What is an Operating System?

- Software that abstracts the computer hardware
  - Hides the messy details of the underlying hardware
  - Presents users with a resource abstraction that is easy to use
  - Extends or virtualizes the underlying machine
- Manages the resources
  - Processors, memory, timers, disks, mice, network interfaces, printers, displays, ...
  - Allows multiple users and programs to share the resources and coordinates the sharing, provides protection

Operating Systems Concepts

- Processes
- Memory management
- File systems
- Device management
- Security/protection

Resource Abstraction

```c
load(block, length, device);
seek(device, track);
out(device, sector);
write(char *block, int len, int device, int track, int sector) {
    ...
    load(block, length, device);
    seek(device, track);
    out(device, sector);
    ...
}
write(char *block, int len, int device, int addr);
fprintf(fileID, “%d”, datum);
```
**Disk Abstractions**

- load(…);
- seek(…);
- out(…);

```c
void write() {
    load(...);
    seek(...);
    out(...)
}
```

```c
int fprintf(...) {
    ...write(...)
    ...
}
```

(a) Direct Control  
(b) write() abstraction  
(c) fprintf() abstraction

**Under the Abstraction**

- functional complexity
- a single abstraction over multiple devices
- replication → reliability

**Resource Sharing**

Program P_i, Program P_j, …, Program P_k

Extended machine interface (resource abstraction)

OS Resource Sharing

Time-multiplexed Physical Processor

Space-multiplexed Physical Memory

**Objectives of Resource Sharing**

- Efficiency
- Fairness
- Security/protection
I/O Operations

- How is I/O done?
  - I/O devices are much slower than CPU

- Synchronous (polling)
  - After I/O starts, busy-wait while polling the device status register until it shows the operation completes

- Asynchronous (interrupt-driven)
  - After I/O starts, control returns to the user program without waiting for I/O completion
  - Device controller later informs CPU that it has finished its operation by causing an interrupt
  - When an interrupt occurs, current execution is put on hold; the CPU jumps to a service routine called an “interrupt handler”

System Protection

- User programs (programs not belonging to the OS) are generally not trusted
  - A user program may use an unfair amount of resource
  - A user program may maliciously cause other programs or the OS to fail

- Need protection against untrusted user programs; the system must differentiate between at least two modes of operations
  1. User mode - execution of user programs
     - untrusted
     - not allowed to have complete/direct access to hardware resources
  2. Kernel mode (also system mode or monitor mode) - execution of the operating system
     - trusted
     - allowed to have complete/direct access to hardware resources

- Hardware support is needed for such protection
Transition between User/Kernel Mode

- When does the machine run in kernel mode?
  - after machine boot
  - interrupt handler
  - system call
  - exception

Memory Protection

- Goal of memory protection?
  - A user program can't use arbitrary amount of memory
  - A user program can't access data belonging to the operating system or other user programs

- How to achieve memory protection?
  - Indirect memory access
    - Memory access with a virtual address which needs to be translated into physical address
  - Add two registers that determine the range of legal addresses a program may access:
    - Base register: holds the smallest legal physical memory address
    - Limit register: contains the size of the range
    - Memory outside the defined range is protected

Hardware Address Protection

- Address of each memory address is checked against “base” and “base+limit”
- Trap to the OS kernel if it falls outside of the range (an exception)

Protection of I/O Devices

- User programs are not allowed to directly access I/O devices
  - Special I/O instructions can only be used in kernel mode
  - Controller registers can only be accessed in kernel mode
- So device drivers, I/O interrupt handlers must run in kernel mode
- User programs perform I/O through requesting the OS (using system calls)
**System Call Using the Trap Instruction**

```
read();
read() {
    trap N_SYS_READ()
    sys_read();
    /* system function */
    return;
}
```

**CPU Protection**

- **Goal of CPU protection**
  - A user program can't hold the CPU for ever
- **Timer** - interrupts computer after specified period to ensure the OS kernel maintains control
  - Timer is decremented every clock tick
  - When timer reaches the value 0, an interrupt occurs
  - CPU time sharing is implemented in the timer interrupt

**Operation System Organization**

- **System Components**
  - process management
  - memory management
  - I/O system
  - file and storage
  - networking, ...
- **Operating System Architectures**
  - monolithic architecture
  - microkernel architecture
  - layered architecture
  - virtual machines

**Process Management**

- **A process is a program in execution**
  - Unit of work - A process needs certain resources, including CPU time, memory, files, and I/O devices, to accomplish its task
  - Protection domain
- **OS responsibilities for process management**:  
  - Process creation and deletion
  - Process scheduling, suspension, and resumption
  - Process synchronization, inter-process communication
Memory Management

- Memory
  - A large array of addressable words or bytes.
  - A data repository shared by the CPU and I/O devices.
- OS responsibility for memory management:
  - Allocate and deallocate memory space as requested
  - Efficient utilization when the memory resource is heavily contended
  - Keep track of which parts of memory are currently being used and by whom

I/O System Management

- A computer needs I/O to interact with the outside world:
  - Console/terminal
  - Non-volatile secondary storage - disks
  - Networking
- The I/O system consists of:
  - A buffer-caching system
  - A general device-driver interface
  - Drivers for specific hardware devices

File and Secondary Storage Management

- A file is a collection of information defined by its user.
  Commonly, both programs and data are stored as files
- OS responsibility for file management:
  - Manipulation of files and directories
  - Map files onto (nonvolatile) secondary storage - disks
- OS responsibility for disk management:
  - Free space management and storage allocation
  - Disk scheduling
- They are not all always together
  - Not all files are mapped to secondary storage!
  - Not all disk space is used for the file system!

Networking and Communication

- A distributed system
  - A collection of processors that do not share memory
  - Processors are connected through a communication network
  - Communication takes place using a protocol
  - OS provides communication end-points or sockets
- Inter-process communication (msg, shm, sem)
**OS Architecture: Monolithic Structure**

Interactive User

<table>
<thead>
<tr>
<th>Libraries</th>
<th>Commands</th>
<th>Application Programs</th>
<th>OS System Call Interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Device Driver</td>
<td>Device Driver</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

Monolithic Kernel Module
- Process Management
- Memory Management
- File Management
- Device Mgmt Infrastructure

Trap Table

Most modern OSes fall into this category!

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**Microkernel System Architecture**

- Microkernel architecture:
  - Moves as much from the kernel into "user" space (still protected from normal users).
  - Communication takes place between user modules using message passing.
- What must be in the kernel and what can be in user space?
  - Mechanisms determine how to do something.
  - Policies decide what will be done.
- Benefits:
  - More reliable (less code is running in kernel mode)
  - More secure (less code is running in kernel mode)
- Disadvantage?

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**Layered Structure**

- Layered structure
  - 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.
  - Decreased privileges for higher layers.
- Benefits:
  - more reliable
  - more secure
  - more flexibility, easier to extend
- Disadvantage?
  - Weak integration results in performance penalty (similar to the microkernel structure).
Virtual Machine Architecture

- **Non-VM**
  - User programs
  - OS
  - Hardware
  - VM monitor
  - Hardware

- **Native VM**
  - User programs
  - OS
  - Native OS
  - Hardware

- **Hosted VM**
  - User programs on native OS
  - OS
  - VMM
  - Native OS
  - Hardware

System Boot

- How does the hardware know where the kernel is or how to load that kernel?
  - Use a bootstrap program or loader
  - Execution starts at a predefined memory location in ROM (read-only memory)
  - Read a single block at a fixed location on disk and execute the code from that boot block
  - Easily change operating system image by writing new versions to disk

User Operating-System Interface

- Command interpreter – special program initiated when a user first logs on
- Graphical user interface
  - Common desktop environment (CDE)
  - K desktop environment (KDE)
  - GNOME desktop (GNOME)
  - Aqua (MacOS X)

System Calls and Interfaces/Abstractions

- Examples: Win32, POSIX, or Java APIs
- Process management
  - fork, waitpid, execve, exit, kill
- File management
  - open, close, read, write, lseek
- Directory and file system management
  - mkdir, rmdir, link, unlink, mount, umount
- Inter-process communication
  - sockets, ipc (msg, shm, sem)
Process and Its Image
- An operating system executes a variety of programs:
  - A program that browses the Web
  - A program that serves Web requests
- Process - a program in execution.
- A process's state/image in a computer includes:
  - User-mode address space
  - Kernel data structure
  - Registers (including program counter and stack pointer)
- Address space and memory protection
  - Physical memory is divided into user memory and kernel memory
  - Kernel memory can only be accessed when in the kernel mode
  - Each process has its own exclusive address space in the user-mode memory space (sort-of)

User-mode Address Space
User-mode address space for a process:
- **Text**: program code, instructions
- **Data**: initialized global and static variables (those data whose size is known before the execution)
- **BSS** (block started by symbol): uninitialized global and static variables
- **Heap**: dynamic memory (those being malloc-ed)
- **Stack**: local variables and other stuff for function invocations

Process Control Block (PCB)
OS data structure (in kernel memory) maintaining information associated with each process.
- Process state
- Program counter
- CPU registers
- CPU scheduling information
- Memory-management information
- Accounting information
- Information about open files
  - maybe kernel stack?

Process Creation
- When a process (parent) creates a new process (child)
  - Execution sequence?
  - Address space sharing?
  - Open files inheritance?
  - ... ...
- UNIX examples
  - **fork** system call creates new process with a duplicated copy of everything.
  - **exec** system call used after a **fork** to replace the process' memory space with a new program.
  - child and parent compete for CPU like two normal processes.

Copy-on-write
### Context Switching

- Processes are managed by a shared chunk of OS code called the **kernel**.
  - Important: the kernel is not a separate process, but rather runs as part of some user process.
- Control flow passes from one process to another via a **context switch**.

![Context Switching Diagram](image)

### Private Address Spaces

- Each process has its own private address space.

![Private Address Spaces Diagram](image)

### Simple Shell `eval` Function

```c
void eval(char *cmdline) {
    char *argv[MAXARGS]; /* argv for execve() */
    int bg; /* should the job run in bg or fg? */
    pid_t pid; /* process id */

    bg = parseline(cmdline, argv);
    if (!bg) { /* child runs user job */
        if ((pid = Fork()) == 0) { /* child runs user job */
            if (execve(argv[0], argv, environ) < 0) {
                printf("%s: Command not found.
"), argv[0]);
            exit(0);
        }
    } else if (!bg) { /* parent waits for fg job to terminate */
        int status;
        if (waitpid(pid, &status, 0) < 0) { /* parent waits for fg job to terminate */
            unix_error("waitfg: waitpid error");
        }
    } else if (!bg) { /* otherwise, don't wait for bg job */
        printf("%d %s", pid, cmdline);
    }
}
```

### Problem with Simple Shell Example

- Shell correctly waits for and reaps foreground jobs.
- But what about background jobs?
  - Will become zombies when they terminate.
- Will never be reaped because shell (typically) will not terminate.
- Creates a memory leak that will eventually crash the kernel when it runs out of memory.
- Solution: Reaping background jobs requires a mechanism called a **signal**.
Signals

- A signal is a small message that notifies a process that an event of some type has occurred in the system.
  - Kernel abstraction for exceptions and interrupts.
  - Sent from the kernel (sometimes at the request of another process) to a process.
  - Different signals are identified by small integer ID's
  - The only information in a signal is its ID and the fact that it arrived.

<table>
<thead>
<tr>
<th>ID</th>
<th>Name</th>
<th>Default Action</th>
<th>Corresponding Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>SIGINT</td>
<td>Terminate</td>
<td>Interrupt from keyboard (\texttt{ctl-c})</td>
</tr>
<tr>
<td>9</td>
<td>SIGKILL</td>
<td>Terminate</td>
<td>Kill program (cannot override or ignore)</td>
</tr>
<tr>
<td>11</td>
<td>SIGSEGV</td>
<td>Terminate &amp; Dump</td>
<td>Segmentation violation</td>
</tr>
<tr>
<td>14</td>
<td>SIGALRM</td>
<td>Terminate</td>
<td>Timer signal</td>
</tr>
<tr>
<td>17</td>
<td>SIGCHLD</td>
<td>Ignore</td>
<td>Child stopped or terminated</td>
</tr>
</tbody>
</table>

Signal Concepts

- Sending a signal
  - Kernel sends (delivers) a signal to a destination process by updating some state in the context of the destination process.
  - Kernel sends a signal for one of the following reasons:
    - Kernel has detected a system event such as divide-by-zero (SIGFPE) or the termination of a child process (SIGCHLD)
    - Another process has invoked the \texttt{kill} system call to explicitly request the kernel to send a signal to the destination process.

Signal Concepts (cont)

- Receiving a signal
  - A destination process receives a signal when it is forced by the kernel to react in some way to the delivery of the signal.
  - Three possible ways to react:
    - Ignore the signal (do nothing)
    - Terminate the process.
    - Catch the signal by executing a user-level function called a signal handler.
      - Akin to a hardware exception handler being called in response to an asynchronous interrupt.

Signal Concepts (cont)

- A signal is pending if it has been sent but not yet received.
  - There can be at most one pending signal of any particular type.
  - Important: Signals are not queued
    - If a process has a pending signal of type \( k \), then subsequent signals of type \( k \) that are sent to that process are discarded.
  - A process can block the receipt of certain signals.
    - Blocked signals can be delivered, but will not be received until the signal is unblocked.
  - A pending signal is received at most once.
Signal Concepts

- Kernel maintains pending and blocked bit vectors in the context of each process.
  - pending - represents the set of pending signals
    - Kernel sets bit k in pending whenever a signal of type k is delivered.
    - Kernel clears bit k in pending whenever a signal of type k is received
  - blocked - represents the set of blocked signals
    - Can be set and cleared by the application using the sigprocmask function.

Process Groups

- Every process belongs to exactly one process group

Sending Signals with kill
Program

- kill program sends arbitrary signal to a process or process group

  Examples
  - kill -9 24818
    - Send SIGKILL to process 24818
  - kill -9 -24817
    - Send SIGKILL to every process in process group 24817.

Sending Signals from the Keyboard

- Typing ctrl-c (ctrl-z) sends a SIGINT (SIGTSTP) to every job in the foreground process group.
  - SIGTERM - default action is to terminate each process
  - SIGTSTP - default action is to stop (suspend) each process
Receiving Signals

- Suppose kernel is returning from exception handler and is ready to pass control to process \( p \).
- Kernel computes \( pnb = \text{pending} \&\! \& \! \text{~blocked} \)
  - The set of pending nonblocked signals for process \( p \)
- If \( (pnb == 0) \)
  - Pass control to next instruction in the logical flow for \( p \).
- Else
  - Choose least nonzero bit \( k \) in \( pnb \) and force process \( p \) to receive signal \( k \).
  - The receipt of the signal triggers some action by \( p \)
  - Repeat for all nonzero \( k \) in \( pnb \).
  - Pass control to next instruction in logical flow for \( p \).

Default Actions

- Each signal type has a predefined default action, which is one of:
  - The process terminates
  - The process terminates and dumps core.
  - The process stops until restarted by a SIGCONT signal.
  - The process ignores the signal.

Installing Signal Handlers

- The `signal` function modifies the default action associated with the receipt of signal `signum`:
  - `handler_t *signal(int signum, handler_t *handler)`
- Different values for `handler`:
  - SIG_IGN: Ignore signals of type `signum`
  - SIG_DFL: Revert to the default action on receipt of signals of type `signum`.
  - Otherwise, handler is the address of a signal handler
    - Called when process receives signal of type `signum`
    - Referred to as “installing” the handler.
    - Executing handler is called “catching” or “handling” the signal.
    - When the handler executes its return statement, control passes back to instruction in the control flow of the process that was interrupted by receipt of the signal.

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