Chapter 2:
Operating-System Structures

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- Operating System Services
- User and Operating-System Interface
- System Calls
- System Services
- Linkers and Loaders
- Why Applications Are Operating-System Specific
- Operating-System Design and Implementation
- Operating-System Structure
- Building and Booting an operating System
- Operating-System Debugging

Objectives

- Identify services provided by an operating system
- Illustrate how system calls are used to provided operating system services.
- Compare and contrast monolithic, layered, microkernel, modular, and hybrid strategies for designing operating systems.
- Illustrate the process for booting an operating system.
- Apply tools for monitoring operating system performance.
- Design and implement kernel modules for interacting with a Linux kernel.

2.1 Operating-System Services

Operating systems provide an environment for execution of programs and services to programs and users

One set of operating-system services provides functions that are helpful to the user:

- **User interface** - Almost all operating systems have a user interface (**UI**).
  - Varies between **Command-Line Interpreter (CLI)**, **Graphics User Interface (GUI)**, **Batch**
- **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 operating-system services provides functions that are helpful to the user (Cont.):

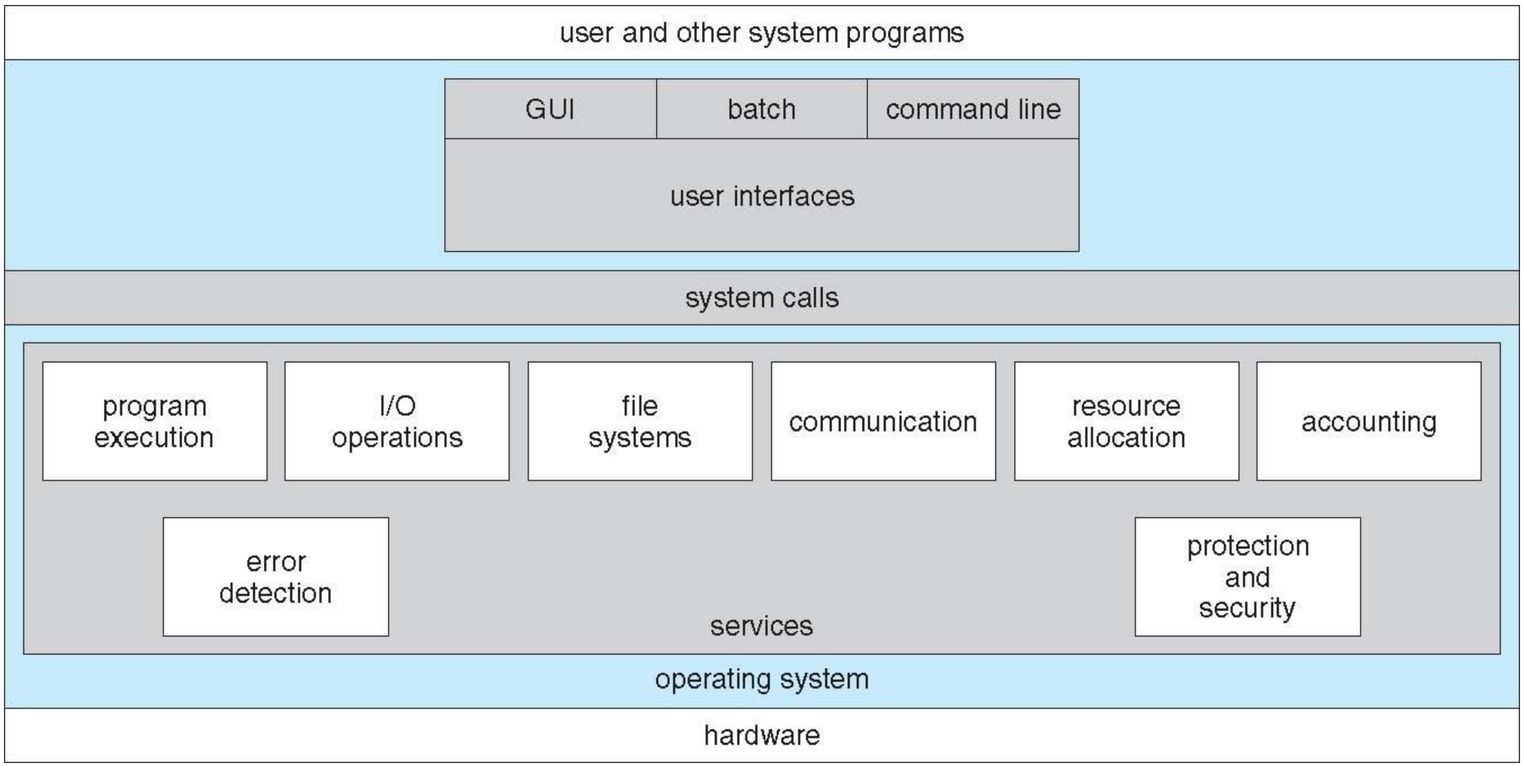
- **File-system manipulation** - The file system is of particular interest. Programs need to read and write files and directories, create and delete them, search them, list file Information, permission management.
- **Communications** – Processes may exchange information, on the same computer or between 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 hardware, in I/O devices, in user program
  - For each type of error, OS should take the appropriate action 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 functions exists for ensuring the efficient operation of the system itself via resource sharing

- **Resource allocation -** When multiple users or multiple jobs running concurrently, resources must be allocated to each of them
  - Many types of resources - CPU cycles, main 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 computer system may want to control 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

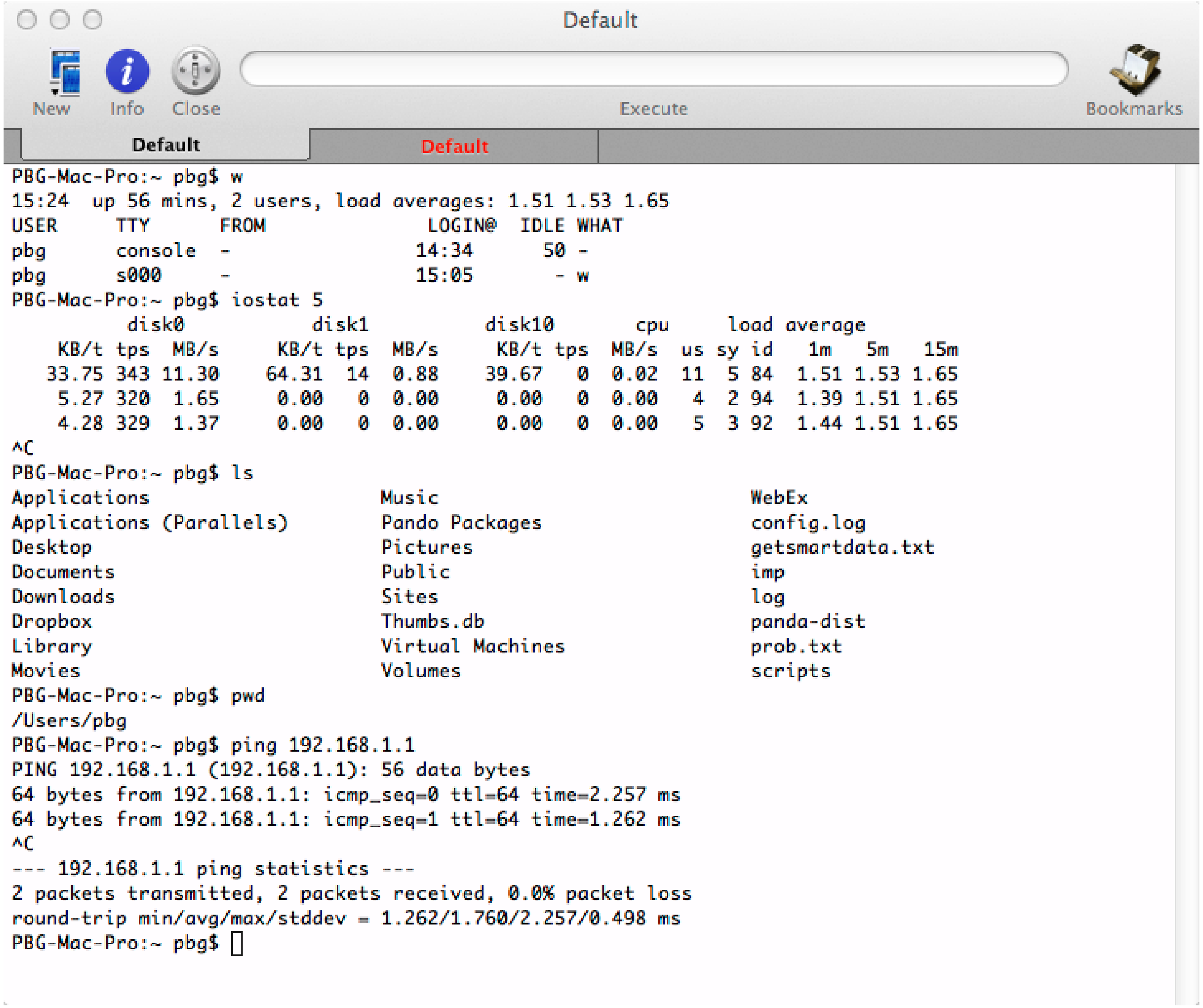


2.2 User Operating-System Interface

CLI or **command interpreter** allows direct command entry

- Sometimes implemented in kernel, sometimes by systems program
- Sometimes multiple flavors implemented – **shells**
- Primarily fetches a command from user and executes it
- Sometimes commands built-in, sometimes just names of programs
  - If the latter, adding new features doesn't require shell modification

Bourne Shell Command Interpreter




```
PBG-Mac-Pro:~ pbg$ w
15:24  up 56 mins, 2 users, load averages: 1.51 1.53 1.65
USER     TTY      FROM              LOGIN@  IDLE WHAT
pbg      console  -                14:34      50 -
pbg      s000     -                15:05       - w
PBG-Mac-Pro:~ pbg$ iostat 5
          disk0           disk1           disk10       cpu     load average
    KB/t tps  MB/s     KB/t tps  MB/s     KB/t tps  MB/s  us sy id   1m   5m   15m
   33.75 343 11.30    64.31  14  0.88    39.67   0  0.02  11  5 84  1.51 1.53 1.65
    5.27 320  1.65     0.00   0  0.00     0.00   0  0.00   4  2 94  1.39 1.51 1.65
    4.28 329  1.37     0.00   0  0.00     0.00   0  0.00   5  3 92  1.44 1.51 1.65
^C
PBG-Mac-Pro:~ pbg$ ls
Applications                Music                      WebEx
Applications (Parallels)    Pando Packages             config.log
Desktop                     Pictures                   getsmartdata.txt
Documents                   Public                     imp
Downloads                   Sites                      log
Dropbox                     Thumbs.db                  panda-dist
Library                     Virtual Machines           prob.txt
Movies                      Volumes                    scripts
PBG-Mac-Pro:~ pbg$ pwd
/Users/pbg
PBG-Mac-Pro:~ pbg$ ping 192.168.1.1
PING 192.168.1.1 (192.168.1.1): 56 data bytes
64 bytes from 192.168.1.1: icmp_seq=0 ttl=64 time=2.257 ms
64 bytes from 192.168.1.1: icmp_seq=1 ttl=64 time=1.262 ms
^C
--- 192.168.1.1 ping statistics ---
2 packets transmitted, 2 packets received, 0.0% packet loss
round-trip min/avg/max/stddev = 1.262/1.760/2.257/0.498 ms
PBG-Mac-Pro:~ pbg$
```

User Operating-System Interface - GUI

- Graphical User Interface (**GUI**)
  - User-friendly **desktop** metaphor interface
    - Usually mouse, keyboard, and monitor
    - **Icons** represent files, programs, actions, etc
    - 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
  - Many systems now include 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 (CDE, KDE, GNOME)

Touchscreen Interfaces

- Touchscreen devices require new interfaces
  - Mouse not possible or not desired
  - Actions and selection based on gestures
  - Virtual keyboard for text entry

  Voice commands.

The Mac OS X GUI

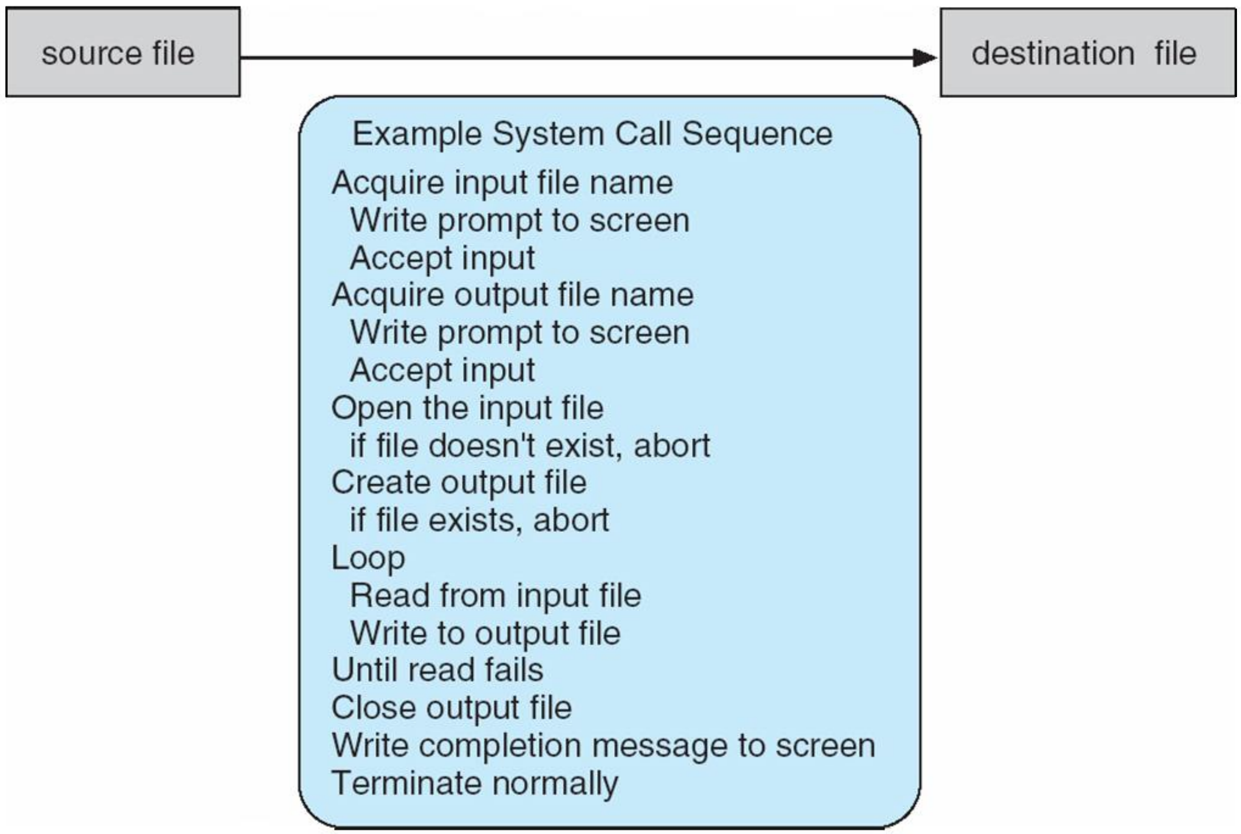
2.3 System Calls

- Programming interface to the services provided by the OS
- Typically written in a high-level language (C or C++)
- Mostly accessed by programs via a high-level **Application Programming Interface (API)** rather than direct system call use
- Three most common APIs are Win32 API for Windows, POSIX API for POSIX-based systems (including virtually all versions of UNIX, Linux, and Mac OS X), and Java API for the Java virtual machine (JVM)

Note that the system-call names used throughout this text are generic

Example of System Calls

System call sequence to copy the contents of one file to another file



Example of Standard API

EXAMPLE OF STANDARD API

As an example of a standard API, consider the `read()` function that is available in UNIX and Linux systems. The API for this function is obtained from the `man` page by invoking the command

```
man read
```

on the command line. A description of this API appears below:

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

$$\underbrace{\texttt{ssize\_t}}_{\text{return value}}\quad \underbrace{\texttt{read}}_{\text{function name}}\underbrace{\texttt{(int fd, void *buf, size\_t count)}}_{\text{parameters}}$$

A program that uses the `read()` function must include the `unistd.h` header file, as this file defines the `ssize_t` and `size_t` data types (among other things). The parameters passed to `read()` are as follows:

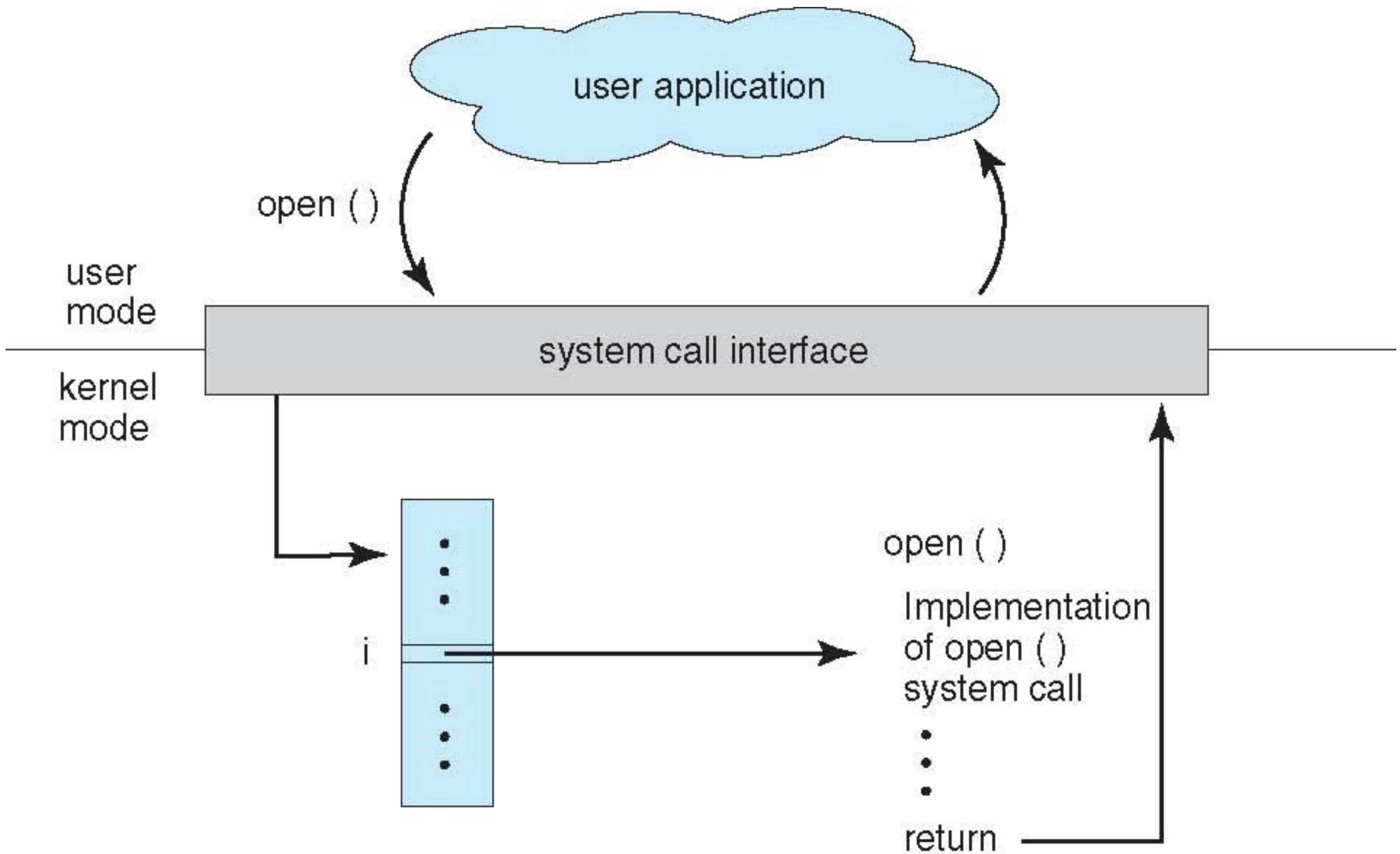
- `int fd`—the file descriptor to be read
- `void *buf`—a buffer where the data will be read into
- `size_t count`—the maximum number of bytes to be read into the buffer

On a successful read, the number of bytes read is returned. A return value of 0 indicates end of file. If an error occurs, `read()` returns −1.

System Call Implementation

- Typically, a number associated with each system call
  - **System-call interface** maintains a table indexed according to these numbers
- The system call interface invokes the intended system call in OS kernel and returns status of the system call and any return values
- The caller need know nothing about how the system call is implemented
  - Just needs to obey API and understand what OS will do as a result call
  - Most details of OS interface hidden from programmer by API
    - Managed by run-time support library (set of functions built into libraries included with compiler)

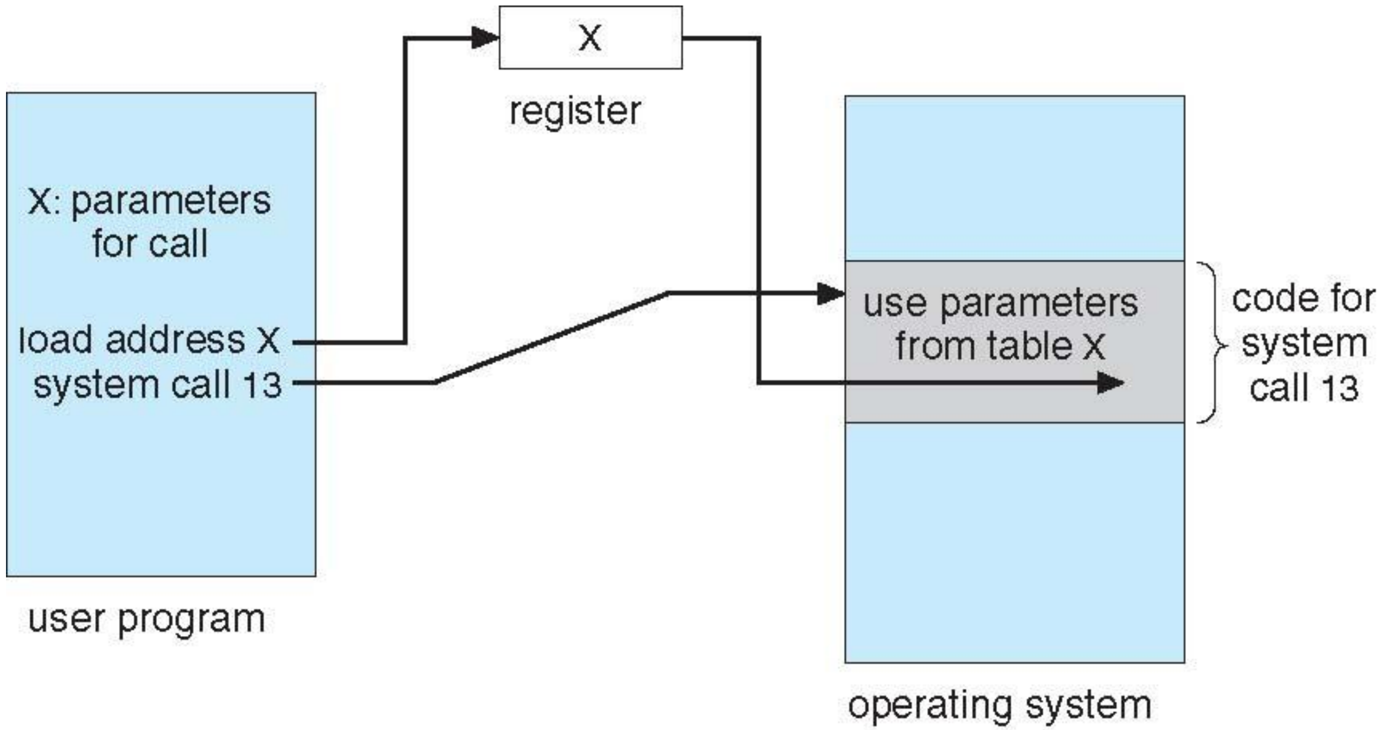
API – System Call – OS Relationship



System Call Parameter Passing

- Often, more information is required than simply 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
  - Parameters stored in a block, or table, in memory, and address of block passed as a parameter in a register
    - This approach taken by Linux and Solaris
  - Parameters placed, or **pushed**, onto the **stack** by the program and **popped** off the stack by the operating system
  - 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

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**
  - From **client** to **server**
- **Shared-memory model** create and gain access to memory regions
- transfer status information
- attach and detach remote devices

Types of System Calls (Cont.)

Protection

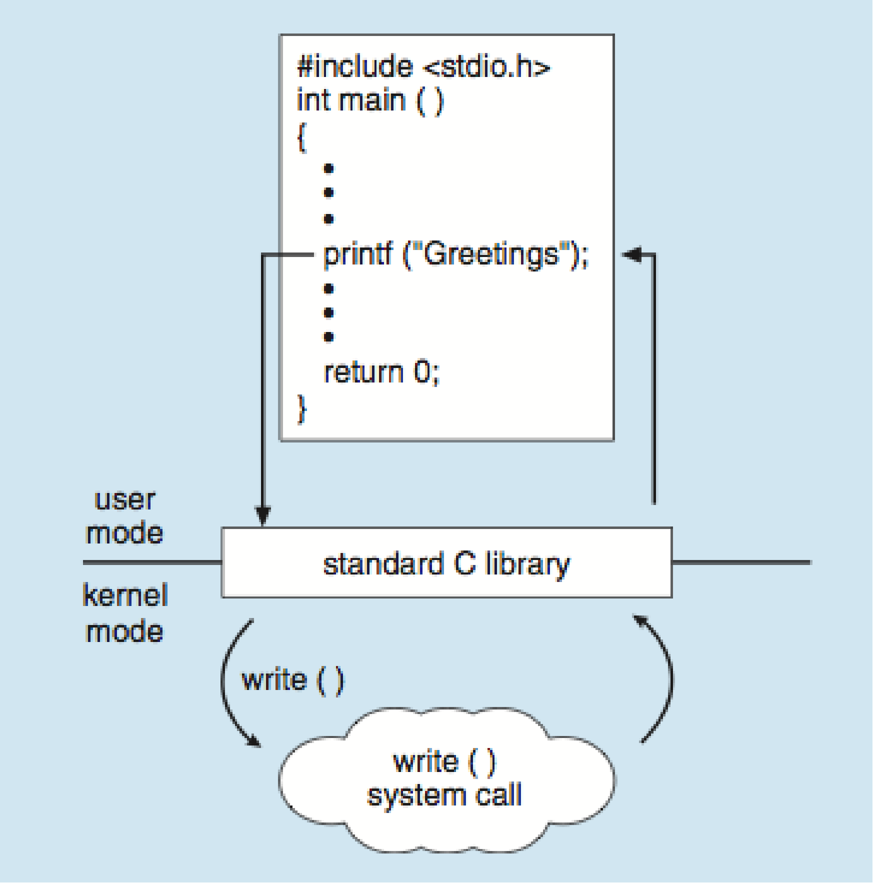
- Control access to resources
- Get and set permissions
- Allow and deny user access

Examples of Windows and Unix System Calls

	Windows	Unix
Process Control	CreateProcess() ExitProcess() WaitForSingleObject()	fork() exit() wait()
File Manipulation	CreateFile() ReadFile() WriteFile() CloseHandle()	open() read() write() close()
Device Manipulation	SetConsoleMode() ReadConsole() WriteConsole()	ioctl() read() write()
Information Maintenance	GetCurrentProcessID() SetTimer() Sleep()	getpid() alarm() sleep()
Communication	CreatePipe() CreateFileMapping() MapViewOfFile()	pipe() shmget() mmap()
Protection	SetFileSecurity() InitlializeSecurityDescriptor() SetSecurityDescriptorGroup()	chmod() umask() chown()

Standard C Library Example

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



Three Examples

There are so many facets of and variations in process control that we use three examples to clarify these concepts.

Example: Arduino

P74 (Figure 2.9)

Single-tasking

No Shell but boot loader only

Simple method to run program

- No process created

Single memory space

Provides no user interface beyond hardware input sensors

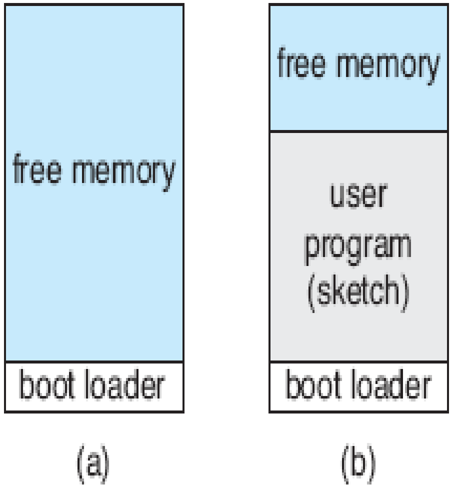


Figure 2.9 Arduino execution. (a) At system startup. (b) Running a sketch.

Example: MS-DOS

Single-tasking

Shell invoked when system booted

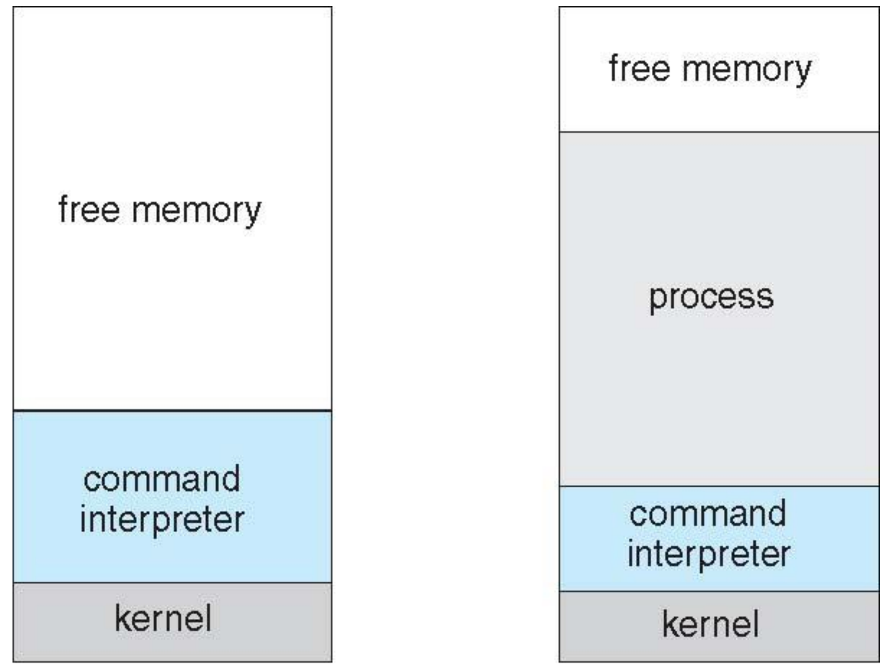
Simple method to run program

No process created

Single memory space

Loads program into memory, overwriting all but the kernel

Program exit -> shell reloaded

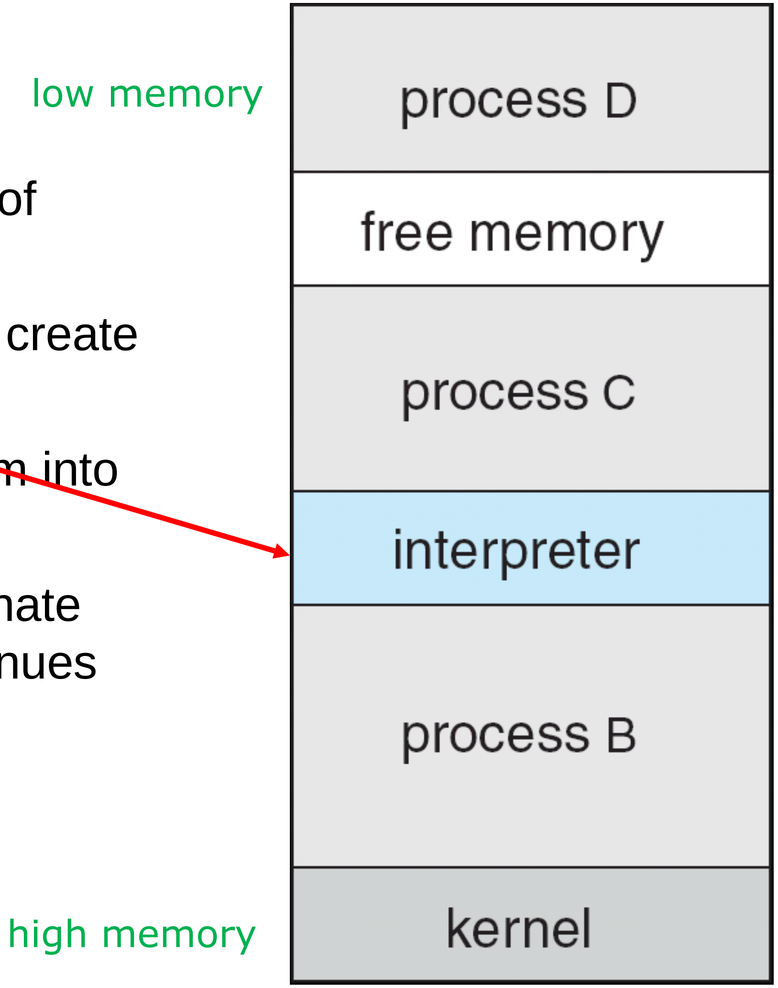


(a) At system startup

(b) running a program

Example: FreeBSD

- Unix variant
- Multitasking
- User login -> invoke user's choice of shell
- Shell executes fork() system call to create process
  - Executes exec() to load program into process
  - Shell waits for process to terminate (with no user interface) or continues with user commands
- Process exits with:
  - code = 0 – no error
  - code > 0 – error code



2.4 System Services

System programs (or services) provide a convenient environment for program development and execution. They can be divided into:

- File management
- Status information
- File modification
- Programming-language support
- Program loading and execution
- Communications
- Background services
- Application programs

Most users' view of the operation system is defined by system programs, not the actual system calls

System Programs

- Provide a convenient environment for program development and execution
  - Some of them are simply user interfaces to system calls; others are considerably more complex
- **File management** - Create, delete, copy, rename, print, dump, list, and generally manipulate files and directories
- **Status information**
  - Some ask the system for info - date, time, amount of available memory, disk space, number of users
  - Others provide detailed performance, logging, and debugging information
  - Typically, these programs format and print the output to the terminal or other output devices
  - Some systems implement a **registry** - used to store and retrieve configuration information

System Programs (Cont.)

- **File modification**
  - Text editors to create and modify files
  - Special commands to search contents of files or perform transformations of the text
- **Programming-language support** - Compilers, assemblers, debuggers and interpreters sometimes 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 for system startup, then terminate
  - Some from system boot to shutdown
- Provide facilities like disk checking, process scheduling, error logging, printing
- Run in user context not kernel context
- Known as **services**, **subsystems**, **daemons**

Application programs

- Don’t pertain to system
- Run by users
- Not typically considered part of OS
- Launched by command line, mouse click, finger poke

2.5 Linkers and Loaders

Source files are compiled into object files (in relocatable format)

The **linker** combines relocatable object files into a single binary executable file

A **loader** is used to load the binary executable file into memory, where it is eligible to run on a CPU core

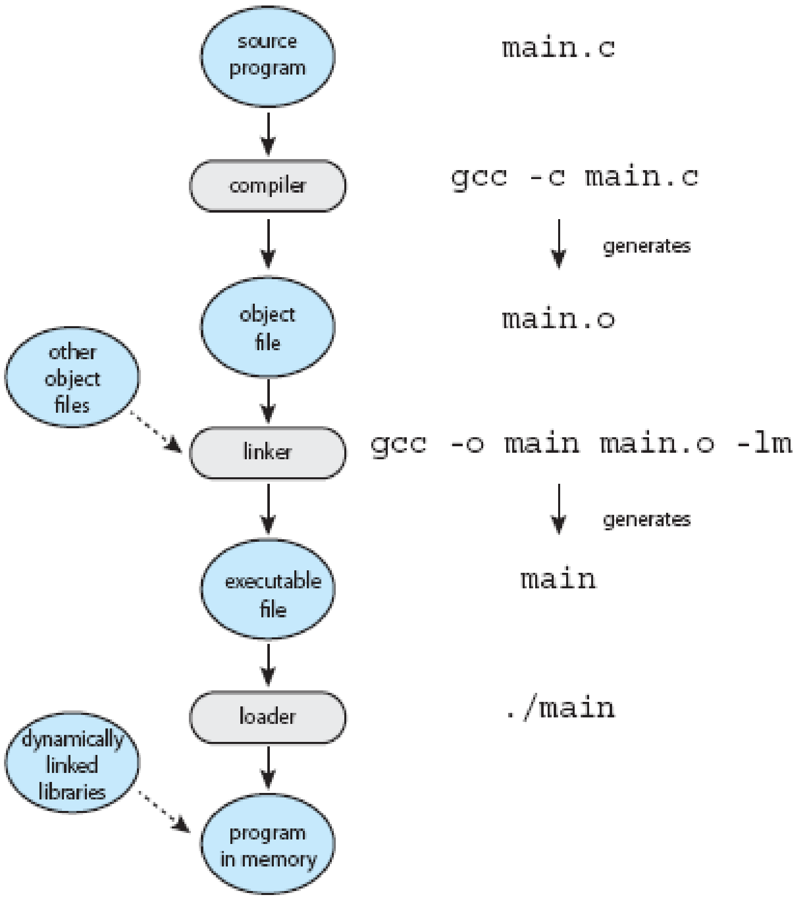


Figure 2.11 The role of the linker and loader.

2.6 Why Applications Are Operating-System Specific

Fundamentally, applications compiled on one operating system are not executable on other operating system.

- Binary format
- CPU instruction set
- System calls or API

Unless an interpreter , full run time environment(RTE), or binary executable file is written for and compiled on a specific operating system on a specific CPU type, the application will fail to run.

2.7 Operating System Design and Implementation

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

Internal structure of different Operating Systems can vary widely

Start the design by defining goals and specifications

Affected by choice of hardware, type of system

User goals and **System** goals

- User goals – operating system should be convenient to use, easy to learn, 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

Operating System Design and Implementation (Cont.)

Important principle to separate

Policy: ***What*** will be done?
Mechanism: ***How*** to do it?

Mechanisms determine how to do something, policies decide what will be done

The separation of policy from mechanism is a very important principle, it allows maximum flexibility if policy decisions are to be changed later (example – timer)

Specifying and designing an OS is highly creative task of **software engineering**

Implementation

- Much variation
  - Early OSes in assembly language
  - Then system programming languages like Algol, PL/1
  - Now C, C++
- Actually usually a mix of languages
  - Lowest levels in assembly
  - Main body in C
  - Systems programs in C, C++, scripting languages like PERL, Python, shell scripts
- More high-level language easier to **port** to other hardware
  - But slower
- **Emulation** can allow an OS to run on non-native hardware

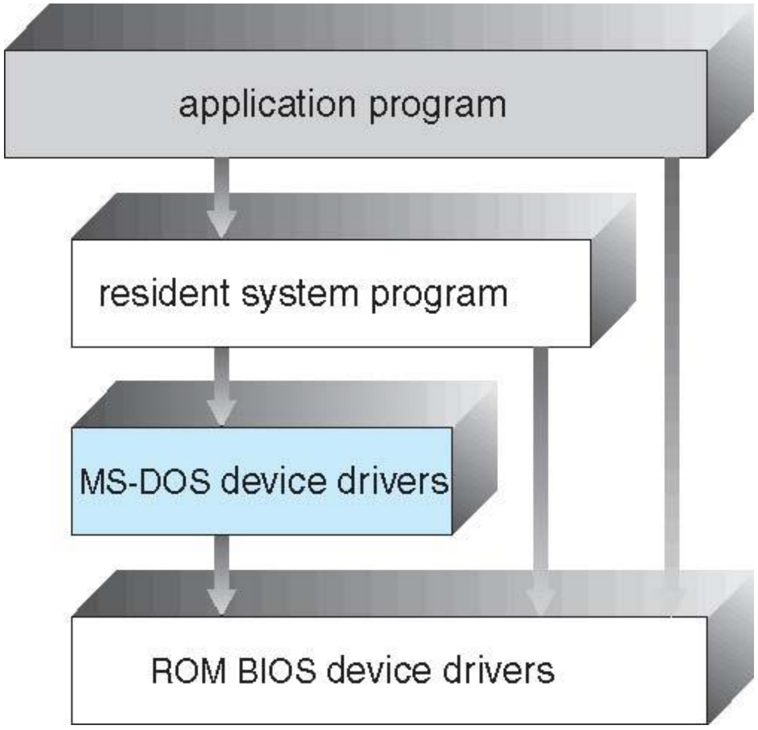
2.8 Operating System Structure

- General-purpose OS is very large program
- Various ways to structure ones
  - Simple structure – MS-DOS
  - Monolithic structure -- UNIX
  - Layered – an abstraction
  - Microkernel –Mach
  - Modules
  - Hybrid

Simple Structure -- MS-DOS

MS-DOS – written to provide the most functionality in the least space (no structure)

- Not divided into modules
- Although MS-DOS has some structure, its interfaces and levels of functionality are not well separated



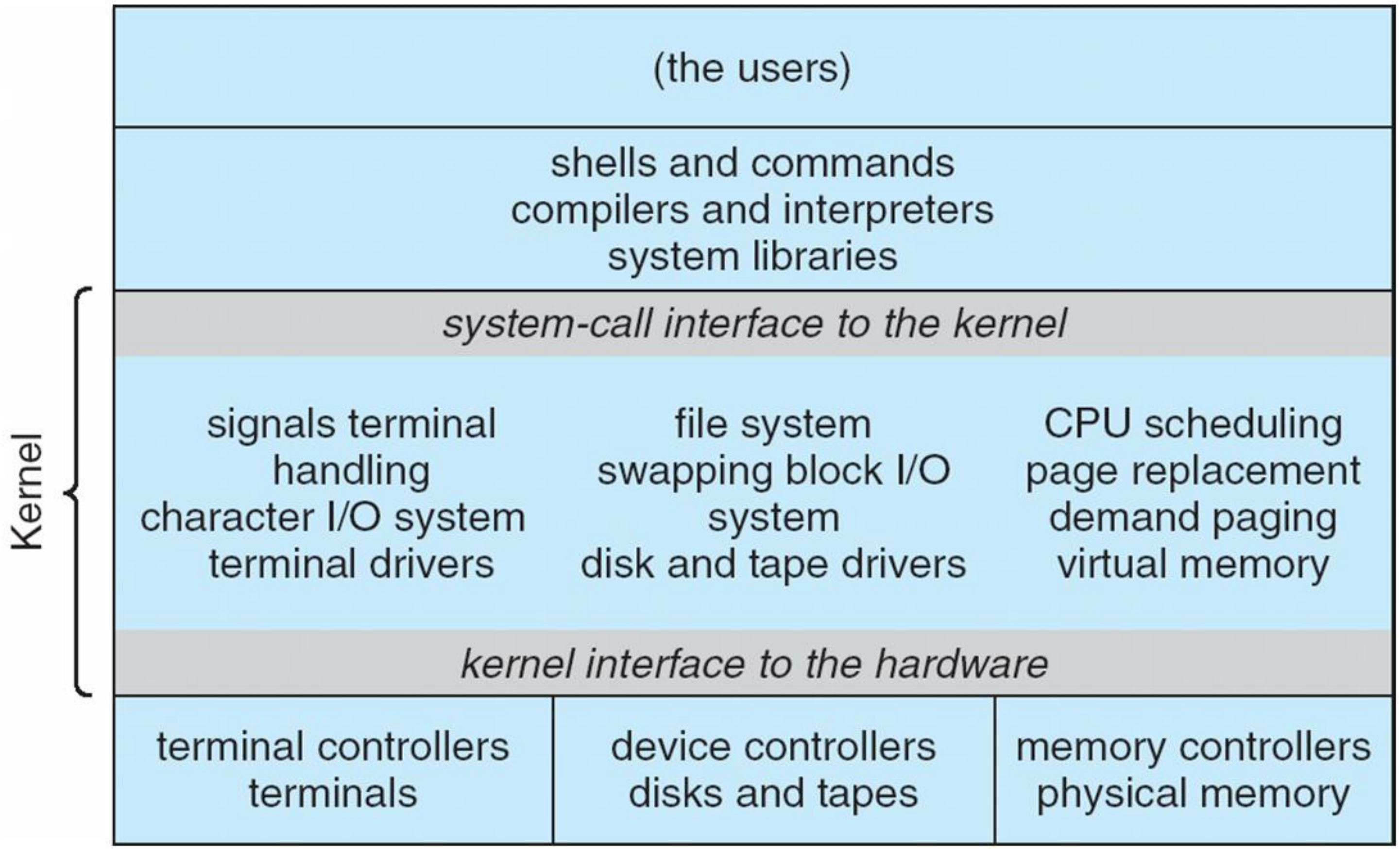
Monolithic Structure -- UNIX

UNIX – limited by hardware functionality, the original UNIX operating system had limited structuring. The UNIX OS consists of two separable parts

- Systems programs
- The kernel
  - Consists of everything below the system-call interface and above the physical hardware
  - Provides the file system, CPU scheduling, memory management, and other operating-system functions; a large number of functions for one level

Traditional UNIX System Structure

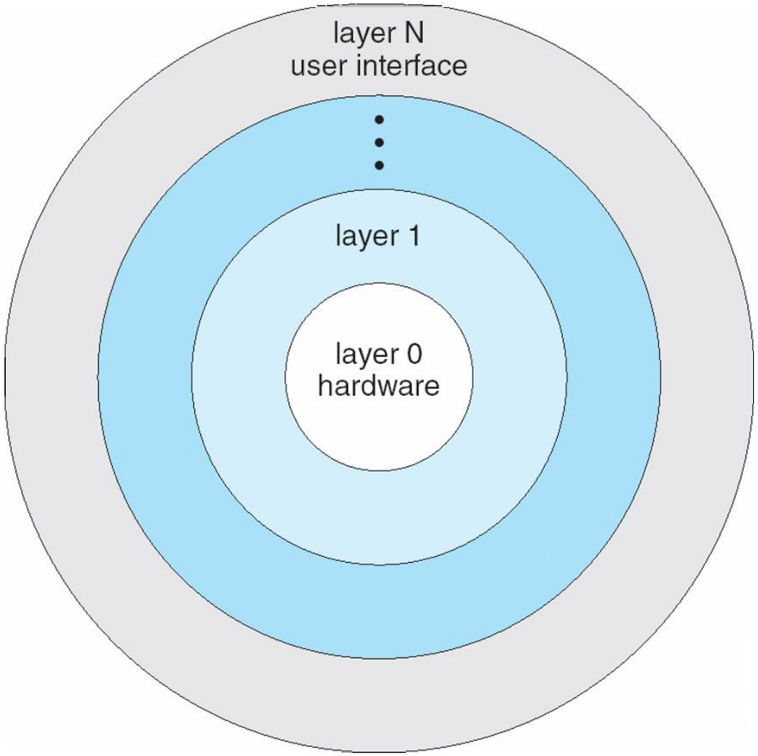
Beyond simple but not fully layered



Layered Approach

The operating system is divided into a number of layers (levels), each built on top of lower layers. The bottom layer (layer 0), is the hardware; the highest (layer N) is the user interface.

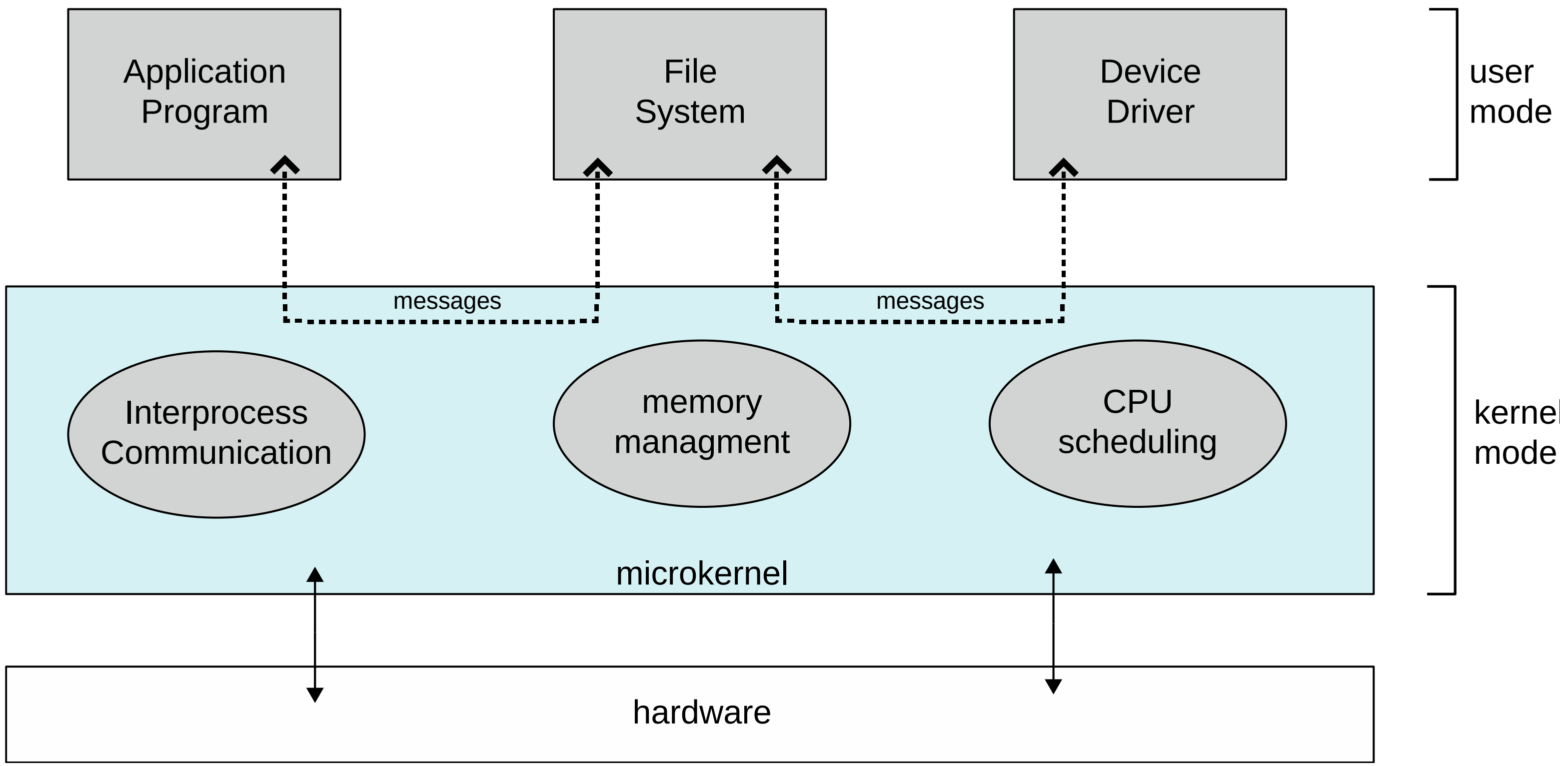
With modularity, layers are selected such that each uses functions (operations) and services of only lower-level layers



Microkernel System Structure

- Moves as much from the kernel into user space
- **Mach** example of **microkernel**
  - Mac OS X kernel (**Darwin**) partly based on Mach
- Communication takes place between user modules using **message passing**
- Benefits:
  - Easier to extend a microkernel
  - Easier to port the operating system to new architectures
  - More reliable (less code is running in kernel mode)
  - More secure
- Detriments:
  - Performance overhead of user space to kernel space communication

Microkernel System Structure



Modules

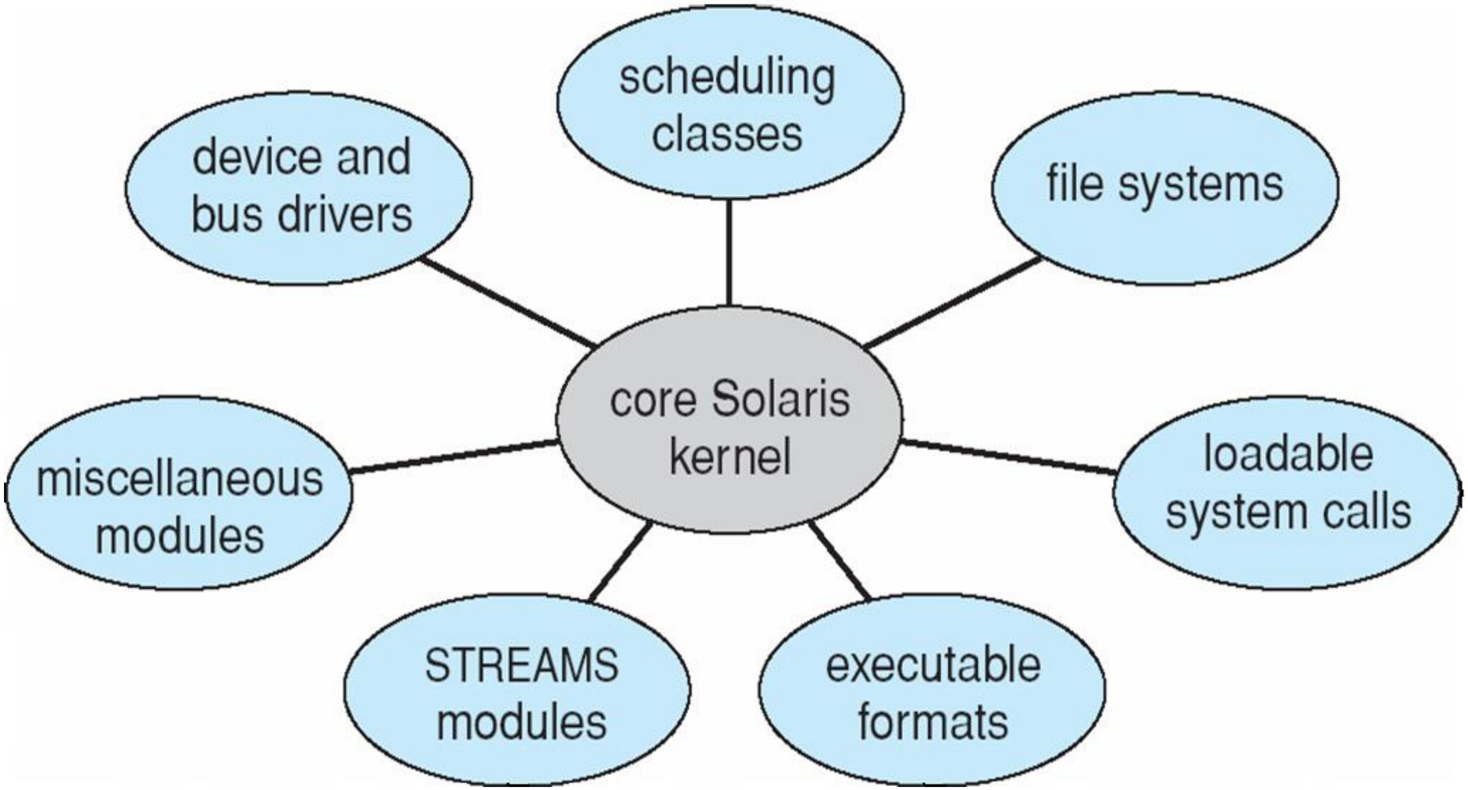
Many modern operating systems implement **loadable kernel modules**

- Uses object-oriented approach
- Each core component is separate
- Each talks to the others over known interfaces
- Each is loadable as needed within the kernel

Overall, similar to layers but with more flexible

- Linux, Solaris, etc

Solaris Modular Approach



Hybrid Systems

Most modern operating systems are actually not one pure model

- Hybrid combines multiple approaches to address performance, security, usability needs
- Linux and Solaris kernels in a kernel address space (for providing very efficient performance), so monolithic, plus modular for dynamic loading of functionality
- Windows is largely monolithic as well, but it retains some behavior typical of microkernel system, including providing support for separate subsystems (known as operating-system ***personalities***) that run as user-mode process.

Hybrid Systems

The general architecture of Mac OS and iOS systems is shown in Figure 2.16.

User experience layer

- Mac OS (Aqua)
- iOS (Springboard)

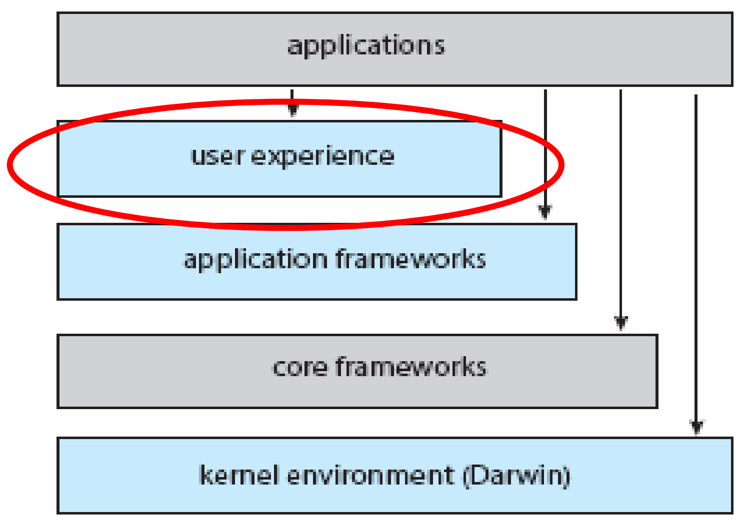


Figure 2.16 Architecture of Apple's macOS and iOS operating systems.

Hybrid Systems

The general architecture of Mac OS and iOS systems is shown in Figure 2.16.

Application frameworks layer

- Mac OS (Cocoa)
- iOS (Cocoa touch)

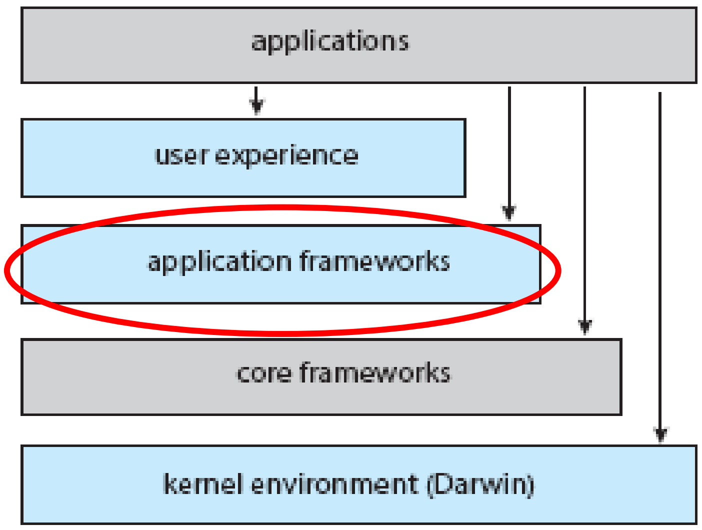


Figure 2.16 Architecture of Apple's macOS and iOS operating systems.

Hybrid Systems

The general architecture of Mac OS and iOS systems is shown in Figure 2.16.

Core frameworks : This layer defines frameworks that support graphics and media including, Quicktime and OpenGL.

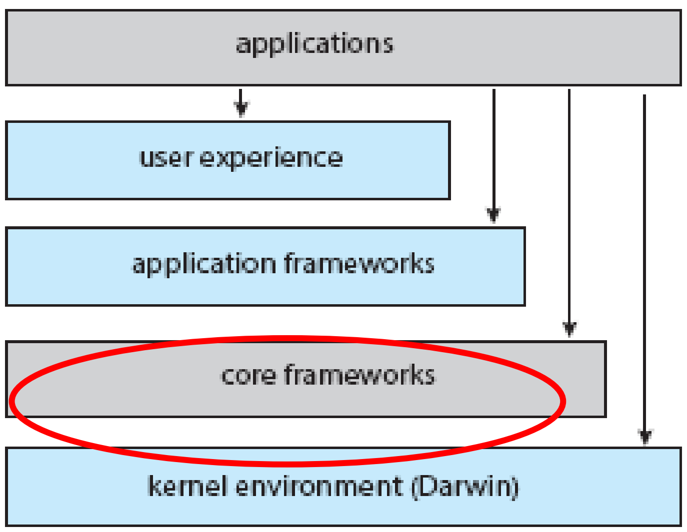


Figure 2.16 Architecture of Apple's macOS and iOS operating systems.

Hybrid Systems

The general architecture of Mac OS and iOS systems is shown in Figure 2.16.

Kernel environment (Darwin) : Mach microkernel + BSD UNIX kernel

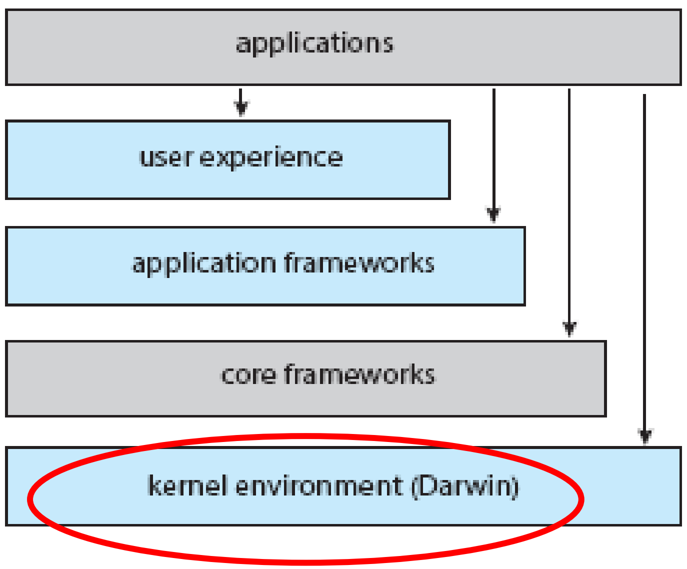


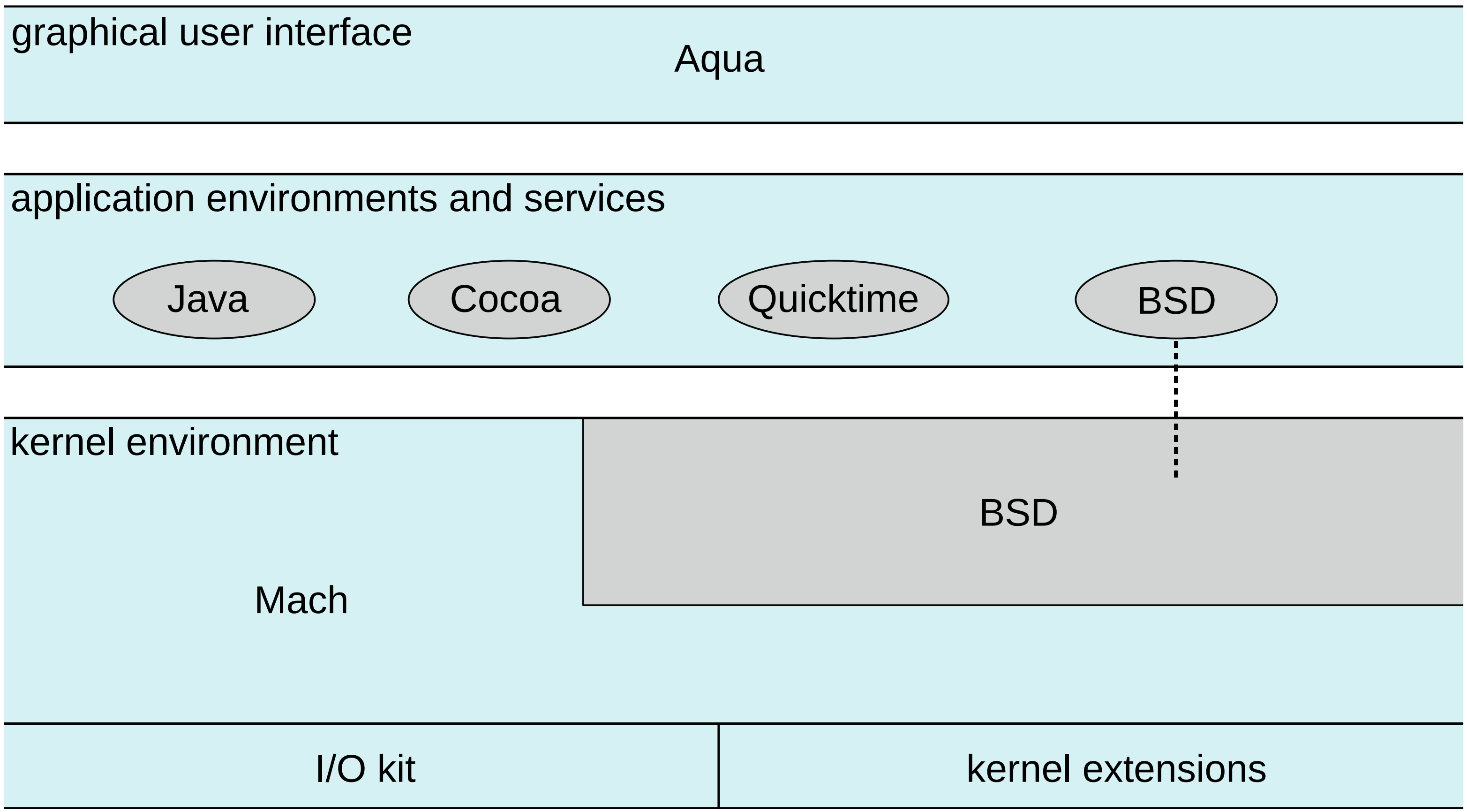
Figure 2.16 Architecture of Apple's macOS and iOS operating systems.

Hybrid Systems

Apple Mac OS X hybrid, layered, **Aqua** UI plus **Cocoa** programming environment

- Below is kernel consisting of Mach microkernel and BSD Unix parts, plus I/O kit and dynamically loadable modules (called **kernel extensions**)

Mac OS X Structure



The Structure of Darwin

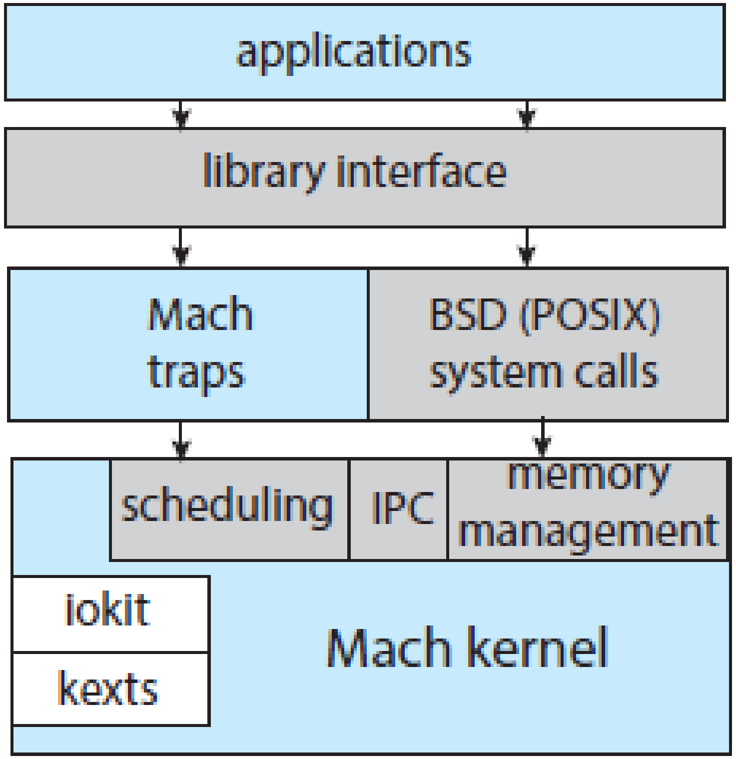
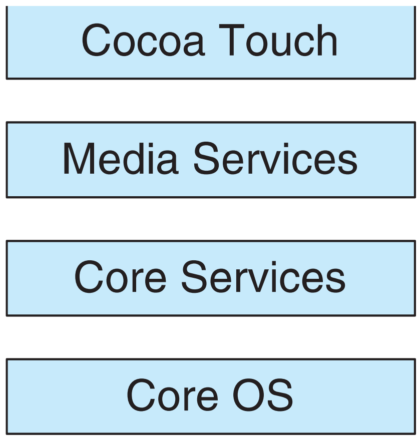


Figure 2.17 The structure of Darwin.

iOS

Apple mobile OS for ***iPhone***, ***iPad***

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



Android

Developed by Open Handset Alliance (mostly Google)

- Open Source

Similar stack to iOS

Based on Linux kernel but modified

- Provides process, memory, device-driver management
- Adds power management

Runtime environment includes core set of libraries and Dalvik virtual machine

- Apps developed in Java plus Android API
  - Java class files compiled to Java bytecode then translated to executable than runs in Dalvik VM

Libraries include frameworks for web browser (webkit), database (SQLite), multimedia, smaller libc

Android Architecture

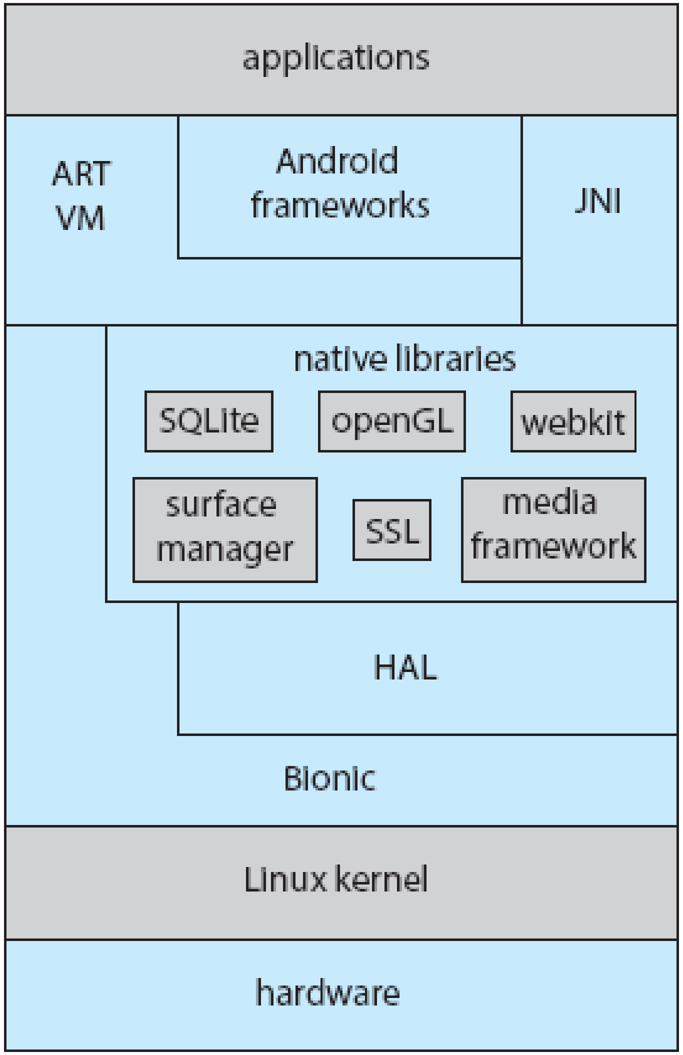


Figure 2.18 Architecture of Google's Android.

2.9 Building and Booting an Operating System

Operating system generation

Operating systems are designed to run on any of a class of machines; the system must be configured for each specific computer site

SYSGEN program obtains information concerning the specific configuration of the hardware system

a. The operating system is tailored to the system described.

b. Link compiled modules

c. All the code is always part of the system and selection occurs at execution time. (table driven)

System Boot

- When power initialized on system, execution starts at a fixed memory location
  - Firmware ROM used to hold initial boot code
- Operating system must be made available to hardware so hardware can start it
  - Small piece of code – **bootstrap loader**, stored in **ROM** or **EEPROM** locates the kernel, loads it into memory, and starts it
  - Sometimes two-step process where **boot block** at fixed location loaded by ROM code, which loads bootstrap loader from disk
- Common bootstrap loader, **GRUB** (open-source bootstrap program for Linux and UNIX), allows selection of kernel from multiple disks, versions, kernel options
- Kernel loads and system is then **running**

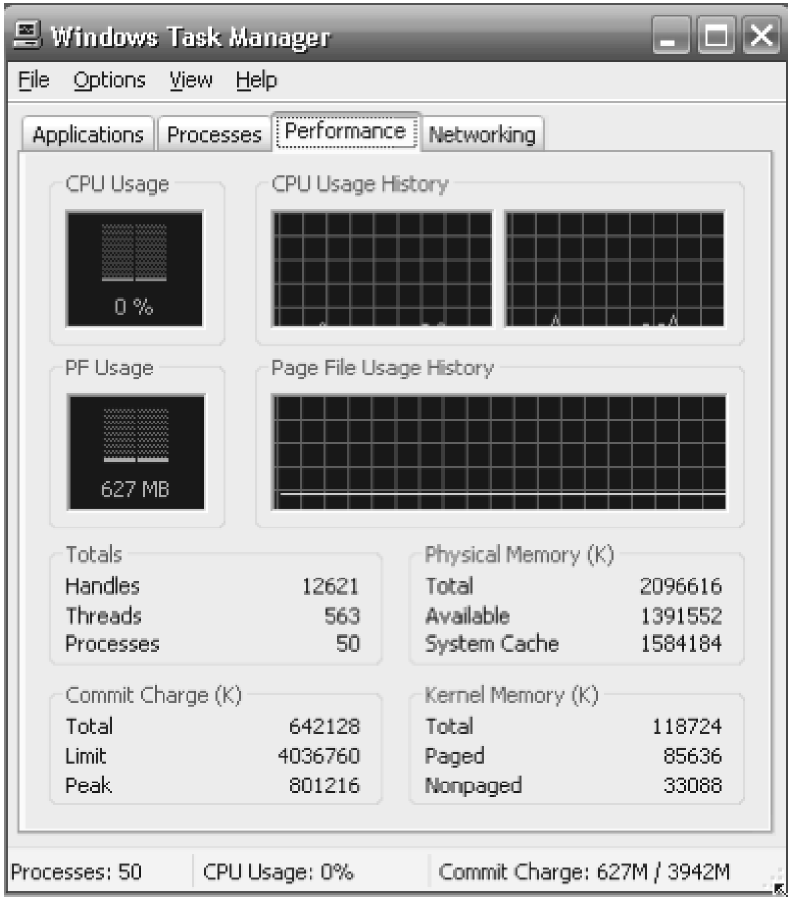
2.10 Operating-System Debugging

- **Debugging** is finding and fixing errors, or **bugs**
- OS generate **log files** containing error information
- Failure of an application can generate **core dump** file capturing memory of the process
- Operating system failure can generate **crash dump** file containing kernel memory
- Beyond crashes, performance tuning can optimize system performance
  - Sometimes using ***trace listings*** of activities, recorded for analysis
  - **Profiling** is periodic sampling of instruction pointer to look for statistical trends

Kernighan's Law: "Debugging is twice as hard as writing the code in the first place. Therefore, if you write the code as cleverly as possible, you are, by definition, not smart enough to debug it."

Performance Tuning

- Improve performance by removing bottlenecks
- OS must provide means of computing and displaying measures of system behavior
- For example, "top" program or Windows Task Manager



DTrace

DTrace tool in Solaris, FreeBSD, Mac OS X allows live instrumentation on production systems

Probes fire when code is executed within a **provider**, capturing state data and sending it to **consumers** of those probes

Example of following XEventsQueued system call move from libc library to kernel and back

```
# ./all.d 'pgrep xclock' XEventsQueued
dtrace: script './all.d' matched 52377 probes
CPU FUNCTION
  0 -> XEventsQueued                      U
  0   -> _XEventsQueued                   U
  0     -> _X11TransBytesReadable         U
  0     <- _X11TransBytesReadable         U
  0     -> _X11TransSocketBytesReadable U
  0     <- _X11TransSocketBytesreadable U
  0     -> ioctl                          U
  0       -> ioctl                        K
  0         -> getf                       K
  0           -> set_active_fd            K
  0           <- set_active_fd            K
  0         <- getf                       K
  0         -> get_udatamodel             K
  0         <- get_udatamodel             K
...
  0         -> releasef                   K
  0           -> clear_active_fd          K
  0           <- clear_active_fd          K
  0           -> cv_broadcast             K
  0           <- cv_broadcast             K
  0         <- releasef                   K
  0       <- ioctl                        K
  0     <- ioctl                          U
  0   <- _XEventsQueued                   U
  0 <- XEventsQueued                      U
```

Dtrace (Cont.)

DTrace code to record amount of time each process with UserID 101 is in running mode (on CPU) in nanoseconds

```
sched:::on-cpu
uid == 101
{
   self->ts = timestamp;
}

sched:::off-cpu
self->ts
{
   @time[execname] = sum(timestamp - self->ts);
   self->ts = 0;
}
```

```
# dtrace -s sched.d
dtrace: script 'sched.d' matched 6 probes
^C
     gnome-settings-d         142354
     gnome-vfs-daemon         158243
     dsdm                     189804
     wnck-applet              200030
     gnome-panel              277864
     clock-applet             374916
     mapping-daemon           385475
     xscreensaver             514177
     metacity                 539281
     Xorg                    2579646
     gnome-terminal          5007269
     mixer_applet2           7388447
     java                   10769137
```

Figure 2.21 Output of the D code.

End of Chapter 2