Outline

- Announcements
  - Project groups
  - Questions?
- History of OSes (cont'd)
- Computer-system structures
  - I/O structures
  - Storage structures and hierarchy
    - memory, secondary storage, tape
  - Hardware support for protection
- Operating-system structures
  - different views: functional, components, services, structure

[Silberschatz/Galvin/Gagne: Chapters 2-3]

(Review) Innovation in 1950’s OSes: Spooling

- Use of *disks* to buffer input/output to tapes
  - disks are random-access I/O devices
- Overlapped I/O and computation
  - one job’s I/O can be overlapped with another’s computation
- Need for independent I/O controllers
  - CPU: starts I/O operation; continues computation
  - Controller: does I/O; interrupts CPU
- Initially off-line spooling, later on-line

(Review) Multiprogramming Systems (1960s)

- Many programs simultaneously in memory
  - objective: to keep CPU busy
  - OS switches between user processes
- How to ensure that these programs do not interfere with each other?
- Hardware innovations to support multiprogramming
  - memory protection
  - privileged instructions
Time Sharing and Interactive Systems

- Originally proposed by Strachey ~1960
  - programs could interact with user
- Programs
  - could wait for I/O for an arbitrary time
    - CPU switched to another job
  - however, resident jobs took up valuable memory
    - needed to be swapped out to disk
  - technique that was developed to support this: virtual memory
- OS research in 60s
  - CTSS, MULTICS at MIT
  - Atlas (spooling, demand paging) at Manchester U

OS Requirements (late 1960s)

- Multiprogramming
  - memory allocation and protection
  - I/O operations were responsibility of OS
- Interactive systems
  - scheduling issues
  - swapping, or virtual memory
- Users wanted permanent files
  - hierarchical directory systems
- But, OSes became very complex
  - IBM: OS/360
  - CDC: Sipros, Chippewa, NOS
  - OS structure was specialized to the hardware

UNIX (early 1970s)

- Originally developed at Bell Labs for the PDP-7
  - Ken Thompson
  - Dennis Ritchie
- Smaller and simpler
  - process spawn and control
    - each command creates a new process (activity)
  - simple inter-process communication
  - command interpreter not built in: runs as another process
  - files were streams of bytes
  - hierarchical file system
- Advantages
  - written in a high-level language
  - distributed in source form
  - powerful OS primitives on an inexpensive platform

Personal Computers (1980s)

- Originally
  - single user
  - simplified OSes
    - no memory protection
    - MS-DOS
- Now run sophisticated OSes
  - Windows NT/2000/XP, Linux
- Accompanied by growth in windowing systems
  - Originally based on work at Xerox Parc
  - Popularized by the Macintosh
  - Characterized by
    - graphical interface
    - mouse control
Networks of Workstations (1990s)

- High-speed network connections
- Local and world-wide
- Client-server systems
  - file systems
  - remote windowing systems
- Support a variety of node OSes
  - Unix, Windows NT

(2000s and) The Future

- Distributed systems
  - network is invisible
- Micro-kernel and extensible OSes
  - support multiple OS flavors
    - e.g., Mach, Amoeba, Windows NT
  - allow insertion of application-specific functionality
- Embedded devices and network computers
  - computer runs a very thin OS (Java Virtual Machine)
- Web Operating Systems
  - standard protocols (HTTP, SOAP)
  - container environments (J2EE, .NET)

- Unfortunately, we will not talk about these in this course
  - but, opportunities in my research group

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  - No lecture on Wednesday, January 29th
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The Hardware of a Modern Computer System

Modern OSes rely on three main structures
I/O
Storage
Protection
Computer-System Structures (1): Input/Output

- Device controllers
  - special-purpose *processors*
  - local buffer *storage*
  - controllers contain *registers*
    - control (write-only)
    - data (read-write)
    - status (read-only)

- How do the CPU and the device controllers communicate?
  - instructions
    - read/write I/O addresses (e.g., video memory)
    - registers in I/O controllers addressed as memory
  - interrupts
    - device controllers can *interrupt* the CPU

Interrupt Handling

- Interrupts are “asynchronous requests for service”
  - signal on a wire connecting the devices
- When an interrupt occurs, the CPU
  - preserves the present CPU state
    - this includes its registers and program counter
  - forces execution of code at an interrupt address
    - this may be dependent on the source of the interrupt
    - typically, table-driven: a table stores addresses of *interrupt handlers*
      - indexed by the interrupt number (ISR)
  - interrupt handlers
    - perform the requested service
    - selective processing of other interrupts
      - e.g., only higher-priority interrupts may be handled
    - resumes the interrupted program

- Most modern OSes are interrupt-driven

Interrupt Handling (contd.)

Interrupts vs. Traps

- Interrupts
  - asynchronous
  - triggered by devices outside the CPU
- Traps
  - synchronous
  - triggered by special instructions in user program

- Other than the above, handling of interrupts and traps is identical
- Traps are the hardware mechanism for implementing *system calls*
I/O Operation

- Two approaches: Synchronous and Asynchronous

  ![Diagram showing request process, device driver, interrupt handler, and HW data transfer]

- Problem with the above schemes: CPU handles all I/O
  - it can spend all its time doing interrupt processing
    - disk I/O, network I/O, video I/O

Solution: Direct Memory Access (DMA)

- The main idea: add a special device to “intervene” between the device controller and the system's memory

  - Operation
    - the CPU tells this DMA controller
      - the “chunk” size to be transferred
        - e.g., 128 - 4096 bytes (sectors) for disks
      - the starting address in memory where this chunk ought to be stored
    - the DMA controller
      - accesses the secondary device via its controller
      - transfers the chunk from the device to system memory (and vice-versa)

- Benefit: Interrupts are now less frequent
  - at the level of chunks of data: only to indicate completion
  - hence, CPU can do a lot of work between interrupts

Memory-Mapped I/O

- Traditionally, the CPU could directly access only main memory
  - all other devices are handled via controllers
  - accessed using special I/O instructions

- In most recent systems
  - controller’s registers are mapped into RAM space
    - results in uniform treatment of the I/O devices
      - can be handled via memory management procedures
      - all addressing is to RAM space
      - DMA access, interrupt handling, polling, …
    - controller’s buffers are mapped into RAM space
      - makes sense if the I/O is to a device that is particularly fast
      - e.g., a CRT screen where each pixel is an addressable location in RAM

Computer-System Structures (2): Storage

- Primary storage: Main memory (volatile)
  - accessed directly using load/store instructions
    - 1 cycle (registers), 2-5 cycles (cache), 20-50 cycles (RAM)
    - before: only one outstanding memory operation, CPU waits for completion
    - now: several outstanding operations

- Secondary storage: Disks (non-volatile)
  - accessed using a disk controller
  - supports random access but with non-uniform cost

- Tertiary storage: Tapes, Optical disks (non-volatile)
  - typically used only for backup
  - very inefficient support for random access

- Organized as a hierarchy
  - small amount of faster, more expensive storage closer to the CPU
  - larger amounts of slower, less expensive storage further away
Storage Hierarchy

- **Rationale**
  - keep CPU busy: lots of fast memory
  - keep system cost down

- **How does it work**
  - **caching**: upon access, move datum or instruction and its neighbors into higher levels of the hierarchy
  - **replacement** when a level fills up
  - copies need to be kept coherent

- **Why does it work**
  - Real programs demonstrate locality
    - e.g.: rows and columns of a matrix
    - e.g.: sequential instructions
  - once a datum or instruction is used, things “near” them are likely to be used “soon”

Computer-System Structures (3): Protection

- **Goal**: Prevent user processes from accidentally/maliciously damaging
  - the OS structures
  - parts of other process’s memory space
  - other user’s I/O devices

- **Mechanisms address different ways in which protection breaks down**
  1. **dual-mode operation**
     - Prevent user process taking over part of the OS and using this to overwrite other processes or even modify the OS itself (as in MS-DOS)
  2. **privileged instructions**
     - Prevent user process intervening in I/O of another process via control of the I/O handlers and indirectly causing damage
  3. **memory protection**
     - Prevent user process directly accessing another user process' storage
  4. **CPU protection via timers**
     - Prevent hanging the OS -- e.g., via an infinite loop

Protection Mechanisms (1):
Dual-mode Operation and Privileged Instructions

- **Dual-mode operation**
  - supervisor and user modes
  - system starts off in supervisor mode and reenters it for interrupt processing
  - operating system gains control in supervisor mode

- **Privileged instructions**
  - restrict use of certain instructions to supervisor mode
    - I/O, including interrupt control
    - may be done by memory mapping
    - affect memory mapping
    - affect CPU mode (user/supervisor)
  - hardware support crucial for performance and for atomicity

Protection Mechanisms (2): Memory Protection

- **Basic method**: Memory is divided into segments

- **Furthermore**
  - logical addresses are mapped to physical addresses
    - provides sharing, etc.
  - hardware support for address mapping
    - a memory protection violation is detected
      - user process traps to (interrupts) the OS
Protection Mechanisms (3): Timers

- OS code can enforce policies only if it gets a chance to run

- Timers maintain a count of elapsed (system) clock ticks
  - when timer expires, the CPU is interrupted → run the OS code

- Used for
  - interrupting hung processes
  - context switching in time-shared systems

- Access to timers is (usually) privileged
  - WHY?

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Hardware and OS Structures

User Applications

<table>
<thead>
<tr>
<th>Support Applications</th>
<th>Functional View</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compilers, Linkers, Windowing Systems, …</td>
<td>what does it do?</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>User-mode</th>
<th>Components View</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protection and Security</td>
<td>what does it contain?</td>
</tr>
<tr>
<td>Process Management</td>
<td>Services View</td>
</tr>
<tr>
<td>I/O Device Management</td>
<td>what does it provide?</td>
</tr>
</tbody>
</table>

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<thead>
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<table>
<thead>
<tr>
<th>Structure View</th>
</tr>
</thead>
<tbody>
<tr>
<td>how is it built?</td>
</tr>
</tbody>
</table>

OS Views (1): Functional View

- What are the functions performed by an OS?

  - Explicit operations
    - program execution and handling
    - I/O operations
    - file-system management
    - inter-process communication
    - exception detection and handling
      - e.g., notifying user that printer is out of paper

  - Implicit operations
    - resource allocation
    - accounting
    - protection
      - e.g., maintaining data integrity, logging invalid login attempts
OS Views (2): Components View

- Processes: run-time representations of user programs
  - create, terminate, suspend, resume
  - access to shared resources (e.g., printers)
- Storage
  - allocation of memory among resident processes
  - disk management (e.g., scheduling of disk accesses)
- I/O
  - device drivers, handling of device interrupts
  - files and directories
- Protection
  - user access to system resources

Course organization follows this view

OS Views (3): Services View

- Two issues
  - What services does an OS provide? (same as functional view)
  - How do users and user programs access these services?
- Interface between the user and the OS: Command Interpreter
  - typical commands
    - process creation and (implicitly) destruction
    - I/O handling and file system manipulation
    - communication: interact with remote devices
    - protection management: changing file/directory access control, etc.
  - different varieties
    - the interpreter contains the code for the requested command (e.g., delete)
    - the interpreter calls a system routine to handle the request
    - the interpreter spawns new process(es) to handle the request
      - process lookup through some general procedure

  you will implement a simple shell in Nachos Lab 5

OS Views (3): Services View (contd.)

- Interface between a user program and the OS: System Calls
  - arguments passed in registers, a memory block, or on the stack
  - entry into the kernel using the trap mechanism

- Standard system calls
  - process control
  - file manipulation
  - device manipulation
  - information maintenance
    - get/set system data (time, memory/cpu usage), process and device attributes
  - communications

OS Views (4): Structure View

- How to structure OS functionality
  - Layering
  - Microkernels
  - Virtual machines
- Designing and implementing an OS

- Read Sections 3.5-3.9, Silberschatz, Galvin, and Gagne
- Look at Nachos source code
  - Thomas Narten’s roadmap
Lecture Summary

• Computer-system structures (Chapter 2)
  – I/O structures
  – storage structures
  – support for protection

• Operating-system structures (Chapter 3)
  – different views: functional, components, services, structure

• Next lecture
  – Processes (Sections 4.1 – 4.5)