6.S081 2020 Lecture 1: O/S overview

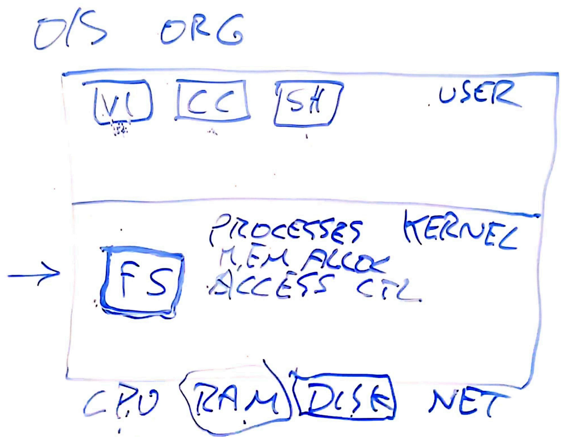
Overview

* 6.S081 goals
  * Understand operating system (O/S) design and implementation
  * Hands-on experience extending a small O/S
  * Hands-on experience writing systems software

* What is the purpose of an O/S?
  * Abstract the hardware for convenience and portability
  * Multiplex the hardware among many applications
  * Isolate applications in order to contain bugs
  * Allow sharing among cooperating applications
  * Control sharing for security
  * Don't get in the way of high performance
  * Support a wide range of applications

* Organization: layered picture
  [user/kernel diagram]
  - user applications: vi, gcc, DB, &c
  - kernel services
  - h/w: CPU, RAM, disk, net, &c
  * we care a lot about the interfaces and internal kernel structure

* What services does an O/S kernel typically provide?
  * process (a running program)
  * memory allocation
  * file contents
  * file names, directories
  * access control (security)
  * many others: users, IPC, network, time, terminals



* What's the application / kernel interface?
  * "System calls"
  * Examples, in C, from UNIX (e.g. Linux, macOS, FreeBSD):

```
          fd = open("out", 1);
          write(fd, "hello\n", 6);
          pid = fork();
```

  * These look like function calls but they aren't

* Why is O/S design+implementation hard and interesting?
  * unforgiving environment: quirky h/w, hard to debug
  * many design tensions:
    - efficient vs abstract/portable/general-purpose
    - powerful vs simple interfaces
    - flexible vs secure
  * features interact: `fd = open(); fork()`
  * uses are varied: laptops, smart-phones, cloud, virtual machines, embedded
  * evolving hardware: NVRAM, multi-core, fast networks

* You'll be glad you took this course if you...
  * care about what goes on under the hood
  * like infrastructure
  * need to track down bugs or security problems
  * care about high performance

Class structure

* Online course information:
  https://pdos.csail.mit.edu/6.828/2020/schedule.html
  https://pdos.csail.mit.edu/6.S081/ -- schedule, assignments, labs
  Piazza -- announcements, discussion, lab help

```
* Lectures
  * O/S ideas
  * case study of xv6, a small O/S, via code and xv6 book
  * lab background
  * O/S papers
  * submit a question about each reading, before lecture.

* Labs:
  The point: hands-on experience
  Mostly one week each.
  Three kinds:
    Systems programming (due next week...)
    O/S primitives, e.g. thread switching.
    O/S kernel extensions to xv6, e.g. network.
  Use piazza to ask/answer lab questions.
  Discussion is great, but please do not look at others' solutions!

* Grading:
  70% labs, based on tests (the same tests you run).
  20% lab check-off meetings: we'll ask you about randomly-selected labs.
  10% home-work and class/piazza discussion.
  No exams, no quizzes.
  Note that most of the grade is from labs. Start them early!

Introduction to UNIX system calls

* Applications see the O/S via system calls; that interface will be a big focus.
  let's start by looking at how programs use system calls.
  you'll use these system calls in the first lab.
  and extend and improve them in subsequent labs.

* I'll show some examples, and run them on xv6.
  xv6 has similar structure to UNIX systems such as Linux.
  but much simpler -- you'll be able to digest all of xv6
    accompanying book explains how xv6 works, and why
  why UNIX?
    open source, well documented, clean design, widely used
    studying xv6 will help if you ever need to look inside Linux
  xv6 has two roles in 6.S081:
    example of core functions: virtual memory, multi-core, interrupts, &c
    starting point for most of the labs
  xv6 runs on RISC-V, as in current 6.004
  you'll run xv6 under the qemu machine emulator

* example: copy.c, copy input to output
  read bytes from input, write them to the output
  $ copy
  copy.c is written in C
    Kernighan and Ritchie (K&R) book is good for learning C
  you can find these example programs via the schedule on the web site
  read() and write() are system calls
  first read()/write() argument is a "file descriptor" (fd)
    passed to kernel to tell it which "open file" to read/write
    must previously have been opened
    an FD connects to a file/device/socket/&c
    a process can open many files, have many FDs
    UNIX convention: fd 0 is "standard input", 1 is "standard output"
  second read() argument is a pointer to some memory into which to read
  third argument is the maximum number of bytes to read
    read() may read less, but not more
  return value: number of bytes actually read, or -1 for error
  note: copy.c does not care about the format of the data
    UNIX I/O is 8-bit bytes
    interpretation is application-specific, e.g. database records, C source, &c
  where do file descriptors come from?
```

```c
// copy.c: copy input to output.

#include "kernel/types.h"
#include "user/user.h"

int main()
{
  char buf[64];

  while(1){
    int n = read(0, buf, sizeof(buf));
    if(n <= 0)
      break;
    write(1, buf, n);
  }

  exit(0);
}
```

```
// open.c: create a file, write to it.

#include "kernel/types.h"
#include "user/user.h"
#include "kernel/fcntl.h"

int main()
{
  int fd = open("output.txt", O_WRONLY |
O_CREATE);
  write(fd, "ooo\n", 4);

  exit(0);
}
```

```
* example: open.c, create a file
  $ open
  $ cat output.txt
  open() creates a file, returns a file descriptor (or -1 for error)
  FD is a small integer
  FD indexes into a per-process table maintained by kernel
  [user/kernel diagram]
  different processes have different FD name-spaces
    i.e. FD 1 often means different things to different processes
  these examples ignore errors -- don't be this sloppy!
  Figure 1.2 in the xv6 book lists system call arguments/return
    or look at UNIX man pages, e.g. "man 2 open"

* what happens when a program calls a system call like open()?
  looks like a function call, but it's actually a special instruction
  hardware saves some user registers
  hardware increases privilege level
  hardware jumps to a known "entry point" in the kernel
  now running C code in the kernel
  kernel calls system call implementation
    open() looks up name in file system
    it might wait for the disk
    it updates kernel data structures (cache, FD table)
  restore user registers
  reduce privilege level
  jump back to calling point in the program, which resumes
  we'll see more detail later in the course

* I've been typing to UNIX's command-line interface, the shell.
  the shell prints the "$" prompts.
  the shell lets you run UNIX command-line utilities
    useful for system management, messing with files, development, scripting
    $ ls
    $ ls > out
    $ grep x < out      cat out
  UNIX supports other styles of interaction too
    window systems, GUIs, servers, routers, &c.
  but time-sharing via the shell was the original focus of UNIX.
  we can exercise many system calls via the shell.

* example: fork.c, create a new process
  the shell creates a new process for each command you type, e.g. for
    $ echo hello
  the fork() system call creates a new process
    $ fork
  the kernel makes a copy of the calling process
    instructions, data, registers, file descriptors, current directory
    "parent" and "child" processes
  only difference: fork() returns a pid in parent, 0 in child
  a pid (process ID) is an integer, kernel gives each process a different pid
  thus:
    fork.c's "fork() returned" executes in *both* processes
    the "if(pid == 0)" allows code to distinguish
  ok, fork lets us create a new process
    how can we run a program in that process?

* example: exec.c, replace calling process with an executable file
  how does the shell run a program, e.g.
    $ echo a b c
  a program is stored in a file: instructions and initial memory
    created by the compiler and linker
  so there's a file called echo, containing instructions
  $ exec
  exec() replaces current process with an executable file
    discards instruction and data memory
    loads instructions and memory from the file
```

```
// fork.c: create a new process

#include "kernel/types.h"
#include "user/user.h"

int main()
{
  int pid;
     pid = fork();
  printf("fork() returned %d\n", pid


  if(pid == 0){
    printf("child\n");
  } else {
    printf("parent\n");}

  exit(0);
}
```

```
// exec.c: replace a process with
an executable file

#include "kernel/types.h"
#include "user/user.h"

int
main()
{
  char *argv[] = { "echo", "this", "is", "echo", 0 };

  exec("echo", argv);

  printf("exec failed!\n");

  exit(0);
}
```

```
    preserves file descriptors
  exec(filename, argument-array)
    argument-array holds command-line arguments; exec passes to main()
    cat user/echo.c
    echo.c shows how a program looks at its command-line arguments

* example: forkexec.c, fork() a new process, exec() a program
  $ forkexec
  forkexec.c contains a common UNIX idiom:
    fork() a child process
    exec() a command in the child
    parent wait()s for child to finish
  the shell does fork/exec/wait for every command you type
    after wait(), the shell prints the next prompt
    to run in the background -- & -- the shell skips the wait()
  exit(status) -> wait(&status)
    status convention: 0 = success, 1 = command encountered an error
  note: the fork() copies, but exec() discards the copied memory
    this may seem wasteful
    you'll transparently eliminate the copy in the "copy-on-write" lab
```

```
int
main()
{
  int pid, status;

  pid = fork();
  if(pid == 0){
    char *argv[] = { "echo", "THIS", "IS", "ECHO", 0 };
    exec("echo", argv);
    printf("exec failed!\n");
    exit(1);
  } else {
    printf("parent waiting\n");
    wait(&status);
    printf("the child exited with status %d\n", status);
  }

  exit(0);
}
```

```
* example: redirect.c, redirect the output of a command
  what does the shell do for this?
    $ echo hello > out
  answer: fork, change FD 1 in child, exec echo
  $ redirect
  $ cat output.txt
  note: open() always chooses lowest unused FD; 1 due to close(1).
  fork, FDs, and exec interact nicely to implement I/O redirection
    separate fork-then-exec give child a chance to change FDs before exec
    FDs provide indirection
      commands just use FDs 0 and 1, don't have to know where they go
    exec preserves the FDs that sh set up
  thus: only sh has to know about I/O redirection, not each program
```

```
int main()
{  int pid;

  pid = fork();
  if(pid == 0){
    close(1);
    open("output.txt", O_WRONLY|O_CREATE);

    char *argv[] = { "echo", "this", "is", "redirected", "echo", 0 };
    exec("echo", argv);
    printf("exec failed!\n");
    exit(1);
  } else {
    wait((int *) 0);
  }

  exit(0);
}
```

```
* It's worth asking "why" about design decisions:
  Why these I/O and process abstractions? Why not something else?
  Why provide a file system? Why not let programs use the disk their own way?
  Why FDs? Why not pass a filename to write()?
  Why are files streams of bytes, not disk blocks or formatted records?
  Why not combine fork() and exec()?
  The UNIX design works well, but we will see other designs!

* example: pipe1.c, communicate through a pipe
  how does the shell implement
    $ ls | grep x
  $ pipe1
  an FD can refer to a "pipe", as well as a file
  the pipe() system call creates two FDs
    read from the first FD
    write to the second FD
  the kernel maintains a buffer for each pipe
    [u/k diagram]
    write() appends to the buffer
    read() waits until there is data
```

```
int main()
{
  int fds[2];
  char buf[100];
  int n;

  // create a pipe, with two FDs in fds[0], fds[1].
  pipe(fds);

  write(fds[1], "this is pipe1\n", 14);
  n = read(fds[0], buf, sizeof(buf));

  write(1, buf, n);

  exit(0);
}
```

```
* example: pipe2.c, communicate between processes
  pipes combine well with fork() to implement ls | grep x
    shell creates a pipe,
    then forks (twice),
    then connects ls's FD 1 to pipe's write FD,
    and grep's FD 0 to the pipe
    [diagram]
  $ pipe2 -- a simplified version
  pipes are a separate abstraction, but combine well w/ fork()
```

```
* example: list.c, list files in a directory
  how does ls get a list of the files in a directory?
  you can open a directory and read it -> file names
  "." is a pseudo-name for a process's current directory
  see ls.c for more details

* Summary
  * We've looked at UNIX's I/O, file system, and process abstractions.
  * The interfaces are simple -- just integers and I/O buffers.
  * The abstractions combine well, e.g. for I/O redirection.

You'll use these system calls in the first lab, due next week.
```

```
struct dirent {
  ushort inum;
  char name[14];
};

int
main()
{
  int fd;
  struct dirent e;

  fd = open(".", 0);
  while(read(fd, &e, sizeof(e)) == sizeof(e)){
    if(e.name[0] != '\0'){
      printf("%s\n", e.name);
    }
  }
  exit(0);
}
```

```
int
main()
{
  int n, pid;
  int fds[2];
  char buf[100];

  // create a pipe, with two FDs in fds[0], fds[1].
  pipe(fds);

  pid = fork();
  if (pid == 0) {
    write(fds[1], "this is pipe2\n", 14);
  } else {
    n = read(fds[0], buf, sizeof(buf));
    write(1, buf, n);
  }

  exit(0);
}
```