-know and implement mechanisms to enforce the principle of least privilege.
- Computer systems contain objects that must be protected from misuse. Objects may be hardware (such as memory, CPU time, and I/O devices) or software (such as files, programs, and semaphores).
- An access right is the permission to perform an operation on an object. A domain is a set of access rights for objects.
  - Processes execute in domains and may use any of the access rights in the domain to access/manipulate objects.

Security

- Security – defense of the system against internal and external attacks
  - Wide range of potential attacks such as denial-of-service, worms, viruses, identity theft, theft of service, DoS, and etc.
- The data must be protected from unauthorized access, malicious destruction or alteration, and accidental introduction of inconsistency
- Several types of attacks can be launched against programs and against individual computers
  - Stack- and buffer-overflow techniques allow successful attackers to change their level of system access.
  - Viruses and malware require human interaction, while worms are self-perpetuating, sometimes infecting thousands of computers.
  - Denial-of-service attacks prevent legitimate use of target systems
- User authentication is used to identify legitimate users of a system.
  - One-time password, for example, change from session to session to avoid reply attacks.
  - Multifactor authentication uses three or more forms. These methods greatly decrease the chance of authentication forgery.

Operating System Design and Implementation

Design and Implementation of OS not "solvable", but some approaches have proven to be successful

- Internal structure of operating systems varies widely
- At the high-level, the design is affected by choice of hardware, type of the system (e.g., desktop/laptop, mobile, distributed system, or real-time)
- Start the design by defining goals and specifications
  - User goals: operating system should be convenient to use, easy to learn and to use, reliable, safe, and fast
  - System goals: operating system should be easy to design, implement, and maintain, as well as flexible, reliable, error-free, and efficient
- Specifying and designing an OS is a highly creative task of software engineering

Operating System Design and Implementation (Cont.)

- Important principle to separate

  Policy: What will be done?
  Mechanism: How to do it?
- Mechanisms specify how to do things, policies decide what will be done
  - A timer construct is a mechanism for ensuring CPU protection, but deciding how long the timer is to be set for a particular user is a policy decision
- The separation of policy from mechanism is a very important principle, it allows flexibility if policy decisions are to be changed later, and they do
  - If properly separated, it can be used either to support a policy decision that I/O-intensive programs have priority over CPU-intensive ones or to support the opposite policy.
- In a nutshell, an operating system is designed with specific goals in mind. These goals ultimately determine the operating system's policies. An operating system implements these policies through specific mechanisms.

Implementation

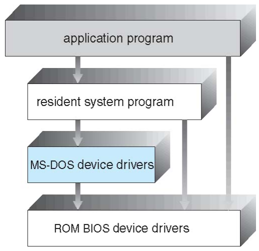
- Early OSes written in assembly languages
- Now, most are written in higher-level languages such as C or C++
  - The lowest levels of the kernel might still be in assembly languages.
  - More than one higher level language is often used. Most Android system libraries are written in C or C++, and its application frameworks are written mostly in Java
- The advantage of using high-level languages are easier to **port** to other hardware
  - The code can be written faster, is more compact, and is easier to understand and debug
- The only possible disadvantages are reduced speed and increased storage requirements – not a major issue in today's systems

Operating System Structure

- General-purpose OS is a very large program
- Various ways to structure ones
  - Monolithic structure
  - Layered – a specific type of modular approach
  - Microkernel – Mach OS
  - Loadable kernel modules or LKMs – modular approach

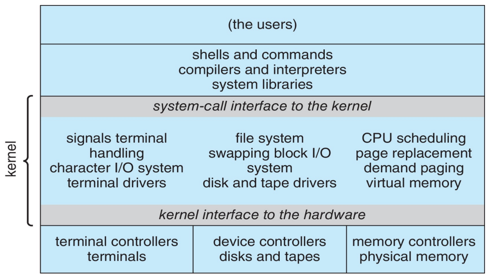
Simple Structure

- Such Oses do not have well-defined structures, usually started as a small, simple and limited system
- MS-DOS – written to provide the most functionality in the least space
  - Not carefully divided into modules
  - Although it has some structure, interfaces and levels of functionality are not well separated – i.e., app programs can access I/O directly
  - Written for Intel 8088 with no dual mode and no hardware protection



Monolithic Structure – Original UNIX

- In traditional UNIX, the kernel consists of everything below the system-call interface and above the physical hardware

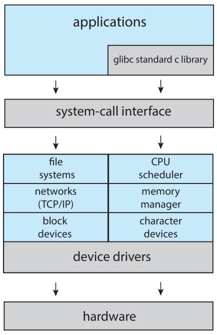


Monolithic Structure – Original UNIX

- UNIX – initially limited by hardware functionality, the original UNIX operating system had limited structuring
- Place all of the functionality of the kernel into a single, static binary file that runs in a single address space - known as a monolithic structure
- The UNIX OS consists of two separable parts: the kernel and system programs
  - The kernel is further separated into a series of interfaces and device drivers, which have been expanded considerably over the years as UNIX evolves
- The drawback is that enormous amount of functionalities are combined to one level, making it difficult to implement and maintain
- Monolithic kernels have a distinct performance advantage, as there is very little overhead in the system-call interface, and communication within the kernel is fast
  - The speed and efficiency – still used in UNIX, Linux, and Windows

Linux System Structure

- The Linux operating system is based on UNIX and is structured similarly
- The Linux kernel is monolithic in that it also runs entirely in kernel mode in a single address space
- Applications use the glibc standard C library when communicating with the system call interface to the kernel
- It has a modular design that allows the kernel to be modified during run time (to be discussed)

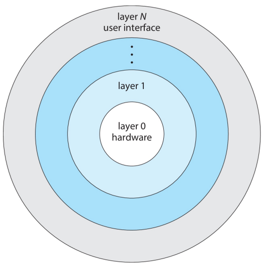


Modular Design

- The monolithic approach often known as a tightly coupled system because changes to one part of the system affect other parts
- Design a loosely coupled system, which is divided into separate, smaller components, each having specific and limited functionalities
  - The advantage of the modular approach is that changes in one component affect only that component, and no others, allowing more freedom and flexibility in creating and changing the component
- A system can be made modular in many ways. One method is the layered approach

Layered Approach

- The OS is divided into a number of layers, each built on top of lower layers. The bottom layer (layer 0) is the hardware; the highest (layer N) is the user interface.
- Each layer consists of data structures and a set of functions that can be invoked by higher-level layers, in turn, can invoke operations on lower-level layers



Layered Approach (Cont.)

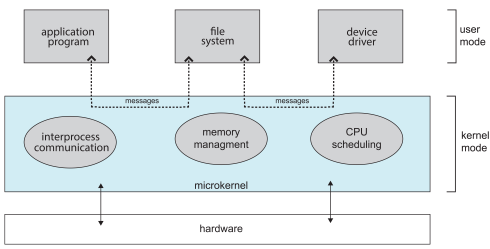
- Information hiding : a layer does not need to know how the lower-layer operations are implemented, only what these operations do
  - Each layer hides the existence of its own data structures, operations, and hardware from higher level layers
- The main advantage of a layered approach is the simplicity of construction and debugging – starting from the lowest layer
  - Layered systems have been successfully used in many other systems such as computer networks (e.g., TCP/IP) and web applications
- Few operating systems use a pure layered approach because
  - There are significant challenges in appropriately defining different layers and their respective functionalities
  - The overall performance can be affected due to the overhead of requiring a program to traverse through multiple layers to obtain a service
- The trend is to have fewer layers with more functionality with modularized code, while avoiding the problems of layer definition and interaction

Microkernel System Structure

- The kernel became large and difficult to manage
- Removing all nonessential components from the kernel and implementing them as system or user-level programs in separate address space
- This results in a much smaller kernel
- Mach developed at CMU in mid-1980s, modularized the kernel using the microkernel approach
  - The best-known microkernel operating system is **Darwin**, used in Mac OS X and iOS. It consists of two kernels, one of which is the Mach microkernel
- There is little consensus regarding which services should remain in the kernel and which should be implemented in user space, but typically, microkernels provide minimal process and memory management, in addition to a communication facility

Microkernel System Structure (Cont.)

- One main function of microkernel is to provide communications between programs and various services running in user space through message passing
- For example, if a application program wishes to access a file, it must interact with the file server. The program and service never interact directly. Rather, they communicate indirectly by exchanging messages with the microkernel.



Microkernel System Structure (Cont.)

- Advantages:
  - Easier to extend a microkernel operating system, as all new services can be added to user space without modification on the kernel
  - When the kernel has to be modified, the changes are fewer, as the kernel is much smaller
  - Easier to port the operating system to new architectures (hardware)
  - More secured and reliable (less code is running in kernel mode), since most services are running as user processes – not kernel processes. If a service fails, the rest of the OS remains untouched
- Drawbacks:
  - The performance of microkernels can greatly suffer due to increased system-function overhead, user space to kernel space communication
  - When two user-level services must communicate, messages must be copied between the services, which reside in separate address space
- Window NT had a layered microkernel, performance worse than Window 95, more monolithic (moving function to the kernel) with Window XP

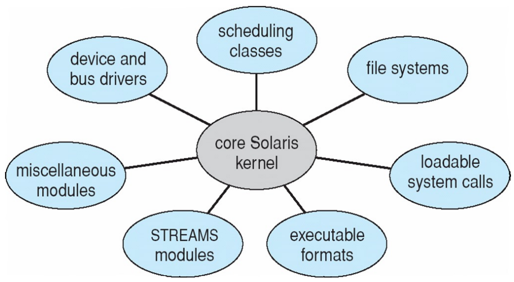
Modular Approach

- The best current methodology in OS design involves using loadable kernel modules or LKMs
- The kernel has a set of core components and can link in additional services via modules, either at boot time or during run time.
- The main idea is for the kernel to provide core services, while other services are implemented and added dynamically, as the kernel is running
- Linking services dynamically is preferable to adding new features directly to the kernel, which would require recompiling the entire kernel every time a change was made
  - For example, the kernel has CPU scheduling and memory management algorithms into the kernel and then add support for different file systems by way of loadable modules

Modular Approach (Cont.)

- This resembles a layered system in that each kernel section has a well-defined, protected interface, but it is more flexible as any module can call any other module
- It also resembles a microkernel in that the primary module has only core functions and knowledge of how to load and communicate with other modules; but this is more efficient than a microkernel design because modules do not need to invoke message passing in order to communicate
- Linux uses loadable kernel modules, primarily for supporting device drivers and file systems.
- LKMs can be "inserted" into the kernel when system is booted or during run time, can also be removed from the kernel during run time as well
  - For example, a USB device is plugged into a running machine. If the Linux kernel does not have the necessary driver, it can be dynamically loaded.
- This allows a dynamic and modular kernel, while maintaining the performance benefits of a monolithic system – efficiency

Solaris Modular Approach



Hybrid Systems

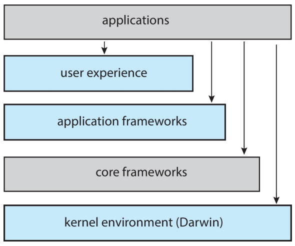
- In practice, very few OSes adopt a single, strictly defined structure. Instead, they combine different structures, resulting in hybrid systems
- Hybrid systems combine multiple approaches to address performance, security, and usability needs
- Linux is monolithic, because OS in a single address space provides very efficient performance. It is also modular, so that new functionality can be dynamically added to the kernel
- Windows is largely monolithic, but it retains some behaviour typical of microkernel systems by providing support for separate subsystems (known as personalities) that run as user-mode processes. Windows systems also provide support for dynamically loadable kernel modules

Summary in Operating System Design

- A monolithic operating system has no structure; all functionality provided in a single, static binary file that runs in a single address space. Although such systems are difficult to modify, their primary benefit is efficiency.
- A layered operating system is divided into a number of discrete layers, where the bottom layer is the hardware interface and the highest layer is the user interface. Although layered software systems have had some success, it is generally not ideal for designing operating systems due to performance problems and difficulty in defining layers.
- The microkernel approach for designing operating systems uses a minimal kernel; most services run as user-level applications, in which communication takes place via message passing.
- The loadable kernel module approach for designing operating systems provides operating-system services through modules that can be loaded and removed during runtime.
- Many contemporary operating systems are constructed as hybrid systems using a combination of a monolithic kernel and modules.

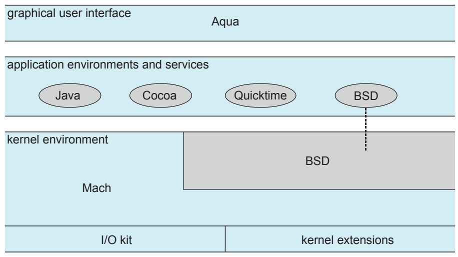
macOS and iOS Structure

- Architecturally, macOS (for desktop and laptops) and iOS (iPhone and iPad) have much in common – user interface, programming (language) support, graphics and media, and kernel environment - Darwin includes the Mach microkernel and the BSD UNIX kernel



Mac OS X Structure

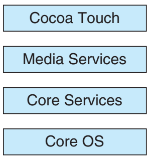
- Apple Mac OS X is hybrid, layered, Aqua UI (for a mouse or trackpad), plus Cocoa programming environment providing an API for the Objective-C
- Core frameworks. support graphics and media including, Quicktime and OpenGL
- The kernel environment, also known as Darwin includes Mach microkernel and BSD Unix



iOS

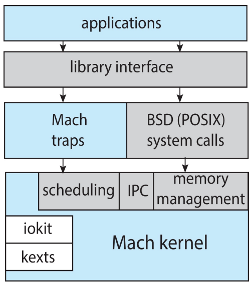
Apple mobile OS for iPhone, iPad

- Structured on Mac OS X, added functionality
- Does not run Mac OS X applications natively
  - Also runs on different CPU architecture (ARM vs. Intel)
- Springboard user interface, designed for touch devices.
- Cocoa Touch Objective-C API for developing apps on mobile devices (touch screen)
- Media services layer for graphics, audio, video – Quicktime, OpenGL
- Core services provides cloud computing, databases
- Core operating system, based on Mac OS X kernel



Darwin

- A layered system that consists of the Mach microkernel and the BSD UNIX kernel – a hybrid system
- Two system-call interfaces - Mach system calls (known as traps) and BSD system calls (which provide POSIX functionality)
- The interface is a rich set of libraries - the standard C library, and libraries supporting networking, security, and programming language
- Mach provides fundamental OS services, including memory management, CPU scheduling, and IPC facilities
- The kernel environment provides an I/O kit for device drivers and dynamically loadable modules refers to as kernel extensions, or kexts

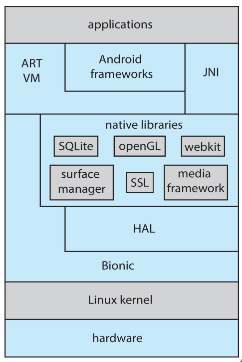


Android

- Developed by Open Handset Alliance (led primarily by Google)
- Android runs on a variety of mobile platforms and is open-sourced, in contrast iOS runs on Apple mobile devices and is closed-sourced
- Android is similar to iOS - a layered system that provides a rich set of frameworks supporting graphics, audio, and hardware features.
- Instead of using standard Java API, Google designed a separate Android API for Java development. Java applications execute on the Android RunTime ART, a virtual machine optimized for mobile devices with limited memory and CPU processing capabilities
- Java native interface or JNI, which allows developers to bypass the virtual machine and write Java programs that can access specific hardware features.
  - Programs written using JNI are generally not portable from one hardware to another.

Android Architecture

- The libraries include frameworks for developing web browsers (webkit), database support (SQLite), and network support, such as secure sockets (SSLs).
- In order for Android to run on any hardware devices, hardware abstraction layer, or HAL abstract all hardware, e.g., camera, GPS chip, and other sensors, and provides applications with a consistent view independent of specific hardware
- Google developed the Bionic standard C library for Android, instead using standard GNU C library (glibc) for Linux systems
- The modified Linux kernel for mobile systems, including power management.



End of Chapter 2