Operating System 101: The Evolution of Operating Systems

Tag: CTSS, Multics, Unix, BSD, Linux, Android, mbed

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What are we about to reach?

- Programs
- Platforms
- Performance
- ...

“The system is all the code your program uses that you didn’t have to write.”
“Software Architecture”

Software architecture

Computer architecture

Physics stops here.

User Applications

Operating System(s)

Substrate / Architecture

Comparative architecture: what works

Reusable / recurring design patterns
  • Used in OS
  • Supported by OS
Platform abstractions

• Platforms provide “building blocks”…
• …and APIs to use them to construct software
  – Instantiate/create/allocate
  – Manipulate/configure
  – Attach/detach
  – Combine in uniform ways
  – Release/destroy

• Abstractions are layered.
  – What to expose? What to hide?

The choice of abstractions reflects a philosophy of how to build and organize software systems.
Managing Complexity

Systems are built from components.

Operating systems define styles of software components and how they interact.

OS maps components onto the underlying machine.

…and makes it all work together.
Comparative software architecture

Large, long-lived software systems are like buildings. They are built by workers using standard design patterns. They depend on some underlying infrastructure. But they can evolve and are not limited by the laws of physics.
A simple module

• A set of procedures/functions/methods.
• An interface (API) that defines a template for how to call/invoke the procedures.
• State (data) maintained and accessed by the procedures.
• A module may be a class that defines a template (type) for a data structure, which may have multiple instances (objects).

Abstract Data Type (ADT): the module’s state is manipulated only through its API (Application Programming Interface).
Code: instructions in memory

_p1:
pushq  %rbp
movq  %rsp, %rbp
movl  $1, %eax
movq  %rdi, -8(%rbp)
popq  %rbp
ret

load   _x, R2 ; load global variable x
add    R2, 1, R2 ; increment: x = x + 1
store  R2, _x ; store global variable x
A Peek Inside a Running Program

- CPU core
- CPU registers: R0, Rn, PC, SP
- Address space (virtual or physical)
- "memory"
- Stack
- Heap
- Common runtime
- Code library
- Your program
- Your data

E.g., a virtual memory for a running program (process)
Data in memory
64 bytes: 3 ways

Pointers (addresses) are 8 bytes on a 64-bit machine.
The “heap” is an ADT in a runtime library: the code to maintain the heap is a heap manager.

It allocates a contiguous slab of virtual memory from the OS kernel, then “carves it up” as needed.

It enables the programming language environment, to store dynamic objects.

E.g., with Unix malloc and free library calls.
But some programs are interpreted. They run on an “abstract machine” (e.g., JVM) implemented in software.

Actually in many cases, a program is distributed in the form of a JAR file, which stands for Java ARchive file.
Platforms are layered/nested
Some lessons of history

• At the time it was created, Unix was the “simplest multi-user OS people could imagine.”
  – It’s in the name: Unix vs. Multics

• Simple abstractions can deliver a lot of power.
  – Many people have been inspired by the power of Unix.

• The community spent four decades making Unix complex again....but the essence is unchanged.

• Unix is a simple context to study core issues for classical OS design. “It’s in there.”

• Unix variants continue to be in wide use.
Virtual Machine

“Classical OS”

Reloaded.
End-to-end application delivery

Where is your application?
Where is your data?
Where is your OS?

Cloud and Software-as-a-Service (SaaS)
Rapid evolution, no user upgrade, no user data management.
Agile/elastic deployment on virtual infrastructure.
SaaS platform elements

[wiki.eeng.dcu.ie]
OpenStack, the Cloud Operating System

Management Layer That Adds Automation & Control

Connects to apps via APIs

Self-service Portals for users

Creates Pools of Resources

Automates The Network

[Anthony Young @ Rackspace]
EC2
The canonical public cloud

Virtual Appliance Image
Canonical OS Example: “Classical OS”

- Unix/Linux, Windows, Mac OS X
- Research systems
  - Multics
  - Mach
  - Minix
  - ...

Drivers of Change

Increasing diversity

Exponential growth

Aggregation
Composition
Orchestration

User Applications

Operating System

Substrate / Architecture

Backward compatibility

Broad view: smartphones to servers, web, and cloud.
Key Interfaces

- Instruction set architecture (ISA)
- Application binary interface (ABI)
- Application programming interface (API)
Operating System as Software

- Functions in the same way as ordinary computer software
- Program, or suite of programs, executed by the processor
- Frequently relinquishes control and must depend on the processor to allow it to regain control
Operating System as Resource Manager

Figure 2.2 The Operating System as Resource Manager
Evolution of Operating Systems

- A major OS will evolve over time for a number of reasons:
  - Hardware upgrades
  - New types of hardware
  - New services
  - Fixes
Evolution of Operating Systems

- Stages include:
  - Serial Processing
  - Simple Batch Systems
  - Multiprogrammed Batch Systems
  - Time Sharing Systems
Desirable Hardware Features

- Memory protection for monitor
  - while the user program is executing, it must not alter the memory area containing the monitor

- Timer
  - prevents a job from monopolizing the system

- Privileged instructions
  - can only be executed by the monitor

- Interrupts
  - gives OS more flexibility in controlling user programs
Modes of Operation

User Mode
- user program executes in user mode
- certain areas of memory are protected from user access
- certain instructions may not be executed

Kernel Mode
- monitor executes in kernel mode
- privileged instructions may be executed
- protected areas of memory may be accessed
Challenge: Interaction Despite Isolation

- How to isolate processes and their resources...
  - While permitting them to request help from the kernel
  - Processes interact while maintaining policies such as security, QoS, etc
- Letting processes interact with one another in a controlled way
  - Through messages, shared memory, etc

Enter the System Call interface

- Layer between the hardware and user-space processes
- Programming interface to the services provided by the OS

Mostly accessed by programs via a high-level Application Program Interface (API) rather than directly

Example: Call to `printf()` in the C library leads to a system call
Modes of Operation

- **User Mode**
  - user program executes in user mode
  - certain areas of memory are protected from user access
  - certain instructions may not be executed

- **Kernel Mode**
  - monitor executes in kernel mode
  - privileged instructions may be executed
  - protected areas of memory may be accessed
Uniprogramming

Program A

Run | Wait | Run | Wait

Time

(a) Uniprogramming

Multiprogramming

Program A

Run | Wait | Run | Wait

Program B

Wait | Run | Wait | Run | Wait

Combined

Run A | Run B | Wait | Run A | Run B | Wait

Time

(b) Multiprogramming with two programs
## Effects on Resource Utilization

<table>
<thead>
<tr>
<th></th>
<th>Uniprogramming</th>
<th>Multiprogramming</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processor use</td>
<td>20%</td>
<td>40%</td>
</tr>
<tr>
<td>Memory use</td>
<td>33%</td>
<td>67%</td>
</tr>
<tr>
<td>Disk use</td>
<td>33%</td>
<td>67%</td>
</tr>
<tr>
<td>Printer use</td>
<td>33%</td>
<td>67%</td>
</tr>
<tr>
<td>Elapsed time</td>
<td>30 min</td>
<td>15 min</td>
</tr>
<tr>
<td>Throughput</td>
<td>6 jobs/hr</td>
<td>12 jobs/hr</td>
</tr>
<tr>
<td>Mean response time</td>
<td>18 min</td>
<td>10 min</td>
</tr>
</tbody>
</table>

Table 2.2  Effects of Multiprogramming on Resource Utilization
Utilization Histograms

Figure 2.6 Utilization Histograms
Compatible Time-Sharing Systems

CTSS

- One of the first time-sharing operating systems
- Developed at MIT by a group known as Project MAC
- Ran on a computer with 32,000 36-bit words of main memory, with the resident monitor consuming 5000 of that
- To simplify both the monitor and memory management a program was always loaded to start at the location of the 5000^{th} word

Time Slicing

- System clock generates interrupts at a rate of approximately one every 0.2 seconds
- At each interrupt OS regained control and could assign processor to another user
- At regular time intervals the current user would be preempted and another user loaded in
- Old user programs and data were written out to disk
- Old user program code and data were restored in main memory when that program was next given a turn
CTSS Operation

Figure 2.7 CTSS Operation
Operating Systems are among the most complex pieces of software ever developed. Major advances in development include:

- Processes
- Memory management
- Information protection and security
- Scheduling and resource management
- System structure
Process

- Fundamental to the structure of operating systems

A process can be defined as:

- a program in execution
- an instance of a running program
- the entity that can be assigned to, and executed on, a processor
- a unit of activity characterized by a single sequential thread of execution, a current state, and an associated set of system resources
Development of the Process

- Three major lines of computer system development created problems in timing and synchronization that contributed to the development:

  - **Multiprogramming Batch Operation**
    - Processor is switched among the various programs residing in main memory

  - **Time Sharing**
    - Be responsive to the individual user but be able to support many users simultaneously

  - **Real-time Transaction Systems**
    - Users are entering queries or updates against a database
Causes of Errors

- **Improper synchronization**
  - a program must wait until the data are available in a buffer
  - improper design of the signaling mechanism can result in loss or duplication

- **Failed mutual exclusion**
  - more than one user or program attempts to make use of a shared resource at the same time
  - only one routine at a time allowed to perform an update against the file

- **Nondeterminate program operation**
  - program execution is interleaved by the processor when memory is shared
  - the order in which programs are scheduled may affect their outcome

- **Deadlocks**
  - it is possible for two or more programs to be hung up waiting for each other
  - may depend on the chance timing of resource allocation and release
Components of a Process

- A process contains three components:
  - an executable program
  - the associated data needed by the program (variables, workspace, buffers, etc.)
  - the execution context (or “process state”) of the program

- The execution context is essential:
  - it is the internal data by which the OS is able to supervise and control the process
  - includes the contents of the various process registers
  - includes information such as the priority of the process and whether the process is waiting for the completion of a particular I/O event
Process Management

- The entire state of the process at any instant is contained in its context
- New features can be designed and incorporated into the OS by expanding the context to include any new information needed to support the feature

Figure 2.8 Typical Process Implementation
Memory Management

- The OS has **five** principal storage management responsibilities:
  - Process isolation
  - Automatic allocation and management
  - Support of modular programming
  - Protection and access control
  - Long-term storage
Virtual Memory

- A facility that allows programs to address memory from a logical point of view, without regard to the amount of main memory physically available.

- Conceived to meet the requirement of having multiple user jobs reside in main memory concurrently.
Paging

- Allows processes to be comprised of a number of fixed-size blocks, called pages
- Program references a word by means of a virtual address
  - consists of a page number and an offset within the page
  - each page may be located anywhere in main memory
- Provides for a dynamic mapping between the virtual address used in the program and a real (or physical) address in main memory
Virtual Memory

- A facility that allows programs to address memory from a logical point of view, without regard to the amount of main memory physically available

- Conceived to meet the requirement of having multiple user jobs reside in main memory concurrently
Virtual Memory Addressing

Figure 2.10 Virtual Memory Addressing
Information Protection and Security

- The nature of the threat that concerns an organization will vary greatly depending on the circumstances.

- The problem involves controlling access to computer systems and the information stored in them.

Main issues
- availability
- confidentiality
- data integrity
- authenticity
Key Elements of an Operating System

Figure 2.11 Key Elements of an Operating System for Multiprogramming
Different Architectural Approaches

Demands on operating systems require new ways of organizing the OS

Different approaches and design elements have been tried:

- Microkernel architecture
- Multithreading
- Symmetric multiprocessing
- Distributed operating systems
- Object-oriented design
Microkernel Architecture

- Assigns only a few essential functions to kernel:
  - address spaces
  - interprocess communication (IPC)
  - basic scheduling

- The approach:
  - simplifies implementation
  - provides flexibility
  - is well suited to a distributed environment
Multithreading

Technique in which a process, executing an application, is divided into threads that can run concurrently

**Thread**
- dispatchable unit of work
- includes a processor context and its own data area to enable subroutine branching
- executes sequentially and is interruptible

**Process**
- a collection of one or more threads and associated system resources
- programmer has greater control over the modularity of the application and the timing of application related events
Symmetric Multiprocessing (SMP)

- Term that refers to a computer hardware architecture and also to the OS behavior that exploits that architecture
- Several processes can run in parallel
- Multiple processors are transparent to the user
  - these processors share same main memory and I/O facilities
  - all processors can perform the same functions
- The OS takes care of scheduling of threads or processes on individual processors and of synchronization among processors
SMP Advantages

Performance: more than one process can be running simultaneously, each on a different processor.

Availability: failure of a single process does not halt the system.

Incremental Growth: performance of a system can be enhanced by adding an additional processor.

Scaling: vendors can offer a range of products based on the number of processors configured in the system.
Multiprogramming

(a) Interleaving (multiprogramming, one processor)

(b) Interleaving and overlapping (multiprocessing; two processors)

Figure 2.12 Multiprogramming and Multiprocessing
OS Design

**Distributed Operating System**
- Provides the illusion of
  - a single main memory space
  - single secondary memory space
  - unified access facilities
- State of the art for distributed operating systems lags that of uniprocessor and SMP operating systems

**Object-Oriented Design**
- Used for adding modular extensions to a small kernel
- Enables programmers to customize an operating system without disrupting system integrity
- Eases the development of distributed tools and full-blown distributed operating systems
Virtual Machines and Virtualization

- Virtualization
  - enables a single PC or server to simultaneously run multiple operating systems or multiple sessions of a single OS
  - a machine can host numerous applications, including those that run on different operating systems, on a single platform
  - host operating system can support a number of virtual machines (VM)
    - each has the characteristics of a particular OS and, in some versions of virtualization, the characteristics of a particular hardware platform
Virtual Memory Concept

Figure 2.13  Virtual Memory Concept
Virtual Machine Architecture

**Process perspective:**
- the machine on which it executes consists of the virtual memory space assigned to the process
- the processor registers it may use
- the user-level machine instructions it may execute
- OS system calls it may invoke for I/O
- ABI defines the machine as seen by a process

**Application perspective:**
- machine characteristics are specified by high-level language capabilities and OS system library calls
- API defines the machine for an application

**OS perspective:**
- processes share a file system and other I/O resources
- system allocates real memory and I/O resources to the processes
- ISA provides the interface between the system and machine
Process and System Virtual Machines

Figure 2.14  Process and System Virtual Machines
Process and System Virtual Machines

Figure 2.14 Process and System Virtual Machines
SMP OS Considerations

- A multiprocessor OS must provide all the functionality of a multiprogramming system plus additional features to accommodate multiple processors

- **Key design issues:**
  - The design challenge for a many-core multicore system is to efficiently harness the multicore processing power and intelligently manage the substantial on-chip resources efficiently
Virtual Machine Approach

- Allows one or more cores to be dedicated to a particular process and then leave the processor alone to devote its efforts to that process.

- Multicore OS could then act as a hypervisor that makes a high-level decision to allocate cores to applications but does little in the way of resource allocation beyond that.
Description of UNIX
Traditional UNIX Kernel
Monolithic Structure: UNIX System Structure

<table>
<thead>
<tr>
<th>User Mode</th>
<th>Kernel Mode</th>
<th>Hardware</th>
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<tbody>
<tr>
<td>Applications</td>
<td>(the users)</td>
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<tr>
<td>Standard Libs</td>
<td>shells and commands</td>
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<td>compilers and interpreters</td>
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<td>system libraries</td>
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<td>User Mode</td>
<td>Kernel Mode</td>
<td>Hardware</td>
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<tr>
<td>kernel interface to the hardware</td>
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<td>system-call interface to the kernel</td>
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<td>signals terminal handling</td>
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<td>character I/O system</td>
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<td>terminal drivers</td>
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<td>file system swapping</td>
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<td>block I/O system</td>
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<td>disk and tape drivers</td>
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<td>CPU scheduling</td>
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<td>page replacement</td>
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<td>demand paging</td>
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<td>virtual memory</td>
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<td>terminal controllers</td>
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<td>terminals</td>
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<td>device controllers</td>
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<td>disks and tapes</td>
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<td></td>
<td>memory controllers</td>
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<tr>
<td></td>
<td>physical memory</td>
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</tbody>
</table>

- **Two-Layered Structure: User vs Kernel**
  - All code representing protection and management of resources placed in same address space
  - Compromise of one component can compromise whole OS
Modern UNIX Kernel
Microkernel Structure

• Moves functionality from the kernel into "user" space
  – Small core OS running at kernel level
  – OS Services built from many independent user-level processes
  – Communication between modules with message passing

• Benefits:
  – Easier to extend
  – Easier to port OS to new architectures
  – More reliable (less code is running in kernel mode)
  – Fault Isolation (parts of kernel protected from other parts)
  – More secure

• Detriments:
  – Performance overhead can be severe for naïve implementation
• Most modern operating systems implement modules
  – Uses object-oriented approach
    » careful API design/Few if any global variables
• 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
  – May or may not utilize hardware enforcement
ExoKernel: Separate Protection from Management

• Thin layer exports hardware resources directly to users
  – As little abstraction as possible
  – Secure Protection and Multiplexing of resources
• LibraryOS: traditional OS functionality at User-Level
  – Customize resource management for every application
  – Is this a practical approach?
• Very low-level abstraction layer
  – Need extremely specialized skills to develop LibraryOS
Linux Kernel Components
Split monolithic scheduling into two pieces:

- Course-Grained Resource Allocation and Distribution to Cells
  - Chunks of resources (CPUs, Memory Bandwidth, QoS to Services)
  - Ultimately a hierarchical process negotiated with service providers

- Fine-Grained (User-Level) Application-Specific Scheduling
  - Applications allowed to utilize their resources in any way they see fit
  - Performance Isolation: Other components of the system cannot interfere with Cells use of resources
Concurrencey

• “Thread” of execution
  – Independent Fetch/Decode/Execute loop
  – Operating in some Address space

• Uniprogramming: *one thread at a time*
  – MS/DOS, early Macintosh, Batch processing
  – Easier for operating system builder
  – Get rid concurrency by defining it away
  – Does this make sense for personal computers?

• Multiprogramming: *more than one thread at a time*
  – Multics, UNIX/Linux, OS/2, Windows NT/2000/XP, Mac OS X
  – Often called “multitasking”, but multitasking has other meanings (talk about this later)
How can we give the illusion of multiple processors?

• Assume a single processor. How do we provide the illusion of multiple processors?
  – Multiplex in time!

• **Each virtual “CPU” needs a structure to hold:**
  – Program Counter (PC), Stack Pointer (SP)
  – Registers (Integer, Floating point, others...?)
  – Call result a “Thread” for now...

• **How switch from one CPU to the next?**
  – Save PC, SP, and registers in current state block
  – Load PC, SP, and registers from new state block

• **What triggers switch?**
  – Timer, voluntary yield, I/O, other things
Properties of this simple multiprogramming technique

• All virtual CPUs share same non-CPU resources
  – I/O devices the same
  – Memory the same

• Consequence of sharing:
  – Each thread can access the data of every other thread (good for sharing, bad for protection)
  – Threads can share instructions (good for sharing, bad for protection)
  – Can threads overwrite OS functions?

• This (unprotected) model common in:
  – Embedded applications
  – Windows 3.1/Machintosh (switch only with yield)
What needs to be saved in Modern X86?

64-bit Register Set

Also: 6 segment registers, control, status, debug, more Address Space

Legacy x86 registers
New x64 registers
Instruction Pointer/Flags

RIP
RFLAGS

EFLAGS Register

Traditional 32-bit subset

General-Purpose Registers

31 16 15 8 7 0 16-bit 32-bit
AH AL
BH BL
CH CL
CX ECX
DX EDX
EBP
SI
DI
SP

EFLAGS

80-bit floating point and 64-bit MMX registers (overlaid)

80-bit floating point
and 64-bit MMX registers (overlaid)
Modern Technique: SMT/Hyperthreading

- **Hardware technique**
  - Exploit natural properties of superscalar processors to provide illusion of multiple processors
  - Higher utilization of processor resources

- **Can schedule each thread as if were separate CPU**
  - However, not linear speedup!
  - If have multiprocessor, should schedule each processor first

- **Original technique called “Simultaneous Multithreading”**
  - See http://www.cs.washington.edu/research/smt/
  - Alpha, SPARC, Pentium 4 (“Hyperthreading”), Power 5
How to protect threads from one another?

- Need three important things:
  1. Protection of memory
     » Every task does not have access to all memory
  2. Protection of I/O devices
     » Every task does not have access to every device
  3. Protection of Access to Processor:
     Preemptive switching from task to task
     » Use of timer
     » Must not be possible to disable timer from usercode
Program’s Address Space

- **Address space** is the set of accessible addresses + state associated with them:
  - For a 32-bit processor there are $2^{32} = 4$ billion addresses

- **What happens when you read or write to an address?**
  - Perhaps Nothing
  - Perhaps acts like regular memory
  - Perhaps ignores writes
  - Perhaps causes I/O operation
    » (Memory-mapped I/O)
  - Perhaps causes exception (fault)
Providing Illusion of Separate Address Space: Load new Translation Map on Switch

Translation Map 1

Translation Map 2

Physical Address Space
X86 Memory model with segmentation
How do we multiplex processes?

• The current state of process held in a process control block (PCB):
  – This is a “snapshot” of the execution and protection environment
  – Only one PCB active at a time

• Give out CPU time to different processes (Scheduling):
  – Only one process “running” at a time
  – Give more time to important processes

• Give pieces of resources to different processes (Protection):
  – Controlled access to non-CPU resources
  – Sample mechanisms:
    » Memory Mapping: Give each process their own address space
    » Kernel/User duality: Arbitrary multiplexing of I/O through system calls

<table>
<thead>
<tr>
<th>process state</th>
<th>process number</th>
<th>program counter</th>
</tr>
</thead>
<tbody>
<tr>
<td>registers</td>
<td>memory limits</td>
<td>list of open files</td>
</tr>
</tbody>
</table>
CPU Switch From Process to Process

- This is also called a “context switch”
- Code executed in kernel above is overhead
  - Overhead sets minimum practical switching time
  - Less overhead with SMT/hyperthreading, but... contention for resources instead
• PCBs move from queue to queue as they change state
  – Decisions about which order to remove from queues are **Scheduling** decisions
  – Many algorithms possible