CS140 – Operating Systems

Instructor: David Mazières

CAs: Collin Lee, Yilong Li, and Sarah Tollman

Stanford University

Outline

1. Administrivia
2. Substance

Administrivia

- **Class web page:** `http://cs140.scs.stanford.edu/`
  - All assignments, handouts, lecture notes on-line
- **Textbook:** ***Operating System Concepts, 8th Edition*, by Silberschatz, Galvin, and Gagne**
  - Trying to ween class from textbook, so highly optional
- **Goal is to make lecture slides the primary reference**
  - Almost everything I talk about will be on slides
  - PDF slides contain links to further reading about topics
  - Please download slides from class web page
  - Will try to post before lecture for taking notes (but avoid calling out answers if you read them from slides)

Administrivia 2

- **Google group 20wi-cs140 is main discussion forum**
- **Staff mailing list:** `cs140-staff@scs.stanford.edu`
  - Please use google group for questions other people might have
  - Otherwise, please mail staff list, not individual instructors
- **Key dates:**
  - Lectures: MW 1:30pm–2:50pm, Gates B03
  - Section: 6 Fridays, time/location TBD, starting this Friday
  - Midterm exam: Wednesday, February 12, 1:30–2:50pm (in class)
  - Final exam: Wednesday, March 18th, 3:30pm-6:30pm
- **Exams open note, but not open book**
  - Bring notes, slides, any printed materials *except* textbook
  - No electronic devices permitted

Lecture videos

- **Lectures will be televised for SCPD students**
  - Can also watch if you miss a lecture, or to review
  - But resist temptation to miss a bunch of lectures and watch them all at once
- **SCPD students welcome to attend lecture in person**
- **Other notes for SCPD students:**
  - Please attend exams in person if possible
  - Feel free to use google group to find project partners

Course topics

- **Threads & Processes**
- **Concurrency & Synchronization**
- **Scheduling**
- **Virtual Memory**
- **I/O**
- **Disks, File systems**
- **Protection & Security**
- **Virtual machines**
- **Note: Lectures will often take Unix as an example**
  - Most current and future OSes heavily influenced by Unix
  - Won't talk much about Windows

Course goals

- **Introduce you to operating system concepts**
  - Hard to use a computer without interacting with OS
  - Understanding the OS makes you a more effective programmer
- **Cover important systems concepts in general**
  - Caching, concurrency, memory management, I/O, protection
- **Teach you to deal with larger software systems**
  - Programming assignments much larger than many courses
  - Warning: Many people will consider course very hard
  - In past, majority of people report $\geq$15 hours/week
- **Prepare you to take graduate OS classes (CS240, 240[a-z])**

Programming Assignments

- **Implement parts of Pintos operating system**
  - Built for x86 hardware, you will use hardware emulators
- **One setup homework (lab 0) due this Friday**
- **Four implementation projects:**
  - Threads
  - User processes
  - Virtual memory
  - File system
- **Lab 1 distributed at end of this week**
  - Attend section this Friday for project 1 overview
- **Implement projects in groups of up to 3 people**
  - Pick your partners today (lecture may end early for this)
  - Please disclose if you are planning to take class pass/fail

Grading

- **No incompletes**
  - Talk to instructor ASAP if you run into real problems
- **Final grades posted March 24**
- **50% of grade based on exams using this quantity:**
  $\max\left(\textbf{midterm} > 0\ ?\ \textbf{final} : 0, \frac{1}{2}\left(\textbf{midterm} + \textbf{final}\right)\right)$
- **50% of grade from projects**
  - For each project, 50% of score based on passing test cases
  - Remaining 50% based on design and style
- **Most people's projects pass most test cases**
  - Please, please, please turn in working code, or **no credit** here
- **Means design and style matter a lot**
  - Large software systems not just about producing working code
  - Need to produce code other people can understand
  - That's why we have group projects

Style

- **Must turn in a design document along with code**
  - We supply you with templates for each project's design doc
- **CAs will manually inspect code for correctness**
  - E.g., must actually implement the design
  - Must handle corner cases (e.g., handle `malloc` failure)
- **Will deduct points for error-prone code w/o errors**
  - Don't use global variables if automatic ones suffice
  - Don't use deceptive names for variables
- **Code must be easy to read**
  - Indent code, keep lines and (when possible) functions short
  - Use a uniform coding style (try to match existing code)
  - Put comments on structure members, globals, functions
  - Don't leave in reams of commented-out garbage code

Assignment requirements

- **Do not look at other people's solutions to projects**
  - We reserve the right to run MOSS on present and past submissions
  - Do not publish your own solutions in violation of the honor code
  - That means using (public) github can get you in big trouble
- **You may read but not copy other OSes**
  - E.g., Linux, OpenBSD/FreeBSD, etc.
- **Cite any code that inspired your code**
  - As long as you cite what you used, it's not cheating
  - In worst case, we deduct points if it undermines the assignment
- **Projects due Fridays (before section—TBD)**
- **Ask `cs140-staff` for extension if you run into trouble**
  - Be sure to tell us: How much have you done? How much is left? When can you finish by?

Outline

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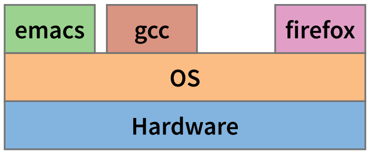
What is an operating system?

- **Layer between applications and hardware**



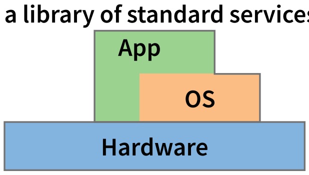
- **Makes hardware useful to the programmer**
- **[Usually] Provides abstractions for applications**
  - Manages and hides details of hardware
  - Accesses hardware through low/level interfaces unavailable to applications
- **[Often] Provides protection**
  - Prevents one process/user from clobbering another

Why study operating systems?

- **Operating systems are a mature field**
  - Most people use a handful of mature OSes
  - Hard to get people to switch operating systems
  - Hard to have impact with a new OS
- **Still open questions in operating systems**
  - Security – Hard to achieve security without a solid foundation
  - Scalability – How to adapt concepts when hardware scales 10× (fast networks, low service times, high core counts, big data…)
- **High-performance servers are an OS issue**
  - Face many of the same issues as OSes, sometimes bypass OS
- **Resource consumption is an OS issue**
  - Battery life, radio spectrum, etc.
- **New "smart" devices need new OSes**

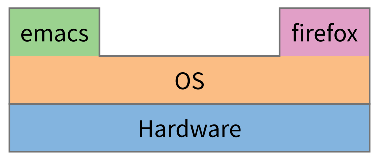
Primitive Operating Systems

- **Just a library of standard services [no protection]**



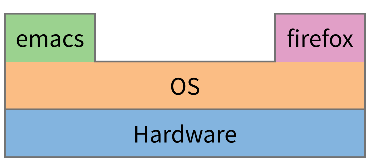
  - Standard interface above hardware-specific drivers, etc.
- **Simplifying assumptions**
  - System runs one program at a time
  - No bad users or programs (often bad assumption)
- **Problem: Poor utilization**
  - …of hardware (e.g., CPU idle while waiting for disk)
  - …of human user (must wait for each program to finish)

Multitasking



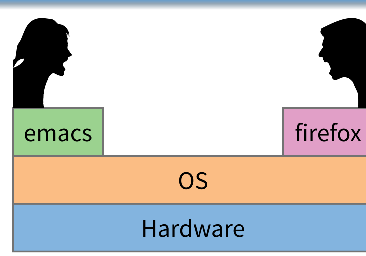
- **Idea: More than one process can be running at once**
  - When one process blocks (waiting for disk, network, user input, etc.) run another process
- **Problem: What can ill-behaved process do?**

Multitasking



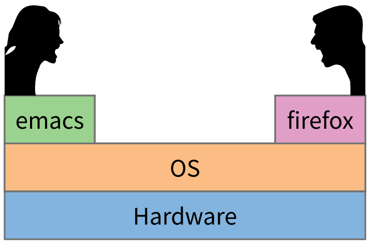
- **Idea: More than one process can be running at once**
  - When one process blocks (waiting for disk, network, user input, etc.) run another process
- **Problem: What can ill-behaved process do?**
  - Go into infinite loop and never relinquish CPU
  - Scribble over other processes' memory to make them fail
- **OS provides mechanisms to address these problems**
  - *Preemption* – take CPU away from looping process
  - *Memory protection* – protect process's memory from one another

Multi-user OSes



- **Many OSes use *protection* to serve distrustful users/apps**
- **Idea: With *N* users, system not *N* times slower**
  - Users' demands for CPU, memory, etc. are bursty
  - Win by giving resources to users who actually need them
- **What can go wrong?**

Multi-user OSes

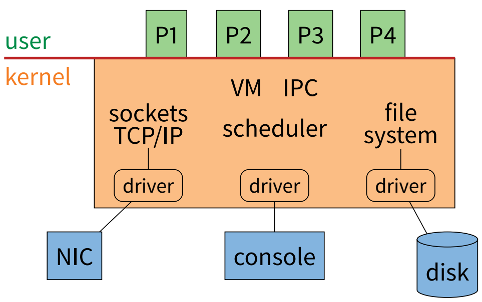


- **Many OSes use *protection* to serve distrustful users/apps**
- **Idea: With *N* users, system not *N* times slower**
  - Users' demands for CPU, memory, etc. are bursty
  - Win by giving resources to users who actually need them
- **What can go wrong?**
  - Users are gluttons, use too much CPU, etc. (need policies)
  - Total memory usage greater than machine's RAM (must virtualize)
  - Super-linear slowdown with increasing demand (thrashing)

Protection

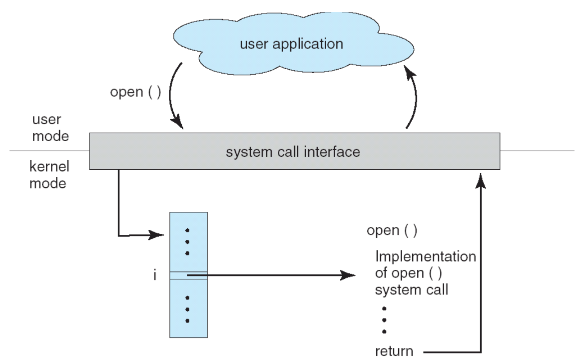
- **Mechanisms that isolate bad programs and people**
- **Pre-emption:**
  - Give application a resource, take it away if needed elsewhere
- **Interposition/mediation:**
  - Place OS between application and "stuff"
  - Track all pieces that application allowed to use (e.g., in table)
  - On every access, look in table to check that access legal
- **Privileged & unprivileged modes in CPUs:**
  - Applications unprivileged (unprivileged *user* mode)
  - OS privileged (privileged supervisor/*kernel* mode)
  - Protection operations can only be done in privileged mode

Typical OS structure



- **Most software runs as user-level processes (P[1-4])**
  - process ≈ instance of a program
- **OS *kernel* runs in *privileged* mode (orange)**
  - Creates/deletes processes
  - Provides access to hardware

System calls

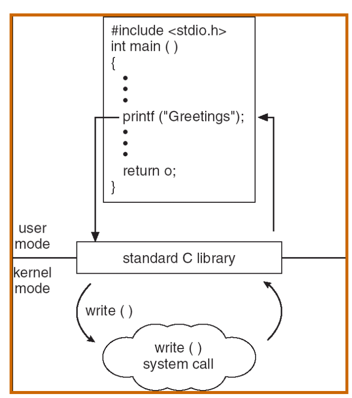


- **Applications can invoke kernel through *system calls***
  - Special instruction transfers control to kernel
  - ...which dispatches to one of few hundred syscall handlers

System calls (continued)

- **Goal: Do things application can't do in unprivileged mode**
  - Like a library call, but into more privileged kernel code
- **Kernel supplies well-defined *system call* interface**
  - Applications set up syscall arguments and *trap* to kernel
  - Kernel performs operation and returns result
- **Higher-level functions built on syscall interface**
  - `printf`, `scanf`, `fgets`, etc. all user-level code
- **Example: POSIX/UNIX interface**
  - `open`, `close`, `read`, `write`, ...

System call example



- **Standard library implemented in terms of syscalls**
  - *printf* – in libc, has same privileges as application
  - calls *write* – in kernel, which can send bits out serial port

UNIX file system calls

- Applications "open" files (or devices) by name
  - I/O happens through open files
- `int open(char *path, int flags, /*int mode*/...);`
  - `flags`: `O_RDONLY`, `O_WRONLY`, `O_RDWR`
  - `O_CREAT`: create the file if non-existent
  - `O_EXCL`: (w. `O_CREAT`) create if file exists already
  - `O_TRUNC`: Truncate the file
  - `O_APPEND`: Start writing from end of file
  - `mode`: final argument with `O_CREAT`
- Returns file descriptor—used for all I/O to file

Error returns

- What if `open` fails? Returns -1 (invalid fd)
- Most system calls return -1 on failure
  - Specific kind of error in global int `errno`
- `#include <sys/errno.h>` for possible values
  - 2 = `ENOENT` "No such file or directory"
  - 13 = `EACCES` "Permission Denied"
- `perror` function prints human-readable message
  - `perror ("initfile");`
    → "`initfile: No such file or directory`"

Operations on file descriptors

- `int read (int fd, void *buf, int nbytes);`
  - Returns number of bytes read
  - Returns 0 bytes at end of file, or -1 on error
- `int write (int fd, const void *buf, int nbytes);`
  - Returns number of bytes written, -1 on error
- `off_t lseek (int fd, off_t pos, int whence);`
  - `whence`: 0 – start, 1 – current, 2 – end
    - Returns previous file offset, or -1 on error
- `int close (int fd);`

File descriptor numbers

- File descriptors are inherited by processes
  - When one process spawns another, same fds by default
- Descriptors 0, 1, and 2 have special meaning
  - 0 – "standard input" (`stdin` in ANSI C)
  - 1 – "standard output" (`stdout`, `printf` in ANSI C)
  - 2 – "standard error" (`stderr`, `perror` in ANSI C)
  - Normally all three attached to terminal
- Example: `type.c`
  - Prints the contents of a file to `stdout`

type.c

```
void
typefile (char *filename)
{
  int fd, nread;
  char buf[1024];

  fd = open (filename, O_RDONLY);
  if (fd == -1) {
    perror (filename);
    return;
  }

  while ((nread = read (fd, buf, sizeof (buf))) > 0)
    write (1, buf, nread);

  close (fd);
}
```

- Can see system calls using strace utility (ktrace on BSD)

Protection example: CPU preemption

- Protection mechanism to prevent monopolizing CPU
- E.g., kernel programs timer to interrupt every 10 ms
  - Must be in supervisor mode to write appropriate I/O registers
  - User code cannot re-program interval timer
- Kernel sets interrupt to vector back to kernel
  - Regains control whenever interval timer fires
  - Gives CPU to another process if someone else needs it
  - Note: must be in supervisor mode to set interrupt entry points
  - No way for user code to hijack interrupt handler
- Result: Cannot monopolize CPU with infinite loop
  - At worst get $1/N$ of CPU with N CPU-hungry processes

Protection is not security

- How *can* you monopolize CPU?

Protection is not security

- How *can* you monopolize CPU?
- Use multiple processes
- For many years, could wedge most OSes with

```
int main() { while(1) fork(); }
```

  - Keeps creating more processes until system out of proc. slots
- Other techniques: use all memory (`chill` program)
- Typically solved with technical/social combination
  - Technical solution: Limit processes per user
  - Social: Reboot and yell at annoying users
  - Social: Ban harmful apps from play store

Address translation

- Protect memory of one program from actions of another
- Definitions
  - *Address space*: all memory locations a program can name
  - *Virtual address*: addresses in process' address space
  - *Physical address*: address of real memory
  - *Translation*: map virtual to physical addresses
- Translation done on every load and store
  - Modern CPUs do this in hardware for speed
- Idea: If you can't name it, you can't touch it
  - Ensure one process's translations don't include any other process's memory

More memory protection

- CPU allows kernel-only virtual addresses
  - Kernel typically part of all address spaces, e.g., to handle system call in same address space
  - But must ensure apps can't touch kernel memory
- CPU lets OS disable (invalidate) particular virtual addresses
  - Catch and halt buggy program that makes wild accesses
  - Make virtual memory seem bigger than physical (e.g., bring a page in from disk only when accessed)
- CPU enforced read-only virtual addresses useful
  - E.g., allows sharing of code pages between processes
  - Plus many other optimizations
- CPU enforced execute disable of VAs
  - Makes certain code injection attacks harder

Different system contexts

- A CPU (core) is at any point in one of several contexts
- *User-level* – CPU in user mode running application
- Kernel process context
  - Running kernel code on behalf of a particular process
  - E.g., performing system call
  - Also exception (memory fault, numeric exception, etc.)
  - Or executing a kernel-only process (e.g., network file server)
- Kernel code not associated with a process
  - Timer interrupt (hardclock)
  - Device interrupt
  - "Softirqs", "Tasklets" (Linux-specific terms)
- Context switch code – change which process is running
  - Requires changing the current address space
- Idle – nothing to do (might powerdown CPU)

Transitions between contexts

- User → kernel process context: syscall, page fault
- User/process context → interrupt handler: hardware
- Process context → user/context switch: return
- Process context → context switch: sleep
- Context switch → user/process context

Resource allocation & performance

- **Multitasking permits higher resource utilization**
- **Simple example:**
  - Process downloading large file mostly waits for network
  - You play a game while downloading the file
  - Higher CPU utilization than if just downloading
- **Complexity arises with cost of switching**
- **Example: Say disk 1,000 times slower than memory**
  - 1 GB memory in machine
  - 2 Processes want to run, each use 1 GB
  - Can switch processes by swapping them out to disk
  - Faster to run one at a time than keep context switching

Useful properties to exploit

- **Skew**
  - 80% of time taken by 20% of code
  - 10% of memory absorbs 90% of references
  - Basis behind cache: place 10% in fast memory, 90% in slow, usually looks like one big fast memory
- **Past predicts future (a.k.a. temporal locality)**
  - What's the best cache entry to replace?
  - If past $\approx$ future, then least-recently-used entry
- **Note conflict between fairness & throughput**
  - Higher throughput (fewer cache misses, etc.) to keep running same process
  - But fairness says should periodically preempt CPU and give it to next process

```c
#include <fcntl.h>
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>

void
typefile (char *filename)
{
  int fd, nread;
  char buf[1024];

  fd = open (filename, O_RDONLY);
  if (fd == -1) {
    perror (filename);
    return;
  }

  while ((nread = read (fd, buf, sizeof (buf))) > 0)
    write (1, buf, nread);

  close (fd);
}

int
main (int argc, char **argv)
{
  int argno;
  for (argno = 1; argno < argc; argno++)
    typefile (argv[argno]);
  exit (0);
}
```