Recall: What is an operating system?

- Special layer of software that provides application software access to hardware resources
  - Convenient abstraction of complex hardware devices
  - Protected access to shared resources
  - Security and authentication
  - Communication amongst logical entities

Review: What is an Operating System?

- Referee
  - Manage sharing of resources, Protection, Isolation
    - Resource allocation, isolation, communication

- Illusionist
  - Provide clean, easy to use abstractions of physical resources
    - Infinite memory, dedicated machine
    - Higher level objects: files, users, messages
    - Masking limitations, virtualization

- Glue
  - Common services
    - Storage, Window system, Networking
    - Sharing, Authorization
    - Look and feel

Review: Increasing Software Complexity

From MIT's 6.033 course
Recall: Loading

Very Brief History of OS

- Several Distinct Phases:
  - Hardware Expensive, Humans Cheap
    » Eniac, ... Multics
  - Hardware Cheaper, Humans Expensive
    » PCs, Workstations, Rise of GUIs
  - Hardware Really Cheap, Humans Really Expensive
    » Ubiquitous devices, Widespread networking

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- Rapid Change in Hardware Leads to changing OS
  - Batch ⇒ Multiprogramming ⇒ Timesharing ⇒ Graphical UI ⇒ Ubiquitous Devices
  - Gradual Migration of Features into Smaller Machines

- Situation today is much like the late 60s
  - Small OS: 100K lines/Large: 10M lines (5M browser!)
  - 100-1000 people-years

---

**OS Archaeology**

- Because of the cost of developing an OS from scratch, most modern OSes have a long lineage:

  - Multics → AT&T Unix → BSD Unix → Ultrix, SunOS, NetBSD,...
  - Mach (micro-kernel) + BSD → NextStep → XNU → Apple OSX, iphone iOS
  - Linux → Android OS
  - CP/M → QDOS → MS-DOS → Windows 3.1 → NT → 95 → 98 → 2000 → XP → Vista → 7 → 8 → phone → ...
  - Linux → RedHat, Ubuntu, Fedora, Debian, Suse,...

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**Migration of OS Concepts and Features**

- Thread
  - Single unique execution context
  - Program Counter, Registers, Execution Flags, Stack

- Address Space w/ Translation
  - Programs execute in an *address space* that is distinct from the memory space of the physical machine

- Process
  - An instance of an executing program is a *process* consisting of an *address space* and one or more threads of control

- Dual Mode operation/Protection
  - Only the “system” has the ability to access certain resources
  - The OS and the hardware are protected from user programs and user programs are isolated from one another by controlling the translation from program virtual addresses to machine physical addresses

---

**Today: Four fundamental OS concepts**

- Thread
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OS Bottom Line: Run Programs

- Load instruction and data segments of executable file into memory
- Create stack and heap
- "Transfer control to it"
- Provide services to it
- While protecting OS and it

Recall (61C): What happens during program execution?

Execution sequence:
- Fetch Instruction at PC
- Decode
- Execute (possibly using registers)
- Write results to registers/mem
- PC = Next Instruction(PC)
- Repeat

Thread: Single unique execution context
- Program Counter, Registers, Execution Flags, Stack
- A thread is executing on a processor when it is resident in the processor registers.
- PC register holds the address of executing instruction in the thread.
- Certain registers hold the context of thread
  - Stack pointer holds the address of the top of stack
  - Other conventions: Frame Pointer, Heap Pointer, Data
- May be defined by the instruction set architecture or by compiler conventions
- Registers hold the root state of the thread.
  - The rest is "in memory"
Second OS Concept: Program’s Address Space

- Address space \( \Rightarrow \) the set of accessible addresses + state associated with them:
  - For a 32-bit processor there are \( 2^{32} = 4 \text{ billion} \) 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)

Address Space: In a Picture

- What’s in the code segment? Data?
- What’s in the stack segment?
  - How is it allocated? How big is it?
- What’s in the heap segment?
  - How is it allocated? How big?

Multiprogramming - Multiple Threads of Control

- Start homework 0 immediately \( \Rightarrow \) Due on Friday!
  - Gets `cs162-xx@cory.eecs.berkeley.edu` (and other inst m/c)
  - Github account
  - Registration survey
  - Vagrant virtualbox - VM environment for the course
    » Consistent, managed environment on your machine
  - icluster24.eecs.berkeley.edu is same
  - Get familiar with all the cs162 tools
  - Submit to autograder via git
- Should be going to section already!
- Group sign up form out next week (after drop deadline)
  - Get finding groups ASAP
  - 4 people in a group!
**Administrivia (Con’t)**

- **Upcoming Workshops on Git: From Hackers@Berkeley**
  - Introductory and advanced
  - Details on Piazza (link to Facebook announcement)
- **Kubiatowicz Office Hours:**
  - 2pm–3pm, Monday/Wednesday
  - May change as need arises (still have a bit of fluidity here as well)
- **Online Textbooks:**
  - Click on “Projects” link, under “Resources”, there is a pointer to “Online Textbooks”
  - Can read these for free as long as on campus
  - First ones: Book on Git, two books on C
- **Webcast:**
  - We are webcasting this class
  - Will put link up off main page, but for now, go to:
    » webcast.Berkeley.edu, click on “computer science” department
  - Webcast is *NOT* a replacement for coming to class!

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**CS 162 Collaboration Policy**

- Explaining a concept to someone in another group
- Discussing algorithms/testing strategies with other groups
- Helping debug someone else’s code (in another group)
- Searching online for generic algorithms (e.g., hash table)

**Sharing code or test cases with another group**

**Copying OR reading another group’s code or test cases**

**Copying OR reading online code or test cases from from prior years**

We compare all project submissions against prior year submissions and online solutions and will take actions (described on the course overview page) against offenders.

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**How can we give the illusion of multiple processors?**

![Diagram of virtual CPUs and shared memory]

- 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...?)
- How switch from one virtual 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

---

**The Basic Problem of Concurrency**

- The basic problem of concurrency involves resources:
  - Hardware: single CPU, single DRAM, single I/O devices
  - Multiprogramming API: processes think they have exclusive access to shared resources
- OS has to coordinate all activity
  - Multiple processes, I/O interrupts, ...
  - How can it keep all these things straight?
- Basic Idea: Use Virtual Machine abstraction
  - Simple machine abstraction for processes
  - Multiplex these abstract machines
- Dijkstra did this for the “THE system”
  - Few thousand lines vs 1 million lines in OS 360 (1K bugs)
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 is common in:
  - Embedded applications
  - Windows 3.1/Early Macintosh (switch only with yield)
  - Windows 95—ME (switch with both yield and timer)

Third OS Concept: Process

- Process: execution environment with Restricted Rights
  - Address Space with One or More Threads
  - Owns memory (address space)
  - Owns file descriptors, file system context, ...
  - Encapsulate one or more threads sharing process resources
- Why processes?
  - Protected from each other!
  - OS Protected from them
  - Navigate fundamental tradeoff between protection and efficiency
  - Processes provides memory protection
  - Threads more efficient than processes (later)
- Application instance consists of one or more processes

Protection

- Operating System must protect itself from user programs
  - Reliability: compromising the operating system 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
- It must protect User programs from one another
- Primary Mechanism: limit the translation from program address space to physical memory space
  - Can only touch what is mapped in
- Additional Mechanisms:
  - Privileged instructions, in/out instructions, special registers
  - syscall processing, subsystem implementation
    » (e.g., file access rights, etc)

Fourth OS Concept: Dual Mode Operation

- Hardware provides at least two modes:
  - "Kernel" mode (or "supervisor" or "protected")
  - "User" mode: Normal programs executed
- What is needed in the hardware to support "dual mode" operation?
  - a bit of state (user/system mode bit)
  - Certain operations / actions only permitted in system/kernel mode
    » In user mode they fail or trap
  - User->Kernel transition sets system mode AND saves the user PC
    » Operating system code carefully puts aside user state then performs the necessary operations
  - Kernel->User transition clears system mode AND restores appropriate user PC
    » return-from-interrupt
For example: UNIX System Structure

**User Mode**
- Applications (the users)
- Standard Libs (shells and commands, compilers and interpreters, system libraries)

**Kernel Mode**
- Kernel
  - Signals terminal handling
  - Character I/O system
  - Terminal drivers
- File system
- Swapping block I/O
- Disk and tape drivers
- CPU scheduling
- Page replacement
- Demand paging
- Virtual memory

**Hardware**
- Terminal controllers
- Terminals
- Device controllers
- Disks and tapes
- Memory controllers
- Physical memory

---

User/Kernal (Privileged) Mode

- **User Mode**
  - exec
  - syscall
  - exit
  - rtn
  - rfi
  - exception

- **Kernel Mode**
  - Limited HW access
  - Full HW access

---

Simple Protection: Base and Bound (B&B)

- Base
  - 0000...
  - 1000...
  - 1100...
  - FFFF...

- Bound
  - 0x000...
  - 0xFFF...
  - 0x000...
  - 0xFFF...

- Requires relocating loader
- Still protects OS and isolates pgm
- No addition on address path

---

Another idea: Address Space Translation

- Program operates in an address space that is distinct from the physical memory space of the machine
A simple address translation with Base and Bound

- Can the program touch OS?
- Can it touch other programs?

Tying it together: Simple B&B: OS loads process

Simple B&B: OS gets ready to switch

Simple B&B: "Return" to User
3 types of Mode Transfer

- **Syscall**
  - Process requests a system service, e.g., exit
  - Like a function call, but “outside” the process
  - Does not have the address of the system function to call
  - Like a Remote Procedure Call (RPC) - for later
  - Marshall the syscall id and args in registers and exec syscall

- **Interrupt**
  - External asynchronous event triggers context switch
  - e.g., Timer, I/O device
  - Independent of user process

- **Trap or Exception**
  - Internal synchronous event in process triggers context switch
  - e.g., Protection violation (segmentation fault), Divide by zero, ...

- **All 3 are an UNPROGRAMMED CONTROL TRANSFER**
  - Where does it go?

How do we get the system target address of the "unprogrammed control transfer?"

**Interrupt Vector**

- Where else do you see this dispatch pattern?

**Simple B&B: User => Kernel**

- How to return to system?
Simple B&B: Interrupt

- How to save registers and set up system stack?

Simple B&B: Switch User Process

- How to save registers and set up system stack?

Simple B&B: "resume"

- How to save registers and set up system stack?

What's wrong with this simplistic address translation mechanism?
Virtual Address Translation

- Simpler, more useful schemes too!
- Give every process the illusion of its own BIG FLAT ADDRESS SPACE
  - Break it into pages
  - More on this later

Running Many Programs ???

- We have the basic mechanism to
  - switch between user processes and the kernel,
  - the kernel can switch among user processes,
  - Protect OS from user processes and processes from each other

- Questions ???
  - How do we decide which user process to run?
  - How do we represent user processes in the OS?
  - How do we pack up the process and set it aside?
  - How do we get a stack and heap for the kernel?
  - Aren’t we wasting are lot of memory?
  - …
Process Control Block

- Kernel represents each process as a process control block (PCB)
  - Status (running, ready, blocked, ...)
  - Register state (when not ready)
  - Process ID (PID), User, Executable, Priority, ...
  - Execution time, ...
  - Memory space, translation, ...
- Kernel Scheduler maintains a data structure containing the PCBs
- Scheduling algorithm selects the next one to run

Scheduler

if ( readyProcesses(PCBs) )
    nextPCB = selectProcess(PCBs);
    run( nextPCB );
} else {
    run_idle_process();
}

Putting it together: web server

Digging Deeper: Discussion & Questions
Simultaneous MultiThreading/Hyperthreading

- Hardware technique
  - Superscalar processors can execute multiple instructions that are independent.
  - Hyperthreading duplicates register state to make a second “thread,” allowing more instructions to run.
- Can schedule each thread as if were separate CPU
  - But, sub-linear speedup!
- Original technique called “Simultaneous Multithreading”
  - SPARC, Pentium 4/Xeon ("Hyperthreading"), Power 5

Implementing Safe Mode Transfers

- Carefully constructed kernel code packs up the user process state an sets it aside.
  - Details depend on the machine architecture
- Should be impossible for buggy or malicious user program to cause the kernel to corrupt itself.
- Interrupt processing not be visible to the user process:
  - Occurs between instructions, restarted transparently
  - No change to process state
  - What can be observed even with perfect interrupt processing?

Kernel Stack Challenge

- Kernel needs space to work
- Cannot put anything on the user stack (Why?)
- Two-stack model
  - OS thread has interrupt stack (located in kernel memory) plus User stack (located in user memory)
  - Syscall handler copies user args to kernel space before invoking specific function (e.g., open)
- Interrupts (???)

Hardware support: Interrupt Control

- Interrupt Handler invoked with interrupts ‘disabled’
  - Re-enabled upon completion
  - Non-blocking (run to completion, no waits)
  - Pack it up in a queue and pass off to an OS thread to do the hard work
    » wake up an existing OS thread
- OS kernel may enable/disable interrupts
  - On x86: CLI (disable interrupts), STI (enable)
  - Atomic section when select next process/thread to run
  - Atomic return from interrupt or syscall
- HW may have multiple levels of interrupt
  - Mask off (disable) certain interrupts, eg., lower priority
  - Certain non-maskable-interrupts (nmi)
    » e.g., kernel segmentation fault
How do we take interrupts safely?

- **Interrupt vector**
  - Limited number of entry points into kernel
- **Kernel interrupt stack**
  - Handler works regardless of state of user code
- **Interrupt masking**
  - Handler is non-blocking
- **Atomic transfer of control**
  - "Single instruction"-like to change:
    - Program counter
    - Stack pointer
    - Memory protection
    - Kernel/user mode
- **Transparent restartable execution**
  - User program does not know interrupt occurred

Before

User-level Process

Registers

Kernel

code:

```
foo ()
  while(...) {
    x=x+1;
    y=y-2;
  }
```

stack:

![Before Diagram]

During

Kernel System Call Handler

- **Locate arguments**
  - In registers or on user(!) stack
- **Copy arguments**
  - From user memory into kernel memory
  - Protect kernel from malicious code evading checks
- **Validate arguments**
  - Protect kernel from errors in user code
- **Copy results back**
  - into user memory

![During Diagram]
Multiprocessors - Multicores - Multiple Threads

- What do we need to support Multiple Threads
  - Multiple kernel threads?
  - Multiple user threads in a process?
- What if we have multiple Processors / Cores

Idle Loop & Power

- Measly do-nothing unappreciated trivial piece of code that is central to low-power

Performance

- Performance = Operations / Time

- How can the OS ruin application performance?
- What can the OS do to increase application performance?

Conclusion: Four fundamental OS concepts

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