intro / what is an OS / processes and system calls

Changelog

14 January 2020: reorganize slides to move process definition earlier

14 January 2020: use “64” instead of “0x40” in write() flow chart to be more consistent with code shown later

course webpage

`https://www.cs.virginia.edu/~cr4bd/4414/S2020/`

linked off Collab

homeworks

there will be programming assignments

first is due **next week**

...mostly in C or C++; one in Python

one or two weeks

- if two weeks "checkpoint" submission after first week

two week assignments worth more

schedule is aggressive...

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!

- (but we'll run it only single-core, in an emulator)

quizzes

there will be online quizzes after each week of lecture

...starting this week (due next Tuesday)

same interface as CS 3330, but no time limit

(haven't seen it? we'll talk more on Thursday)

quizzes are open notes, open book, open Internet

exams

midterm and final

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

final is a **combined final** on 4 May at 7PM

- not during a "normal" final slot

late policy

there is a late policy on the website

textbook

recommended textbook:
Anderson and Dahlin, *Operating Systems: Principles and Practice*

no required textbook

alt: Arpaci-Dusseau, *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 (other than your own)

no sharing code, pesudocode, detailed descriptions of code

no using code from Internet/etc., with limited exceptions

- tiny things solving problems that aren't point of assignment
- …*credited* where used in your code
- e.g. code to split string into array for non-text-parsing assignment
- exception: something explicitly referred to by the assignent writeup
- in doubt: ask

citation

if using small amount of code *clearly not point of assignment*

- e.g. split string into array for non-text-parsing assignment
- e.g. filling arrays of pointers from vectors of strings

not sure what counts? ask

then make sure you cite where you got it in your code

- should not be other student, etc. — no sharing code

if using code clearly part of major objective of assignment

then don't

- e.g. if you find a shell online, don't use it solve the shell assignment

cheating: quizzes

don't

quizzes: also individual

don't share answers

don't IM people for answers

don't ask on StackOverflow for answers

waitlisted?

if you need this course now to graduate on time, email me with specifics

- please indicate which sections you are able to attend

getting help

Piazza

TA and my office hours (will be posted soon)

emailing me

history: computer operator

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

OS definition ambiguity

different exact defintions

'part of OS' v. 'just a program/library'

- example: code to allow moving windows on the screen part of the OS?
- example: code to support printers is part of the OS?

we'll not sweat the details — give general, common principles

what is an operating system?

software that:

Anderson-Dahlin manages a computer's resources

Arpaci-Dusseau provides 'virtual machine': more convenient than real machine

OS roles

Anderson-Dahlin's taxonomy of things OS's do

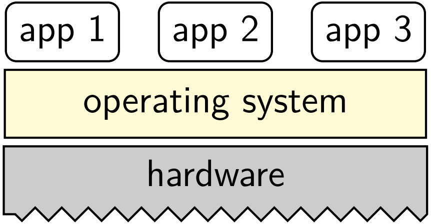
referee — resource sharing, protection, isolation

illusionist — clean, easy abstractions

glue — common services

storage, window systems, authorization, networking, …

OS as abstraction layer



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 ≈ 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" ($\sim$ virtual CPUs)
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 ...

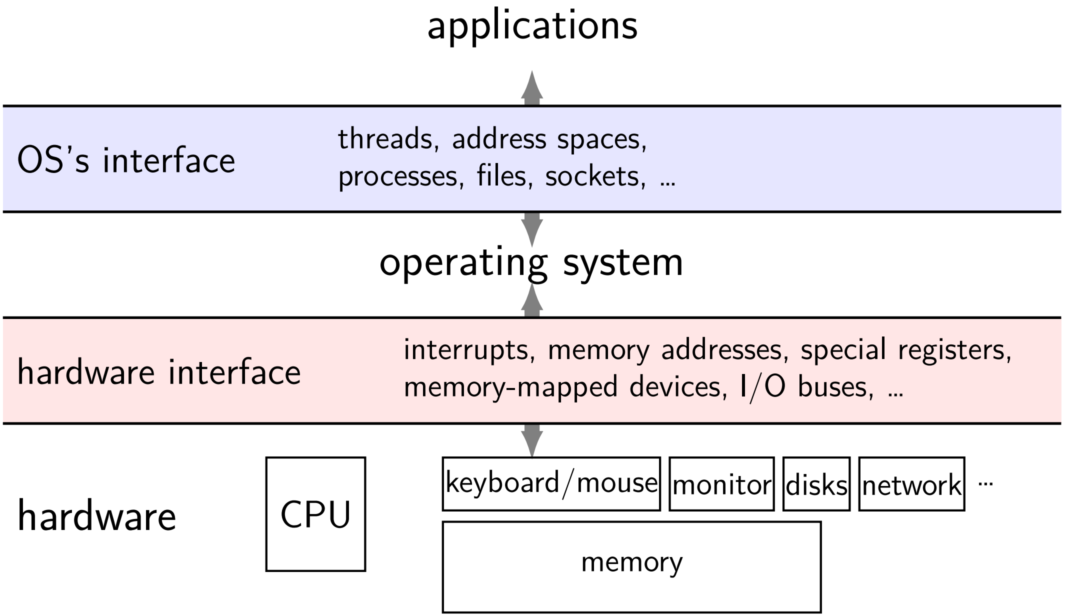
The Process

process = thread(s) + address space + ...

illusion of dedicated machine:

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

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

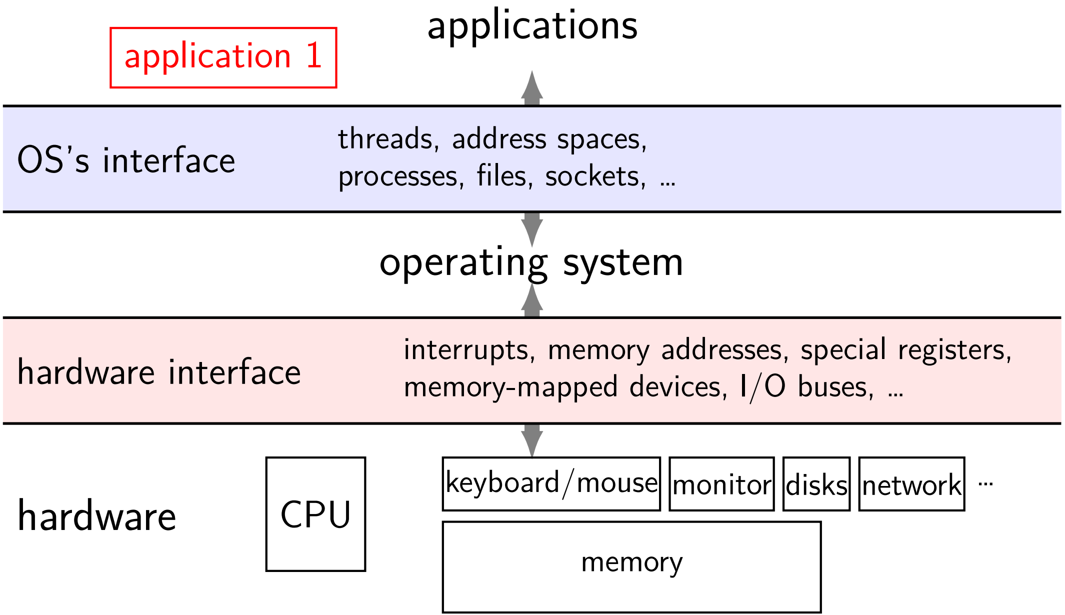
more featureful interfaces than real hardware

abstract VM: OS view

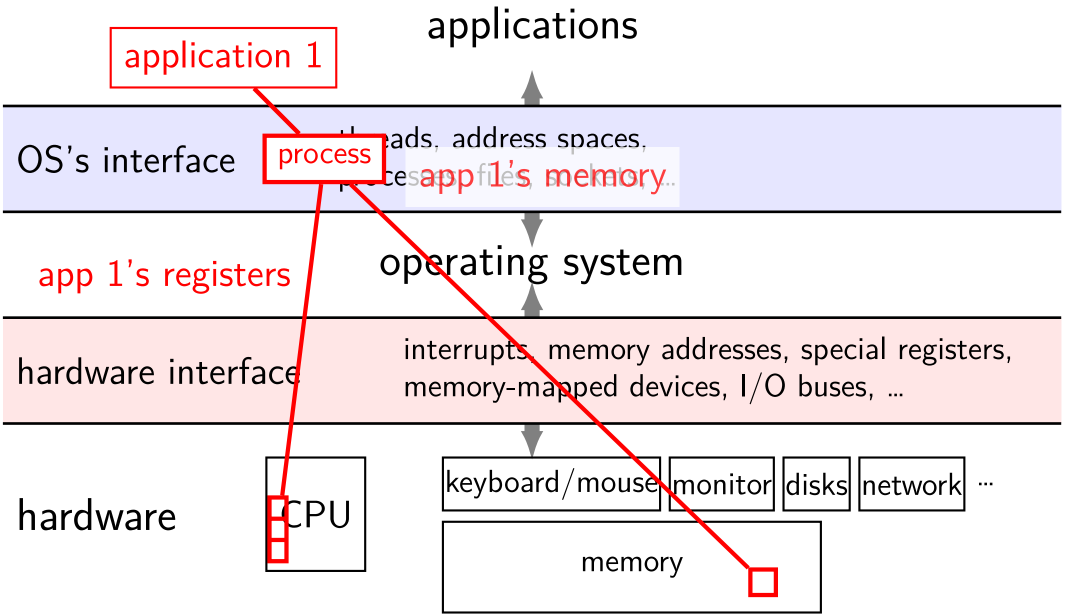
OS's interface	threads, address spaces, processes, files, sockets, ...
operating system	
hardware interface	interrupts, memory addresses, special registers, memory-mapped devices, I/O buses, ...

operating system's job: translate one interface to another

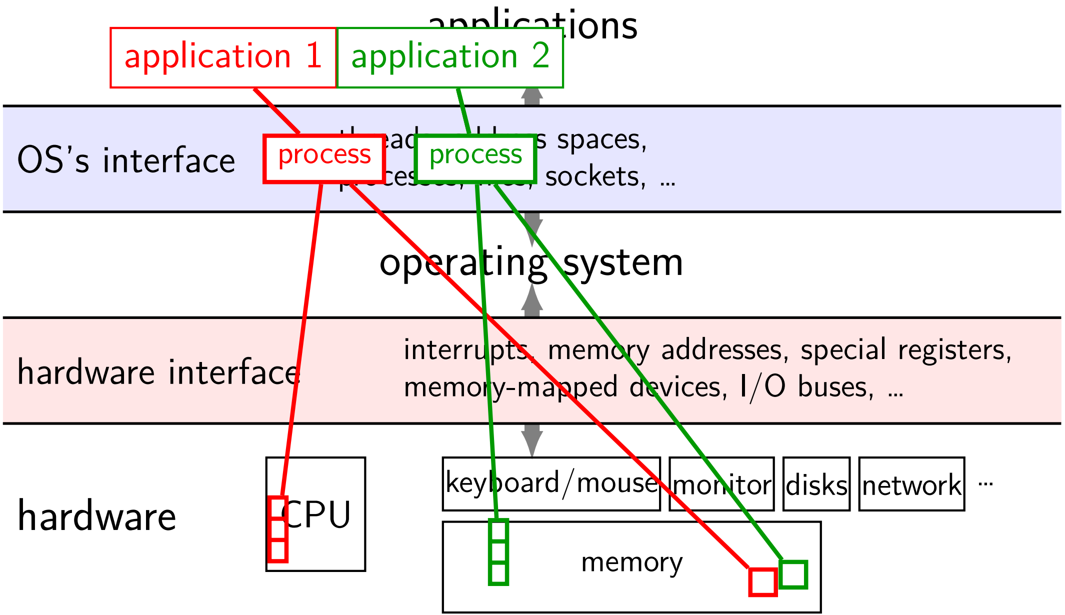
program → process → CPU and memory



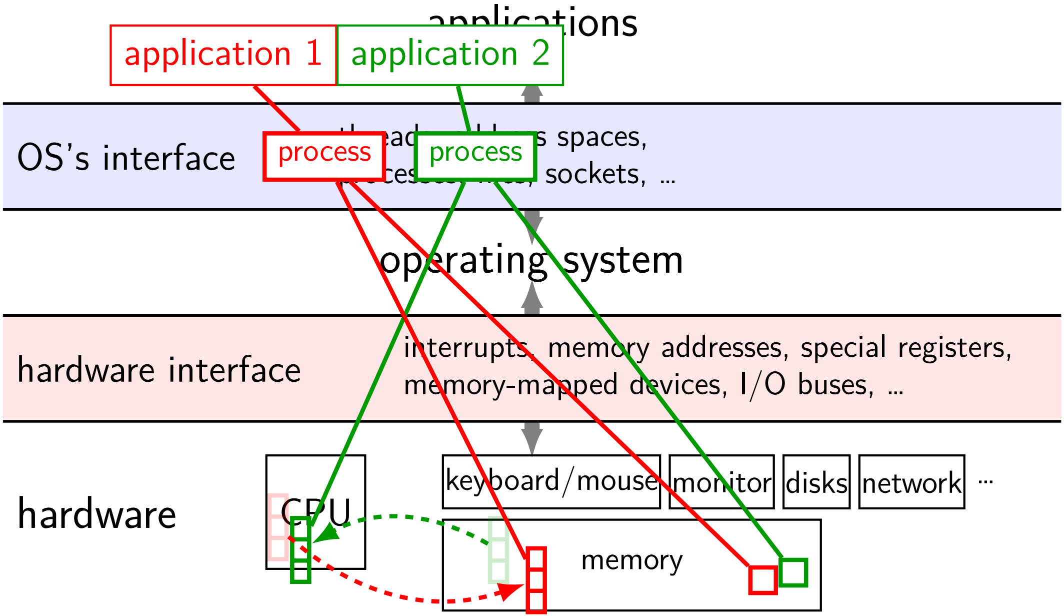
program → process → CPU and memory



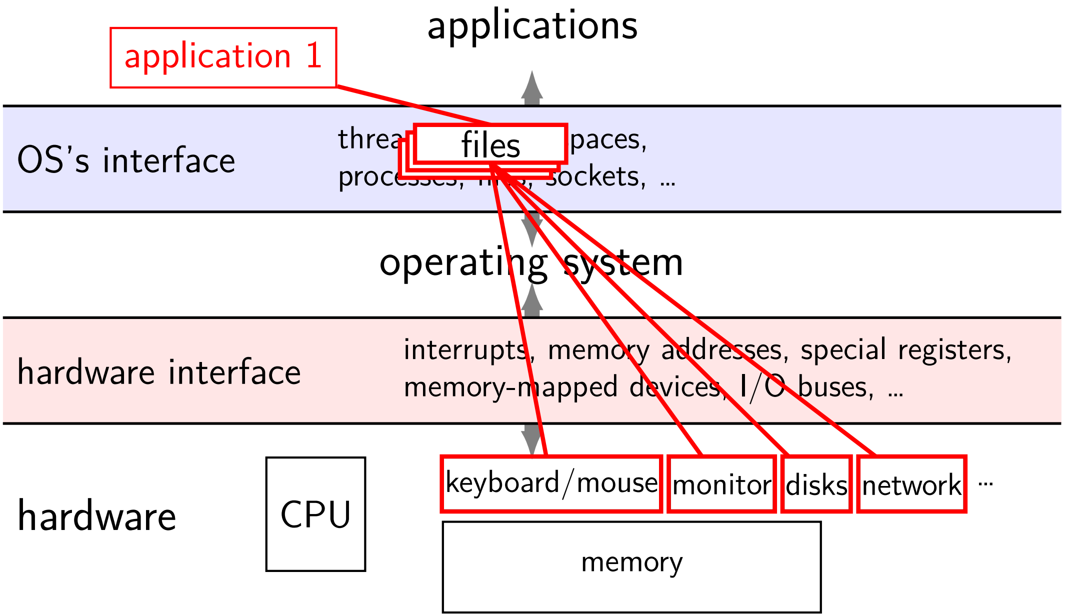
program → process → CPU and memory



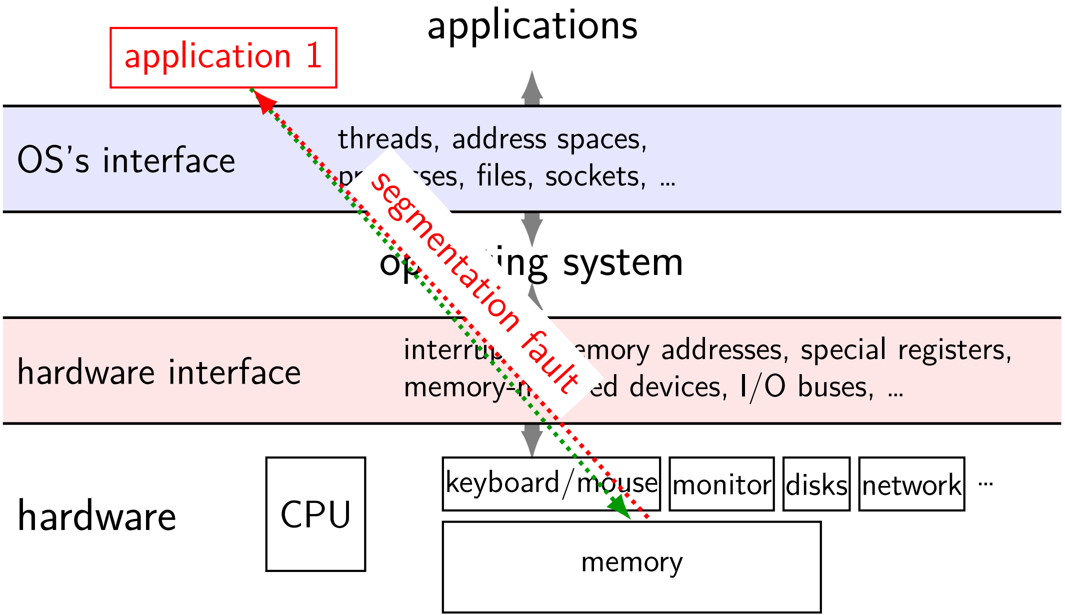
program → process → CPU and memory



files → input/output



security and protection



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?)

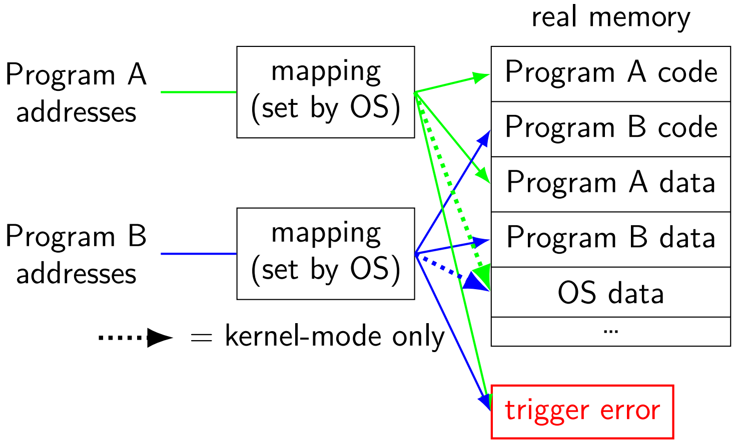
mechanism 1: dual-mode operation

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 keyboard)

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 (x86-64 Linux)

in user mode (the standard library)	in kernel mode (the “kernel”)

```
/* set arguments in registers */
mov $SYS_write, %rax
mov $FILENO_stdout, %rsi
mov $buffer, %rdi
mov $BUFFER_LEN, %r8
/* trigger exception */
syscall  // special instruction
```

```
syscall_handler:
  /* ... save registers and
        actually do read and
        set return value ... */
  /* go back to "user" code */
  iret  // special instruction
```

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

system call timeline (x86-64 Linux)

in user mode (the standard library)

```
/* set arguments in registers */
mov $SYS_write, %rax
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/* trigger exception */
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
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system call timeline (x86-64 Linux)

in user mode

(the standard library)

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/* trigger exception */
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
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system call timeline (x86-64 Linux)

in user mode

(the standard library)

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/* trigger exception */
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 ... */
  /* go back to "user" code */
  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

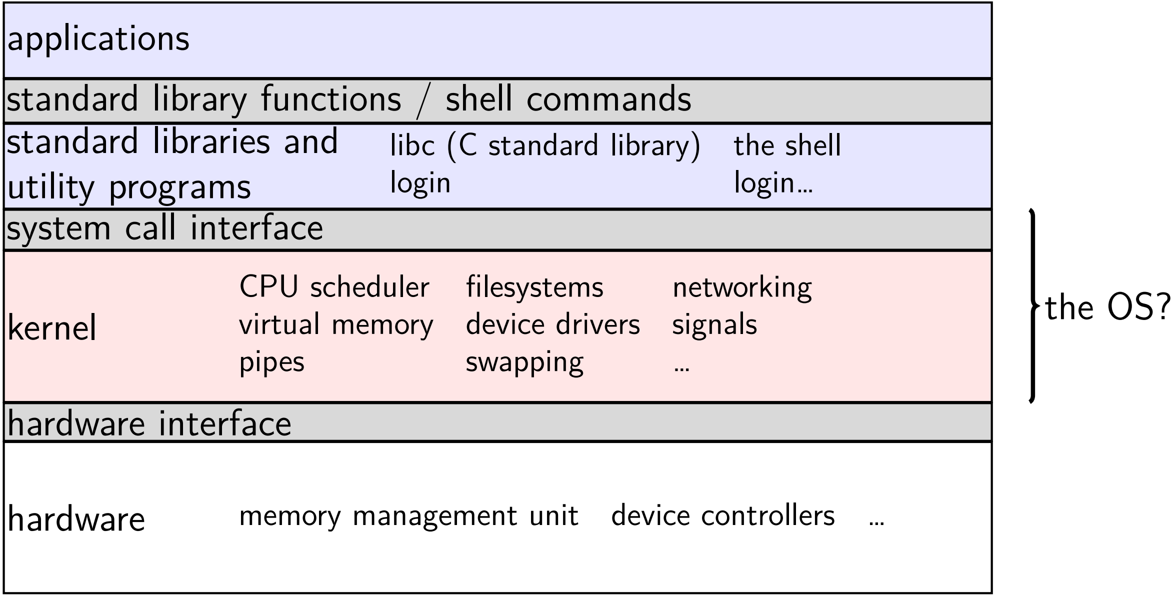
kernel — CPU scheduler, virtual memory, pipes; filesystems, device drivers, swapping; networking, signals, ...

hardware interface

hardware — memory management unit, device controllers, ...

the OS?

the classic Unix design



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 two simple xv6 system calls

includes xv6 download instructions

and link to xv6 book

xv6 technical requirements

you will need a Linux environment

- we will supply one (VM on website), or get your own
- (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

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

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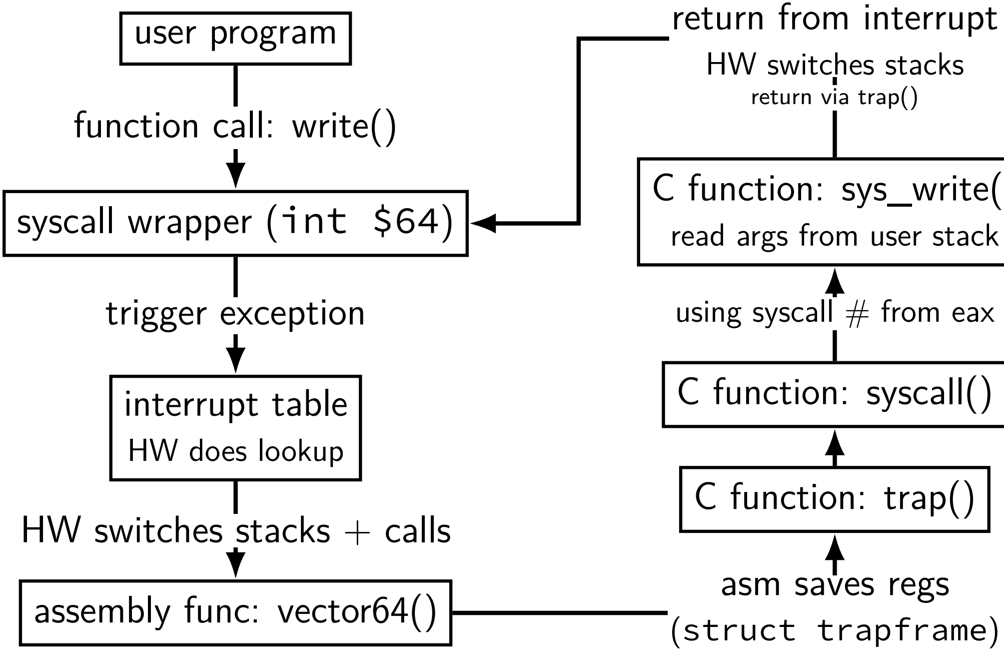
  exit();
}
```

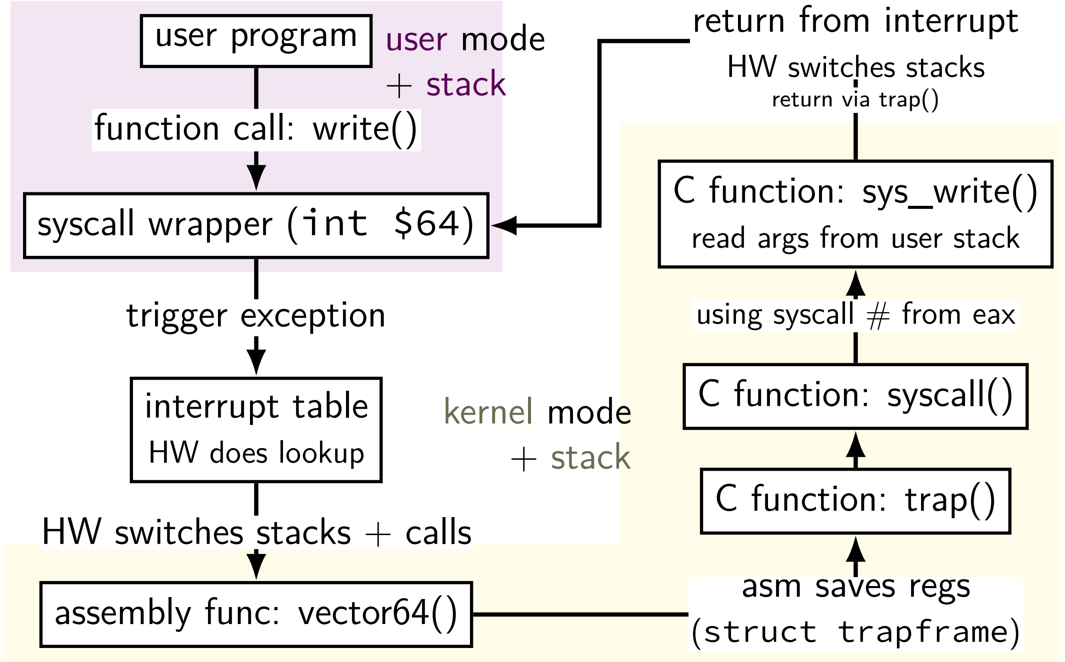
xv6 demo

xv6 demo

write syscall in xv6



write syscall in xv6



write syscall in xv6: user mode

main.c

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

syscall.h / traps.h

```
...
#define SYS_write    16
...
#define T_SYSCALL    64
...
```

usys.S

(partial, after macro replacement)

```
.globl write
write:
    movl $SYS_write, %eax
    int $T_SYSCALL
    ret
```

write syscall in xv6: user mode

main.c

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

syscall.h / traps.h

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#define SYS_write    16
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```

usys.S

(partial, after macro replacement)

```
.globl write
write:
    movl $SYS_write, %eax
    int $T_SYSCALL
    ret
```

interrupt — trigger an exception similar to a keypress

parameter (64 in this case) — type of exception

write syscall in xv6: user mode

main.c

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

syscall.h / traps.h

```
...
#define SYS_write   16
...
#define T_SYSCALL   64
...
```

usys.S

(partial, after macro replacement)

```
.globl write
write:
    movl $SYS_write, %eax
    int $T_SYSCALL
    ret
```

xv6 syscall calling convention:

eax = syscall number

otherwise: same as 32-bit x86 calling convention (arguments *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* to *idt*
idt = array of pointers to *handler functions* for each exception type
(plus a few bits of information about those handler functions)

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);
...
```

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

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 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);
...
```

1: do not disable interrupts during syscalls
e.g. keypress/timer handling can interrupt slow syscall

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);
...
```

1: do not disable interrupts during syscalls

e.g. keypress/timer handling can interrupt slow syscall

con: makes writing system calls safely more complicated

(what if keypress handler runs during system call?)

pro: slow system calls don't stop timers, keypresses, etc. from working

non-system call exceptions: interrupts disabled

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`

eventually calls C function `trap`

hardware jumps here

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)
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  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

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void
trap(struct trapframe *tf)
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    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) = {
...
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};

...

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  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

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  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

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

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

hardware jumps here

vectors.S

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

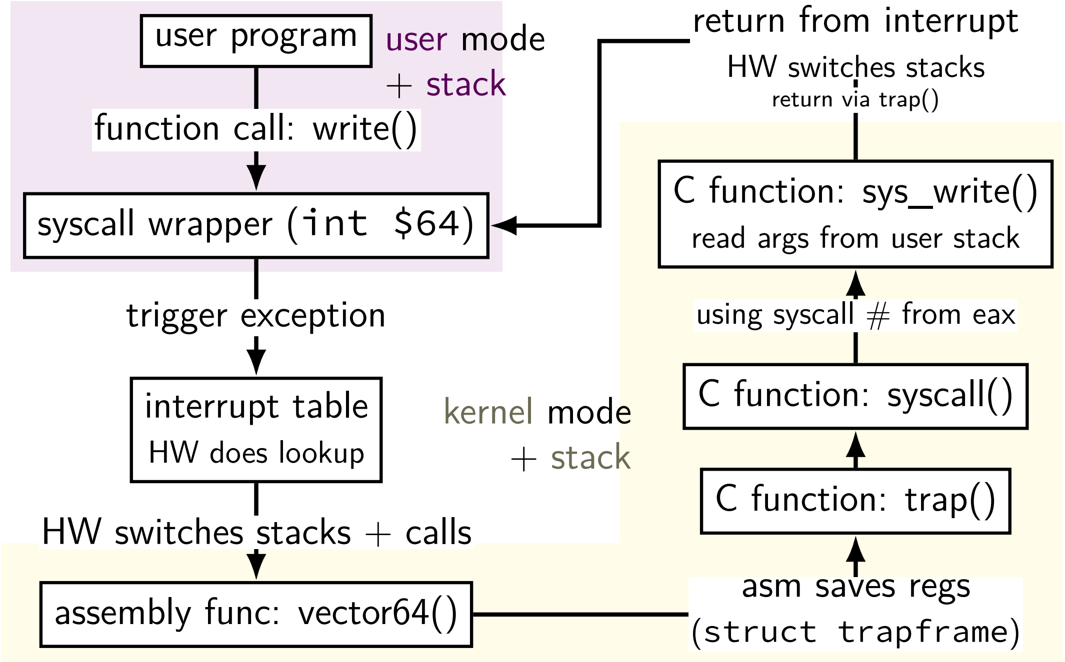
trapasm.S

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

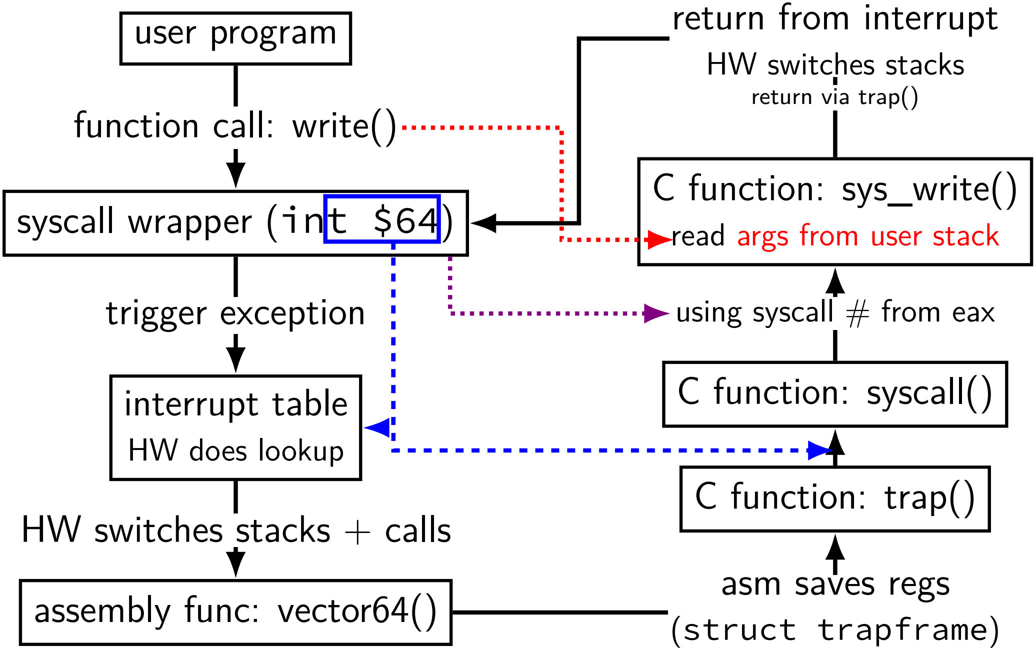
trap.c

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

write syscall in xv6



write syscall in xv6



xv6intro homework

get familiar with xv6 OS

add a new system call: `writecount()`

returns total number of times write call happened

homework steps

system call implementation: sys_writecount

- hint in writeup: imitate sys_uptime
- need a counter for number of writes

add writecount to several tables/lists

- (list of handlers, list of library functions to create, etc.)
- recommendation: imitate how other system calls are listed

create a userspace program that calls writecount

- recommendation: copy from given programs

repeat, adding `setwritecount`

note on locks

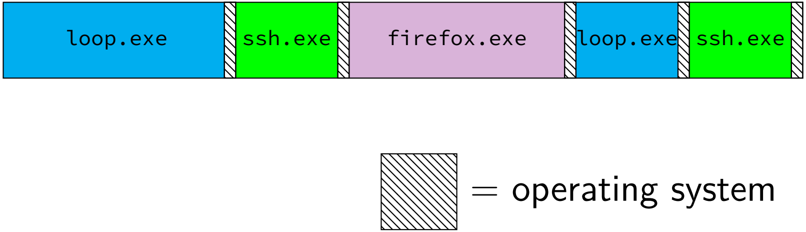
some existing code uses acquire/release

you do not have to do this

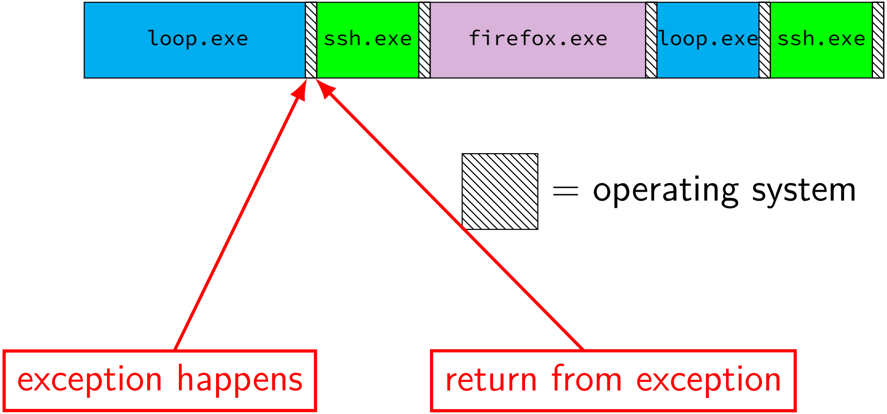
only for multiprocessor support

backup slides

time multiplexing really



time multiplexing really



OS and time multiplexing

starts running instead of normal program via exception

saves old program counter, registers somewhere

sets new registers, jumps to new program counter

called context switch

- saved information called context

context

all registers values

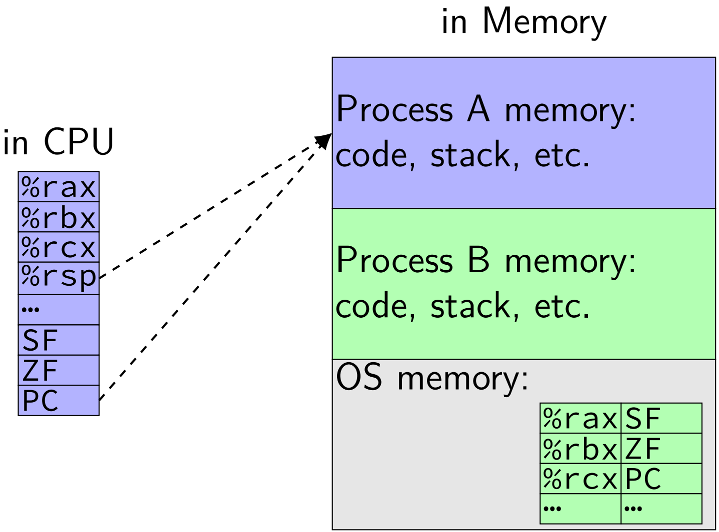
`%rax` `%rbx`, ..., `%rsp`, ...

condition codes

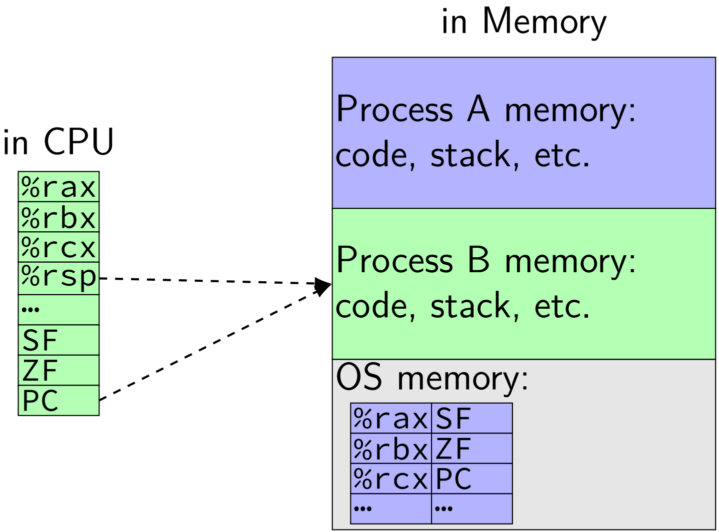
program counter

address space = page table base pointer

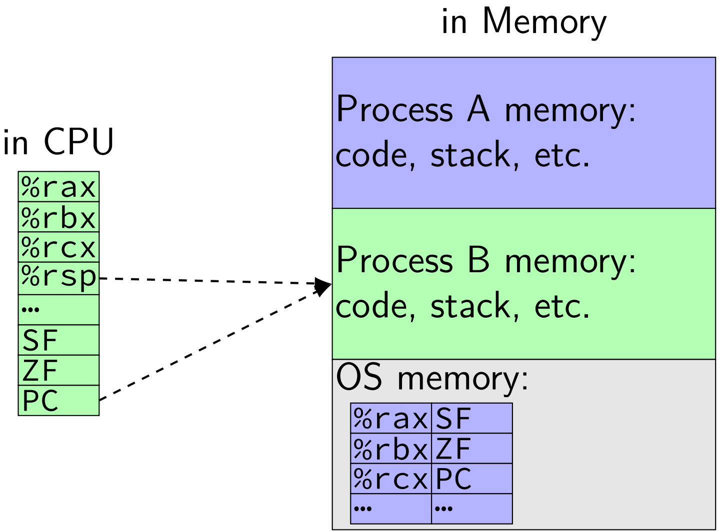
contexts (A running)



contexts (B running)



contexts (B running)



xv6: A's registers saved by exception handler into "trapframe" on A's kernel stack

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