CS 4414 — Operating System — Introduction

two sections

there are two sections of Operating Systems
- Reiss at 9:30am and Grimshaw at 11am

we will share TAs, large parts of assignments/quizzes

…but there will be differences
- e.g. written part in Grimshaw's assignments
- e.g. assignment submission

course webpage

`https://www.cs.virginia.edu/~cr4bd/4414/F2018/`

linked off Collab

homeworks

there will be programming assignments

…mostly in C or C++

- (I recommend C++)

one or two weeks

- if two weeks "checkpoint" submission after first week

schedule is aggressive…

- might push back pre-midterm assignments by one week
- …depending how fast lectures go

xv6

some assignments will use xv6, a teaching operating system

simplified OS based on an old Unix version

- built by some people at MIT

theoretically actually boots on real 32-bit x86 hardware

...and supports multicore!

quizzes

there will be online quizzes after each week of lecture

…starting after next week

same interface as CS 3330, but no time limit

(haven't seen it? we'll talk more next week)

quizzes are open notes, open book, open Internet

exams

midterm and final

let us know soon if you can't make the midterm

textbook

recommended textbook:
Operating Systems: Principles and Practice

no required textbook

alternative: Operating Systems: Three Easy Pieces (free PDFs)

- some topics we'll cover where this may be primary textbook

alternative: Silberchartz (used in previous semesters)

- full version: Operating System Concepts, Ninth Edition

cheating: homeworks

don't

homeworks are individual

no code from prior semesters

no sharing code, pesudocode, detailed descriptions of code

no code from Internet, with extremely limited exceptions

- tiny things solving problems that aren't point of assignment
- e.g. code to split string into array for non-text-parsing assignment
- e.g. something explicitly permitted by the assignent writeup
- in doubt: ask

cheating: quizzes

don't

quizzes: also individual

don't share answers

don't IM people for answers

don't ask on StackOverflow for answers

getting help

Piazza

office hours (will be posted soon)

emailing me

C/C++ refreshers

some TAs will run a refresher on C and C++

totally optional, but 2150 was a while ago...

probably two sessions, probably Thursday

stay tuned

what is an operating system? (1)

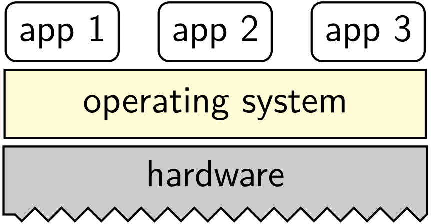
layer of software to provide access to HW

abstraction of complex hardware

protected access to shared resources

communication

security



history: computer operator

via National Library of Medicine; computer operators operating an Honeywell 800

what is an operating system? (2)

software providing a more convenient/featureful machine interface

what is an operating system? (3)

referee — resource sharing, protection, isolation

what is an operating system? (3)

referee — resource sharing, protection, isolation

illusionist — clean, easy abstractions

what is an operating system? (3)

referee — resource sharing, protection, isolation

illusionist — clean, easy abstractions

glue — common services

storage, window systems, authorization, networking, …

common goal: hide complexity

hiding complexity

common goal: hide complexity

hiding complexity

competing applications — failures, malicious applications

text editor shouldn't need to know if browser is running

varying hardware — diverse and changing interfaces

different keyboard interfaces, disk interfaces, video interfaces, etc.

applications shouldn't change

common goal: for application programmer

write once for lots of hardware

avoid reimplementing common functionality

don't worry about other programs

the virtual machine interface

application

virtual machine interface

operating system

physical machine interface

hardware

system virtual machine
(VirtualBox, VMWare, Hyper-V, ...)

process virtual machine
(typical operating systems)

imitate physical interface
(of some real hardware)

chosen for convenience
(of applications)

system virtual machines

run entire operating systems

- for OS development, portability

interface $\approx$ hardware interface (but maybe not the real hardware)

- aid reusing existing raw hardware-targeted code
- different "application programmer"

process virtual machine

process VM	real hardware
thread	processors
memory allocation	page tables
files	devices
…	…

process virtual machine

process VM	real hardware
thread	processors
memory allocation	page tables
files	devices
...	...

(virtually) infinite threads — no matter number of CPUs

process virtual machine

process VM	real hardware
thread	processors
memory allocation	page tables
files	devices
…	…

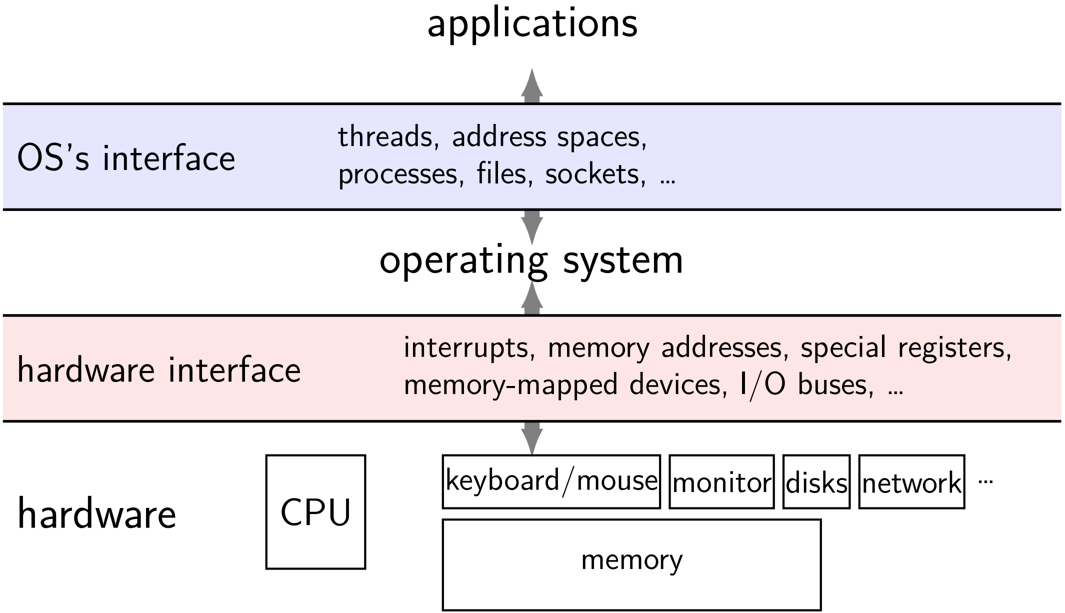
memory allocation functions
no worries about organization of “real” memory

process virtual machine

process VM	real hardware
thread	processors
memory allocation	page tables
files	devices
...	...

files — open/read/write/close interface
no details of hard drive operation
or keyboard operation or ...

the abstract virtual machine



abstract VM: application view

applications

OS's interface — threads, address spaces, processes, files, sockets, ...

the application's "machine" is the operating system

no hardware I/O details visible — future-proof

more featureful interfaces than real hardware

abstract VM: OS view

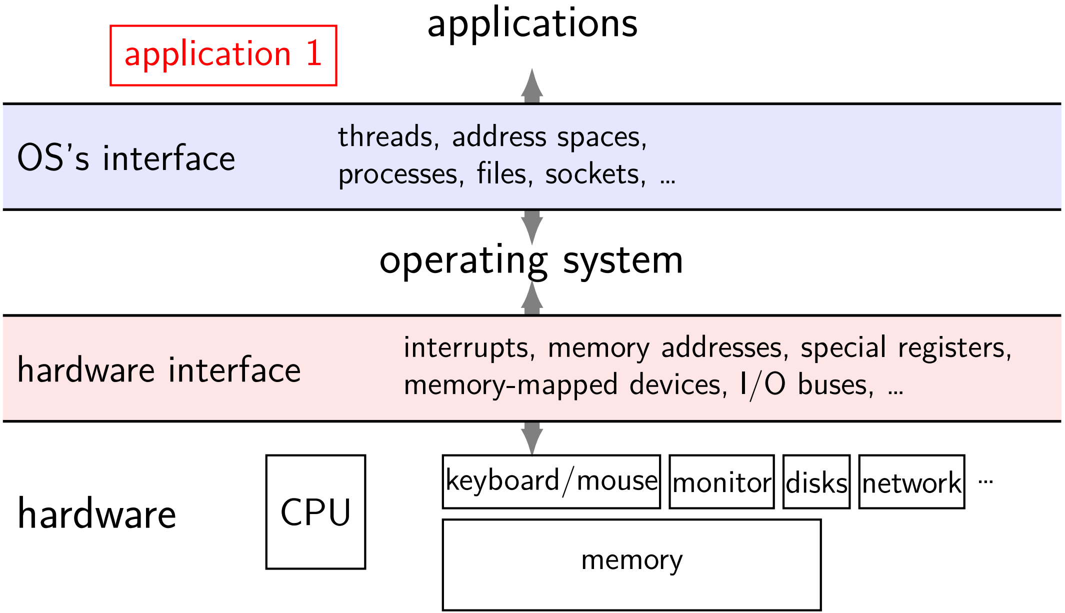
OS's interface	threads, address spaces, processes, files, sockets, …

operating system

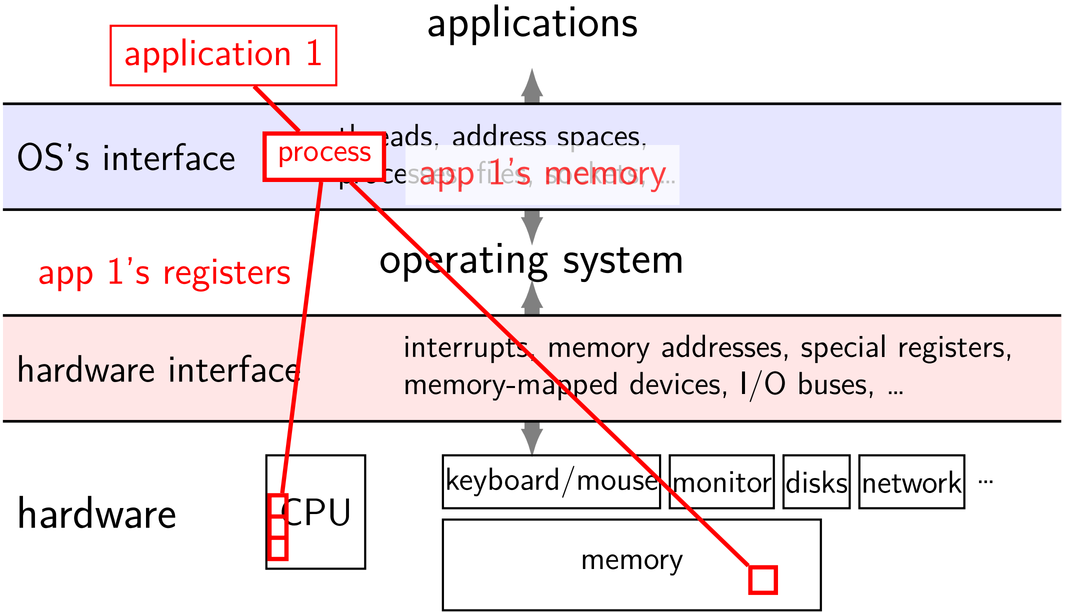
hardware interface	interrupts, memory addresses, special registers, memory-mapped devices, I/O buses, …

operating system's job: translate one interface to another

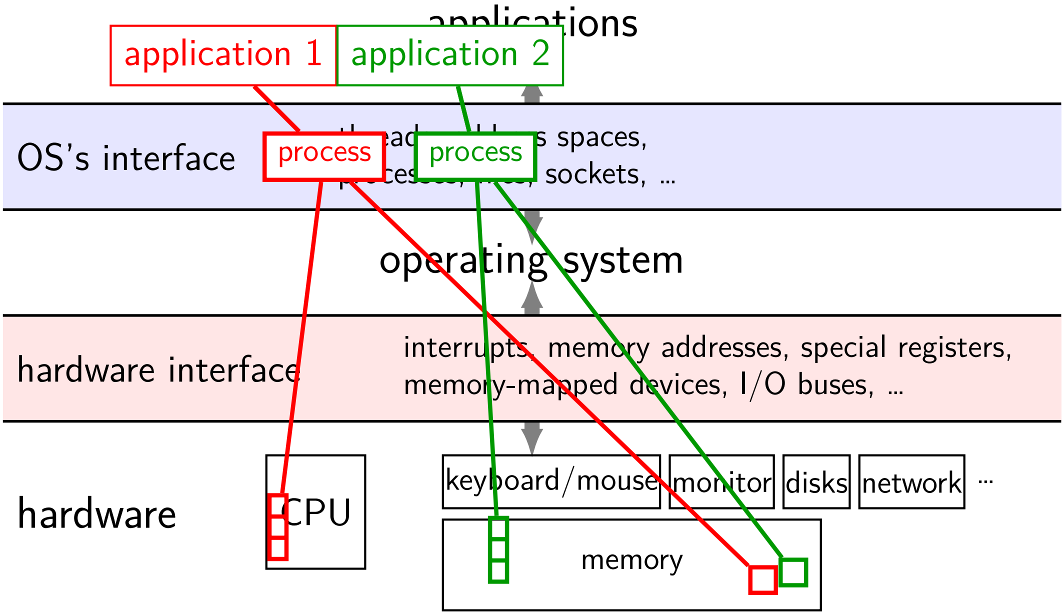
program → process → CPU and memory



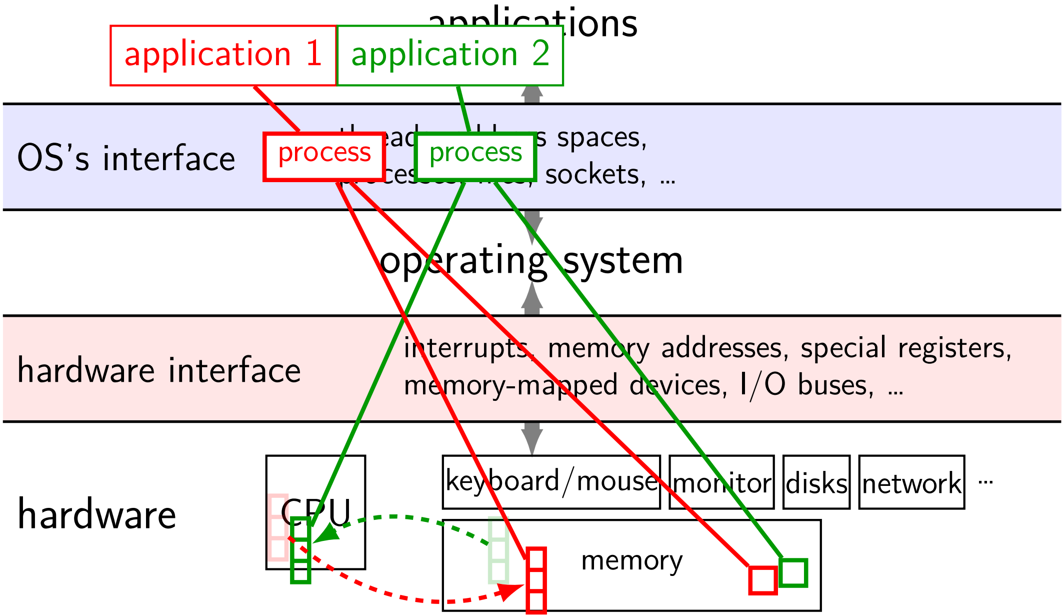
program → process → CPU and memory



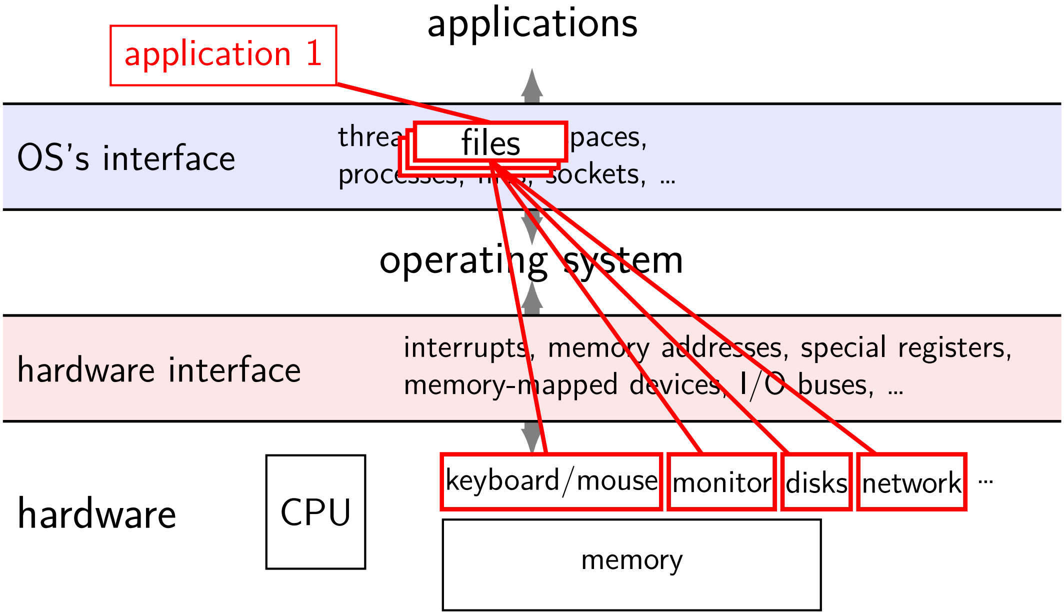
program → process → CPU and memory



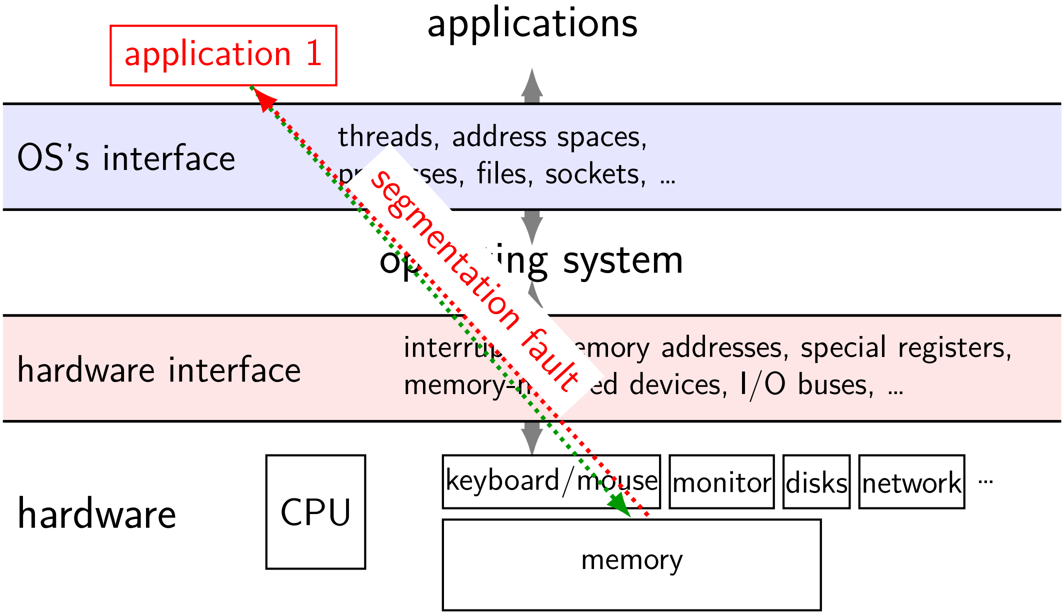
program → process → CPU and memory



files → input/output



security and protection



The Process

process = thread(s) + address space

illusion of dedicated machine:

- thread = illusion of own CPU
- address space = illusion of own memory

goal: protection

run multiple applications, and ...

keep them from crashing the OS

keep them from crashing each other

(keep parts of OS from crashing other parts?)

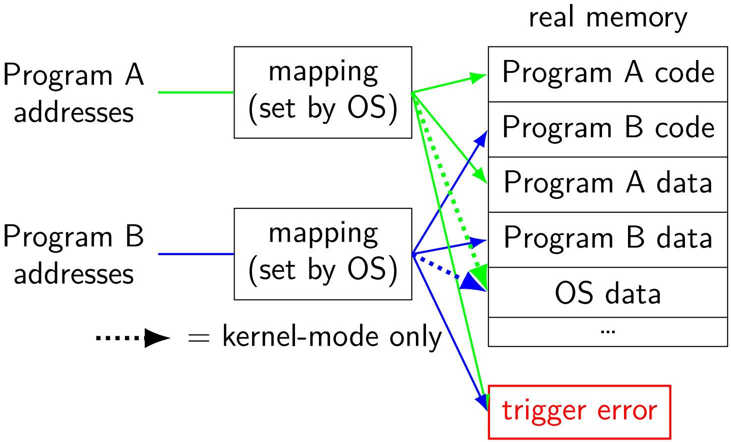
mechanism 1: dual-mode operation

processor has two modes: kernel (privileged) and user

some operations require kernel mode

OS controls what runs in kernel mode

mechanism 2: address translation



aside: alternate mechanisms

dual mode operation and address translation are common today

...so we'll talk about them a lot

not the only ways to implement operating system features
(plausibly not even the most efficient...)

problem: OS needs to respond to events

keypress happens?

program using CPU for too long?

…

problem: OS needs to respond to events

keypress happens?

program using CPU for too long?

…

hardware support for running OS: *exception*

need hardware support because CPU is running application instructions

exceptions and dual-mode operation

rule: user code always runs in user mode

rule: only OS code ever runs in kernel mode

on *exception*: changes from user mode to kernel mode

...and is only mechanism for doing so

  how OS controls what runs in kernel mode

exception terminology

CS 3330 terms:

interrupt: triggered by external event

- timer, keyboard, network, …

fault: triggered by program doing something "bad"

- invalid memory access, divide-by-zero, …

traps: triggered by explicit program action

- system calls

aborts: something in the hardware broke

xv6 exception terms

everything is a called a trap

or sometimes an interrupt

no real distinction in *name* about kinds

real world exception terms

it's all over the place...

context clues

kernel services

allocating memory? (change address space)

reading/writing to file? (communicate with hard drive)

read input? (communicate with keyborad)

all need privileged instructions!

need to run code in kernel mode

hardware mechanism: deliberate exceptions

some instructions exist to trigger exceptions

still works like normal exception

- starts executing OS-chosen handler
- ...in kernel mode

allows program requests privilieged instructions

- OS handler decides what program can request
- OS handler decides format of requests

system call timeline

in user mode

(the standard library)

```
/* set arguments */
movq $SYS_write, %rax
movq $FILENO_stdout, %rsi
movq $buffer, %rdi
movq $BUFFER_LEN, %r8
syscall  // special instruction




// now use return value
testq %rax, %rax
...
```

in kernel mode

(the “kernel”)

```
syscall_handler:
/* ... save registers and
       actually do read and
       set return value ... */
iret  // special instruction
```

system call timeline

in user mode

(the standard library)

```
/* set arguments */
movq $SYS_write, %rax
movq $FILENO_stdout, %rsi
movq $buffer, %rdi
movq $BUFFER_LEN, %r8
syscall  // special instruction
```

```
// now use return value
testq %rax, %rax
...
```

in kernel mode

(the “kernel”)

hardware knows to go here
because of pointer set during boot

```
syscall_handler:
/* ... save registers and
       actually do read and
       set return value ... */
iret  // special instruction
```

system call timeline

in user mode

(the standard library)

```
/* set arguments */
movq $SYS_write, %rax
movq $FILENO_stdout, %rsi
movq $buffer, %rdi
movq $BUFFER_LEN, %r8
syscall  // special instruction
```

'priviliged' operations prohibited

```
// now use return value
testq %rax, %rax
...
```

in kernel mode

(the "kernel")

```
syscall_handler:
/* ... save registers and
       actually do read and
       set return value ... */
iret  // special instruction
```

system call timeline

in user mode

(the standard library)

```
/* set arguments */
movq $SYS_write, %rax
movq $FILENO_stdout, %rsi
movq $buffer, %rdi
movq $BUFFER_LEN, %r8
syscall  // special instruction




// now use return value
testq %rax, %rax
...
```

in kernel mode

(the “kernel”)

‘priviliged’ operations allowed

(change memory layout, I/O, exceptions)

```
syscall_handler:
/* ... save registers and
       actually do read and
       set return value ... */
iret  // special instruction
```

the classic Unix design

applications			
standard library functions / shell commands			
standard libraries and utility programs	libc (C standard library) login	the shell login…	
system call interface			
kernel	CPU scheduler virtual memory pipes	filesystems device drivers swapping	networking signals …
hardware interface			
hardware	memory management unit	device controllers	…

the classic Unix design

applications			
standard library functions / shell commands			
standard libraries and utility programs	libc (C standard library) login	the shell login...	
system call interface			
kernel	CPU scheduler virtual memory pipes	filesystems device drivers swapping	networking signals ...
hardware interface			
hardware	memory management unit	device controllers	...

the OS?

the classic Unix design

applications			
standard library functions / shell commands			
standard libraries and utility programs	libc (C standard library) login	the shell login...	
system call interface			
kernel	CPU scheduler virtual memory pipes	filesystems device drivers swapping	networking signals ...
hardware interface			
hardware	memory management unit	device controllers	...

the OS?

aside: is the OS the kernel?

OS = stuff that runs in kernel mode?

OS = stuff that runs in kernel mode + libraries to use it?

OS = stuff that runs in kernel mode + libraries + utility programs (e.g. shell, finder)?

OS = everything that comes with machine?

no consensus on where the line is

each piece can be replaced separately…

xv6

we will be using an teaching OS called “xv6”

based on Sixth Edition Unix

modified to be multicore and use 32-bit x86 (not PDP-11)

xv6 setup/assignment

first assignment — adding simple xv6 system call

includes xv6 download instructions

and link to xv6 book

xv6 technical requirements

you will need a Linux VM

- we will supply one (soon), or get your own
- should also have department lab accounts (eventually)
- (it's probably possible to use OS X, but you need a cross-compiler and we don't have instructions)

...with qemu installed

- qemu (for us) = emulator for 32-bit x86 system
- Ubuntu/Debian package qemu-system-i386

alternate: hopefully department login server

- working on this

first assignment

get compiled and xv6 working

…toolkit uses an emulator

- could run on real hardware or a standard VM, but a lot of details
- also, emulator lets you use GDB

xv6: what's included

Unix-like kernel

- very small set of syscalls
- some less featureful (e.g. exit without exit status)

userspace library

- very limited

userspace programs

- command line, ls, mkdir, echo, cat, etc.
- some self-testing programs

xv6: echo.c

```
#include "types.h"
#include "stat.h"
#include "user.h"

int
main(int argc, char *argv[])
{
  int i;

  for(i = 1; i < argc; i++)
    printf(1, "%s%s", argv[i], i+1 < argc ? "␣" : "\n");
  exit();
}
```

xv6: echo.c

```
#include "types.h"
#include "stat.h"
#include "user.h"

int
main(int argc, char *argv[])
{
  int i;

  for(i = 1; i < argc; i++)
    printf(1, "%s%s", argv[i], i+1 < argc ? "␣" : "\n");
  exit();
}
```

xv6: echo.c

```
#include "types.h"
#include "stat.h"
#include "user.h"

int
main(int argc, char *argv[])
{
  int i;

  for(i = 1; i < argc; i++)
    printf(1, "%s%s", argv[i], i+1 < argc ? "␣" : "\n");
  exit();
}
```

xv6 demo

syscalls in xv6

fork, exit, wait, kill, getpid — process control

open, read, write, close, fstat, dup — file operations

mknod, unlink, link, chdir — directory operations

…

write syscall in xv6: user mode

syscall.h

```
...
#define SYS_write    16
...
```

main.c

```
...
write(1,
      "Hello,␣World!\n",
      14);
...
```

usys.S

(after macro replacement)

```
#include "syscall.h"
// ...
.globl write
write:
    /* 16 = SYS_write */
    movl $16, %eax
    /* 0x40 = T_SYSCALL */
    int $0x40
    ret
```

write syscall in xv6: user mode

syscall.h

```
...
#define SYS_write    16
...
```

main.c

```
...
write(1,
      "Hello, World!\n",
      14);
...
```

usys.S

(after macro replacement)

```
#include "syscall.h"
// ...
.globl write
write:
    /* 16 = SYS_write */
    movl $16, %eax
    /* 0x40 = T_SYSCALL */
    int $0x40
    ret
```

`int`errupt — trigger an exception similar to a keypress

parameter (`0x40` in this case) — type of exception

write syscall in xv6: user mode

syscall.h

```
...
#define SYS_write   16
...
```

main.c

```
...
write(1,
      "Hello,␣World!\n",
      14);
...
```

usys.S

(after macro replacement)

```
#include "syscall.h"
// ...
.globl write
write:
    /* 16 = SYS_write */
    movl $16, %eax
    /* 0x40 = T_SYSCALL */
    int $0x40
    ret
```

xv6 syscall calling convention:

eax = syscall number

otherwise: same as 32-bit x86 calling convention

(arguments + return value: on stack)

write syscall in xv6: interrupt table setup

trap.c (run on boot)

```
...
lidt(idt, sizeof(idt));
...
SETGATE(idt[T_SYSCALL], 1, SEG_KCODE<<3, vectors[T_SYSCALL], DPL_USER);
...
```

write syscall in xv6: interrupt table setup

trap.c (run on boot)

```
...
lidt(idt, sizeof(idt));
...
SETGATE(idt[T_SYSCALL], 1, SEG_KCODE<<3, vectors[T_SYSCALL], DPL_USER);
...
```

`lidt` —

function (in x86.h) wrapping lidt instruction

sets the *interrupt descriptor table*

table of *handler functions* for each interrupt type

write syscall in xv6: interrupt table setup

trap.c (run on boot)

```
...
lidt(idt, sizeof(idt));
...
SETGATE(idt[T_SYSCALL], 1, SEG_KCODE<<3, vectors[T_SYSCALL], DPL_USER);
...
```

(from mmu.h):

```
// Set up a normal interrupt/trap gate descriptor.
// - istrap: 1 for a trap gate, 0 for an interrupt gate.
//   interrupt gate clears FL_IF, trap gate leaves FL_IF alone
// - sel: Code segment selector for interrupt/trap handler
// - off: Offset in code segment for interrupt/trap handler
// - dpl: Descriptor Privilege Level -
//        the privilege level required for software to invoke
//        this interrupt/trap gate explicitly using an int instruction.
#define SETGATE(gate, istrap, sel, off, d)                \
```

write syscall in xv6: interrupt table setup

trap.c (run on boot)

```
...
lidt(idt, sizeof(idt));
...
SETGATE(idt[T_SYSCALL], 1, SEG_KCODE<<3, vectors[T_SYSCALL], DPL_USER);
...
```

set the T_SYSCALL (= 0x40) interrupt to be callable from user mode via **int** instruction

(otherwise: triggers fault like privileged instruction)

write syscall in xv6: interrupt table setup

trap.c (run on boot)

```
...
lidt(idt, sizeof(idt));
...
SETGATE(idt[T_SYSCALL], 1, SEG_KCODE<<3, vectors[T_SYSCALL], DPL_USER);
...
```

set it to use the kernel “code segment”

meaning: run in kernel mode

(yes, code segments specifies more than that — nothing we care about)

write syscall in xv6: interrupt table setup

trap.c (run on boot)

```
...
lidt(idt, sizeof(idt));
...
SETGATE(idt[T_SYSCALL], 1, SEG_KCODE<<3, vectors[T_SYSCALL], DPL_USER);
...
```

`vectors[T_SYSCALL]` — OS function for processor to run
set to pointer to assembly function `vector64`

write syscall in xv6: interrupt table setup

trap.c (run on boot)

```
...
lidt(idt, sizeof(idt));
...
SETGATE(idt[T_SYSCALL], 1, SEG_KCODE<<3, vectors[T_SYSCALL], DPL_USER);
...
```

`vectors[T_SYSCALL]` — OS function for processor to run
set to pointer to assembly function `vector64`

vectors.S

```
vector64:
  pushl $0
  pushl $64
  jmp alltraps
...
```

trapasm.S

```
alltraps:
  ...
  call trap
  ...
  iret
```

trap.c

```
void
trap(struct trapframe *tf)
{
...
```

write syscall in xv6: the trap function

trap.c

```
void
trap(struct trapframe *tf)
{
  if(tf->trapno == T_SYSCALL){
    if(myproc()->killed)
      exit();
    myproc()->tf = tf;
    syscall();
    if(myproc()->killed)
      exit();
    return;
  }
  ...
}
```

write syscall in xv6: the trap function

trap.c

```
void
trap(struct trapframe *tf)
{
  if(tf->trapno == T_SYSCALL){
    if(myproc()->killed)
      exit();
    myproc()->tf = tf;
    syscall();
    if(myproc()->killed)
      exit();
    return;
  }
  ...
}
```

struct trapframe — set by assembly

interrupt type, application registers, ...

example: `tf->eax` = old value of eax

write syscall in xv6: the trap function

trap.c

```
void
trap(struct trapframe *tf)
{
  if(tf->trapno == T_SYSCALL){
    if(myproc()->killed)
      exit();
    myproc()->tf = tf;
    syscall();
    if(myproc()->killed)
      exit();
    return;
  }
  ...
}
```

`myproc()` — pseudo-global variable represents currently running process

much more on this later in semester

write syscall in xv6: the trap function

trap.c

```
void
trap(struct trapframe *tf)
{
  if(tf->trapno == T_SYSCALL){
    if(myproc()->killed)
      exit();
    myproc()->tf = tf;
    syscall();
    if(myproc()->killed)
      exit();
    return;
  }
  ...
}
```

syscall() — actual implementations uses `myproc()->tf` to determine what operation to do for program

write syscall in xv6: the syscall function

syscall.c

```
static int (*syscalls[])(void) = {
...
[SYS_write]  sys_write,
...
};

...

void
syscall(void)
{
...
  num = curproc->tf->eax;
  if(num > 0 && num < NELEM(syscalls) && syscalls[num]) {
    curproc->tf->eax = syscalls[num]();
  } else {
...
```

write syscall in xv6: the syscall function

syscall.c

```
static int (*syscalls[])(void) = {
...
[SYS_write]  sys_write,
...
};

...

void
syscall(void)
{
...
  num = curproc->tf->eax;
  if(num > 0 && num < NELEM(syscalls) && syscalls[num]) {
    curproc->tf->eax = syscalls[num]();
  } else {
...
```

array of functions — one for syscall

'`[number] value`': syscalls[number] = value

write syscall in xv6: the syscall function

syscall.c

```
static int (*syscalls[])(void) = {
...
[SYS_write]  sys_write,
...
};

...

void
syscall(void)
{
...
  num = curproc->tf->eax;
  if(num > 0 && num < NELEM(syscalls) && syscalls[num]) {
    curproc->tf->eax = syscalls[num]();
  } else {
...
```

(if system call number in range)
call sys_...function from table
store result in user's `eax` register

write syscall in xv6: the syscall function

syscall.c

```
static int (*syscalls[])(void) = {
...
[SYS_write]  sys_write,
...
};

...

void
syscall(void)
{
...
  num = curproc->tf->eax;
  if(num > 0 && num < NELEM(syscalls) && syscalls[num]) {
    curproc->tf->eax = syscalls[num]();
  } else {
...
```

result assigned to eax
(assembly code this returns to
copies `tf->eax` into `%eax`)

write syscall in xv6: sys_write

sysfile.c

```
int
sys_write(void)
{
  struct file *f;
  int n;
  char *p;

  if(argfd(0, 0, &f) < 0 || argint(2, &n) < 0 || argptr(1, &p, n) < 0)
    return -1;
  return filewrite(f, p, n);
}
```

write syscall in xv6: sys_write

sysfile.c

```
int
sys_write(void)
{
  struct file *f;
  int n;
  char *p;

  if(argfd(0, 0, &f) < 0 || argint(2, &n) < 0 || argptr(1, &p, n) < 0)
    return -1;
  return filewrite(f, p, n);
}
```

utility functions that read arguments from user's stack
returns -1 on error (e.g. stack pointer invalid)
(more on this later)
(note: 32-bit x86 calling convention puts all args on stack)

write syscall in xv6: sys_write

sysfile.c

```
int
sys_write(void)
{
  struct file *f;
  int n;
  char *p;

  if(argfd(0, 0, &f) < 0 || argint(2, &n) < 0 || argptr(1, &p, n) < 0)
    return -1;
  return filewrite(f, p, n);
}
```

actual internal function that implements writing to a file
(the terminal counts as a file)

write syscall in xv6: interrupt table setup

trap.c (run on boot)

```
...
lidt(idt, sizeof(idt));
...
SETGATE(idt[T_SYSCALL], 1, SEG_KCODE<<3, vectors[T_SYSCALL], DPL_USER);
...
```

`trap` returns to `alltraps`

alltraps restores registers from `tf`, then returns to user-mode

vectors.S

```
vector64:
  pushl $0
  pushl $64
  jmp alltraps
...
```

trapasm.S

```
alltraps:
  ...
  call trap
  ...
  iret
```

trap.c

```
void
trap(struct trapframe *tf)
{
...
```

write syscall in xv6: summary

`write` function — syscall wrapper uses `int $0x40`

interrupt table entry setup points to assembly function `vector64()`

…which calls `trap()` with trap number set to 64 (`T_SYSCALL`)

  (after saving all registers into `struct trapframe`)

…which checks trap number, then calls `syscall()`

…which checks syscall number (from eax)

…and uses it to call `sys_write`

…which reads arguments from the stack and does the write

write syscall in xv6: summary

`write` function — syscall wrapper uses `int $0x40`

interrupt table entry setup points to assembly function `vector64()`

...which calls `trap()` with trap number set to 64 (`T_SYSCALL`)

(after saving all registers into `struct trapframe`)

...which checks trap number, then calls `syscall()`

...which checks syscall number (from eax)

...and uses it to call `sys_write`

...which reads arguments from the stack and does the write

summary

dual-mode operation:

- kernel-mode: can do anything
- user-mode: normal programs run here, no direct access to devices

exceptions/interrupts

- hardware runs OS for important events
- only way to switch to kernel mode — do special things

address spaces:

- each program gets its own memory

system calls:

- controlled entry into kernel mode