

last time

make macros/variables (FOO=x)

pattern rules

user IDs, group IDs

chmod-style permissions

user read/write/execute; group rwx; other rwx

general access control lists

superuser / root

quiz demo

superuser

user ID 0 is special

superuser or *root*

(non-Unix) or Administrator or SYSTEM or ...

some OS functionality: only work for uid 0

shutdown, mount new file systems, etc.

automatically passes all (or almost all) permission checks

superuser v kernel mode

processor has two modes

- kernel mode (what core part of OS uses)

- user mode (every thing else)

programs running as **superuser still in user mode**

- just change in how OS acts when program asks for things

superuser : OS :: kernel mode : hardware

how does login work?

```
somemachine login: jo  
password: *****
```

```
jo@somemachine$ ls  
...
```

this is a program which...

checks if the password is correct, and

changes user IDs, and

runs a shell

how does login work?

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Unix password storage

typical single-user system: `/etc/shadow`

only readable by root/superuser

department machines: network service

Kerberos / Active Directory:

server takes (encrypted) passwords

server gives tokens: “yes, really this user”

can cryptographically verify tokens come from server

aside: beyond passwords

/bin/login entirely user-space code

only thing special about it: when it's run

could use any criteria to decide, not just passwords

- physical tokens

- biometrics

- ...

how does login work?

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jo@somemachine$ ls  
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```

this is a program which...

checks if the password is correct, and

changes user IDs, and

runs a shell

changing user IDs

```
int setuid(uid_t uid);
```

if superuser: sets effective user ID to arbitrary value
and a “real user ID” and a “saved set-user-ID” (we’ll talk later)

system starts in/login programs run as superuser
voluntarily restrict own access before running shell, etc.

sudo

```
tj1a@somemachine$ sudo restart  
Password: ****
```

sudo: run command with superuser permissions
started by non-superuser

recall: inherits non-superuser UID

can't just call `setuid(0)`

set-user-ID sudo

extra metadata bit on *executables*: set-user-ID

if set: `exec()` syscall changes effective user ID to owner's ID
“extra” user IDs track what original user was

sudo program: owned by root, marked set-user-ID
sudo's code: if (original user allowed) ...; else print error

marking setuid: `chmod u+s`

uses for setuid programs

mount USB stick

- setuid program controls option to kernel mount syscall
- make sure user can't replace sensitive directories
- make sure user can't mess up filesystems on normal hard disks
- make sure user can't mount new setuid root files

control access to device — printer, monitor, etc.

- setuid program talks to device + decides who can

write to secure log file

- setuid program ensures that log is append-only for normal users

bind to a particular port number < 1024

- setuid program creates socket, then becomes not root

set-user ID programs are very hard to write

what if stdin, stdout, stderr start closed?

what if signals setup weirdly?

what if the PATH env. var. set to directory of malicious programs?

what if `argc == 0`?

what if dynamic linker env. vars are set?

what if some bug allows memory corruption?

...

privilege escalation

privilege escalation — vulnerabilities that allow more privileges

code execution/corruption in utilities that run with high privilege

e.g. buffer overflow, command injection

login, sudo, system services, ...

bugs in system call implementations

logic errors in checking delegated operations

things programs on portal shouldn't do

read other user's files

modify OS's memory

read other user's data in memory

hang the entire system

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privileged operation: problem

how can hardware (HW) plus operating system (OS) allow:
 read your own files from hard drive

but disallow:
 read others files from hard drive

some ideas

OS tells HW 'okay' parts of hard drive before running program code

complex for hardware and for OS

some ideas

OS tells HW 'okay' parts of hard drive before running program code

- complex for hardware and for OS

OS verifies your program's code can't do bad hard drive access

- no work for HW, but complex for OS

- may require compiling differently to allow analysis

some ideas

OS tells HW 'okay' parts of hard drive before running program code

- complex for hardware and for OS

OS verifies your program's code can't do bad hard drive access

- no work for HW, but complex for OS

- may require compiling differently to allow analysis

OS tells HW to only allow OS-written code to access hard drive

- that code can enforce only 'good' accesses

- requires program code to call OS routines to access hard drive

- relatively simple for hardware

kernel mode

extra one-bit register: “are we in *kernel mode*”

other names: privileged mode, supervisor mode, ...

not in kernel mode = *user mode*

certain operations only allowed in kernel mode

privileged instructions

example: talking to any I/O device

what runs in kernel mode?

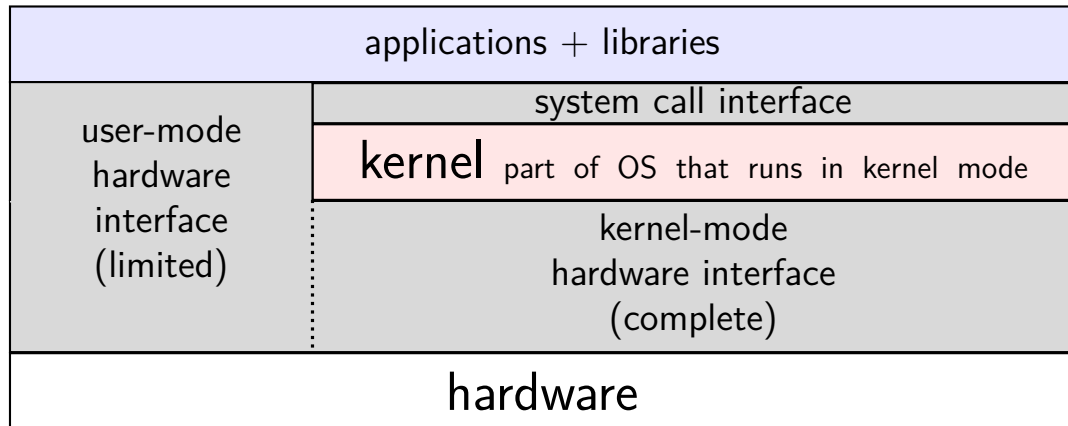
system boots in kernel mode

OS switches to user mode to run program code

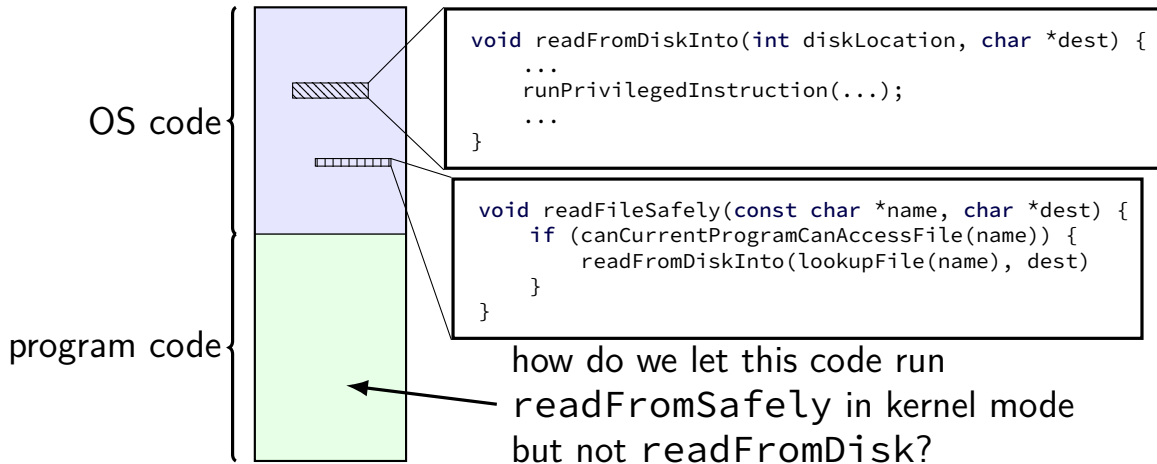
next topic: when does system switch back to kernel mode?

how does OS tell HW where the (trusted) OS code is?

hardware + system call interface



calling the OS?



controlled entry to kernel mode (1)

special instruction: “make system call”

similar idea as `call` instruction — jump to function elsewhere
(and allow that function to return later)

runs OS code in kernel mode at location specified earlier

OS sets up at boot

location can't be changed without privileged instruction

controlled entry to kernel mode (2)

OS needs to make specified location:

figure out what operation the program wants

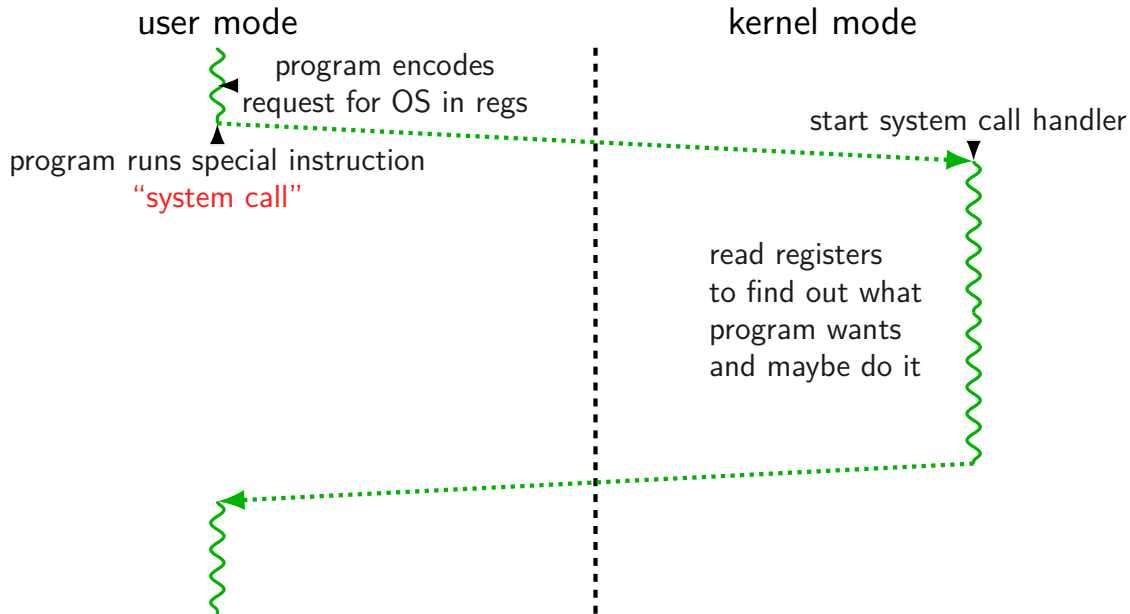
calling convention, similar to function arguments + return value

be “safe” — not allow the program to do ‘bad’ things

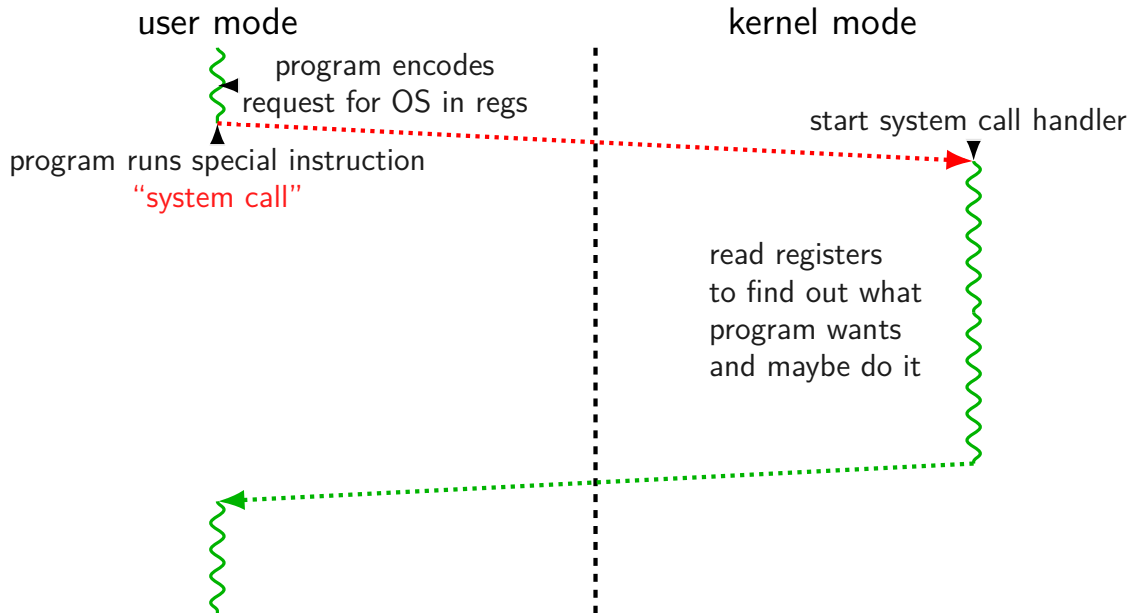
example: checks whether current program is allowed to read file before reading it

requires exceptional care — program can try weird things

system call process



system call process



system call terminology

some inconsistency:

system call = event of entering kernel mode on request?

system call = whole process from beginning to end?

same issue as with 'function call'

is it just starting the function, or the whole time the function runs?

Linux x86-64 system calls

special instruction: `syscall`

runs OS specified code in kernel mode

Linux syscall calling convention

before `syscall`:

`%rax` — system call number

`%rdi`, `%rsi`, `%rdx`, `%r10`, `%r8`, `%r9` — args

after `syscall`:

`%rax` — return value

on error: `%rax` contains -1 times “error number”

almost the same as normal function calls

Linux x86-64 hello world

```
.globl _start
.data
hello_str: .asciz "Hello, World!\n"
.text
_start:
    movq $1, %rax # 1 = "write"
    movq $1, %rdi # file descriptor 1 = stdout
    movq $hello_str, %rsi
    movq $15, %rdx # 15 = strlen("Hello, World!\n")
    syscall

    movq $60, %rax # 60 = exit
    movq $0, %rdi
    syscall
```

approx. system call handler

```
sys_call_table:
    .quad handle_read_syscall
    .quad handle_write_syscall
    // ...

handle_syscall:
    ... // save old PC, etc.
    pushq %rcx // save registers
    pushq %rdi
    ...
    call *sys_call_table(,%rax,8)
    ...
    popq %rdi
    popq %rcx
    return_from_exception
```

Linux system call examples

`mmap`, `brk` — allocate memory

`fork` — create new process

`execve` — run a program in the current process

`_exit` — terminate a process

`open`, `read`, `write` — access files

`socket`, `accept`, `getpeername` — socket-related

Linux system call examples

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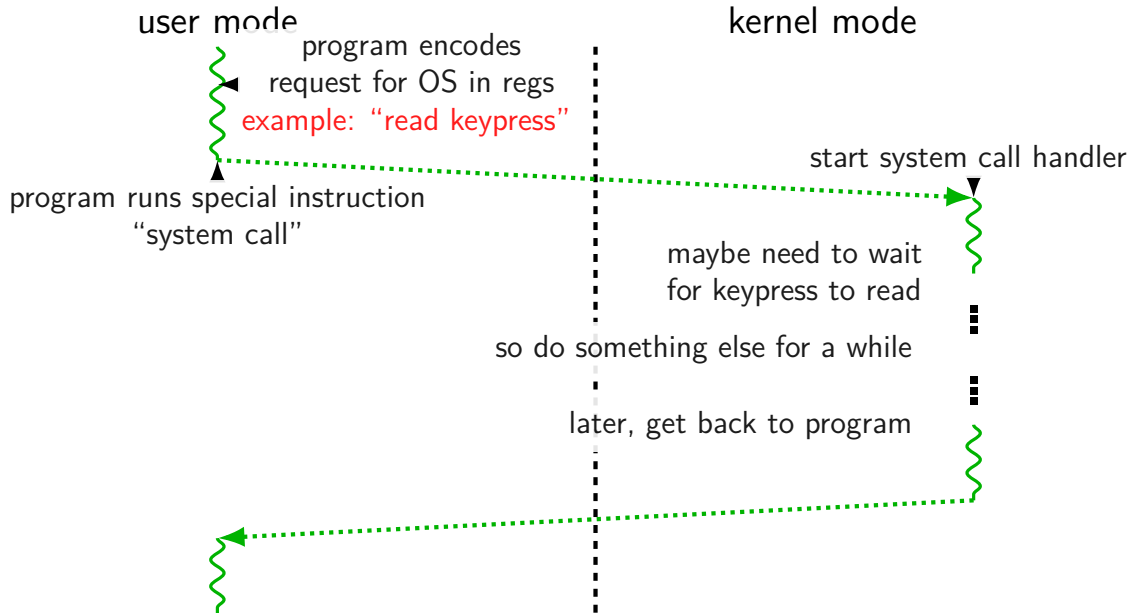
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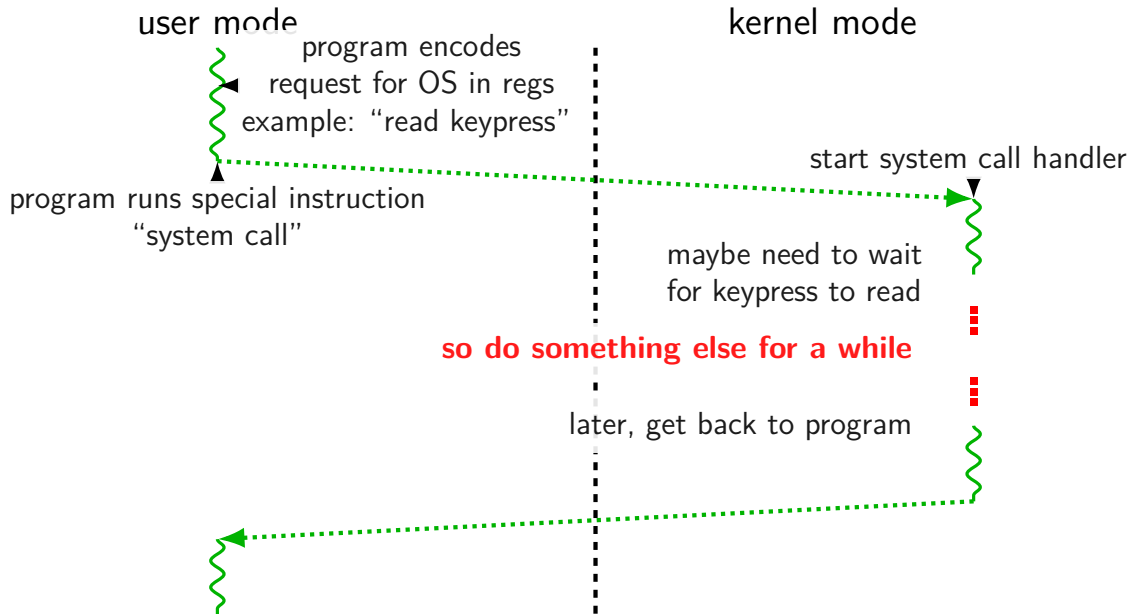
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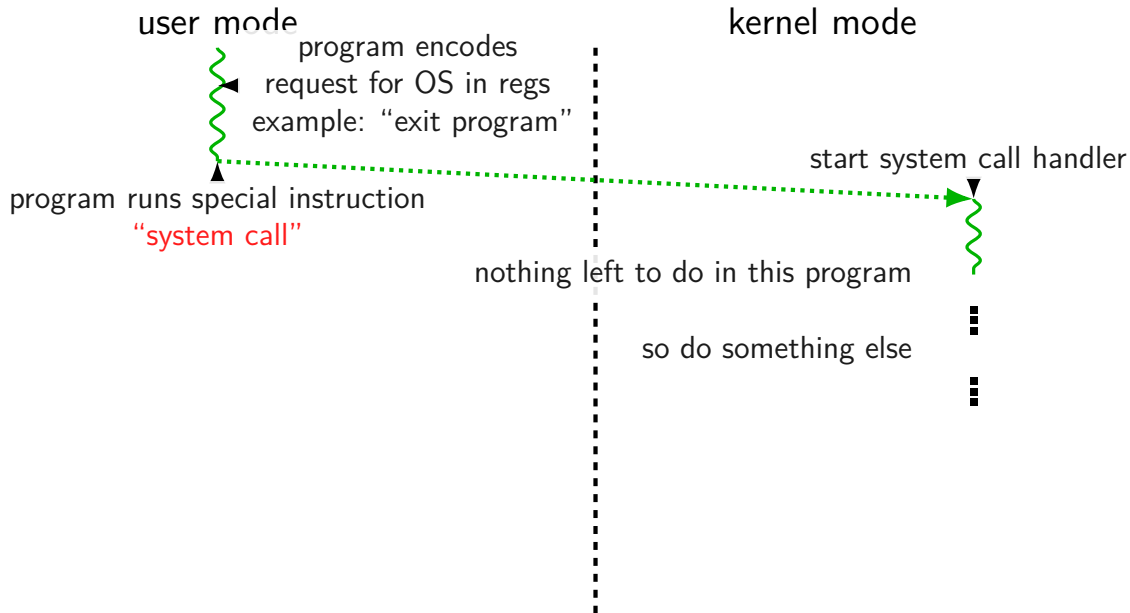
system call handled slowly?



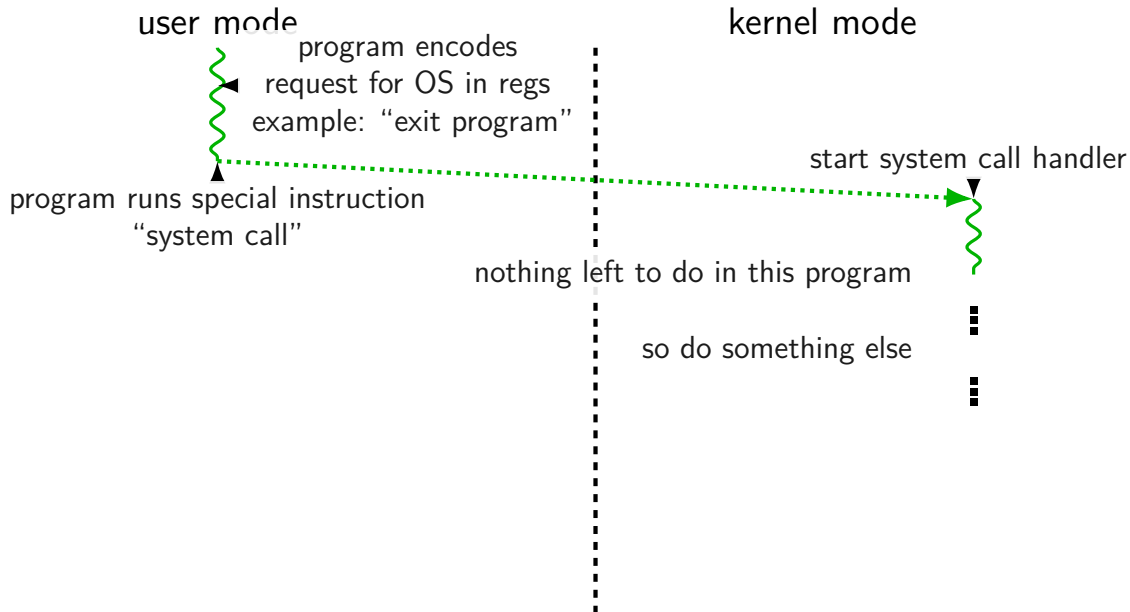
system call handled slowly?



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system call handled slowly?



system call wrappers

library functions to not write assembly:

open:

```
movq $2, %rax // 2 = sys_open
// 2 arguments happen to use same registers
syscall
// return value in %eax
cmp $0, %rax
jl has_error
ret
```

has_error:

```
neg %rax
movq %rax, errno
movq $-1, %rax
ret
```

system call wrappers

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has_error:

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neg %rax
movq %rax, errno
movq $-1, %rax
ret
```

system call wrapper: usage

```
/* unistd.h contains definitions of:  
    O_RDONLY (integer constant), open() */  
#include <unistd.h>  
int main(void) {  
    int file_descriptor;  
    file_descriptor = open("input.txt", O_RDONLY);  
    if (file_descriptor < 0) {  
        printf("error: %s\n", strerror(errno));  
        exit(1);  
    }  
    ...  
    result = read(file_descriptor, ...);  
    ...  
}
```

system call wrapper: usage

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/* unistd.h contains definitions of:  
    O_RDONLY (integer constant), open() */  
#include <unistd.h>  
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    int file_descriptor;  
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        exit(1);  
    }  
    ...  
    result = read(file_descriptor, ...);  
    ...  
}
```

strace hello_world (1)

strace — Linux tool to trace system calls

run on assembly program we saw earlier:

```
$ strace -o trace.txt ./hello_world
```

```
$ cat trace.txt
```

```
execve("./hello_world", ["./hello_world"],  
        0x7ffeedafdf0a0 /* 28 vars */) = 0  
write(1, "Hello, World!\n\0", 14)      = 14  
exit(0)                                = ?  
+++ exited with 0 +++
```

strace hello_world (2)

```
#include <stdio.h>
int main() { puts("Hello, World!"); }
```

when statically linked:

```
execve("./hello_world", ["./hello_world"], 0x7ffeb4127f70 /* 28 vars */)
    = 0
brk(NULL)
    = 0x22f8000
brk(0x22f91c0)
    = 0x22f91c0
arch_prctl(ARCH_SET_FS, 0x22f8880)
    = 0
uname({sysname="Linux", nodename="reiss-t3620", ...}) = 0
readlink("/proc/self/exe", "/u/cr4bd/spring2023/cs3130/slide"..., 4096)
    = 57
brk(0x231a1c0)
    = 0x231a1c0
brk(0x231b000)
    = 0x231b000
access("/etc/ld.so.nohwcap", F_OK)
    = -1 ENOENT (No such file or
                                directory)
fstat(1, {st_mode=S_IFCHR|0620, st_rdev=makedev(136, 4), ...}) = 0
write(1, "Hello, World!\n", 14)
    = 14
exit_group(0)
    = ?
+++ exited with 0 +++
```

aside: what are those syscalls?

`execve`: run program

`brk`: allocate heap space

`arch_prctl(ARCH_SET_FS, ...)`: thread local storage pointer
may make more sense when we cover concurrency/parallelism later

`uname`: get system information

`readlink` of `/proc/self/exe`: get name of this program

`access`: can we access this file [in this case, a config file]?

`fstat`: get information about open file

`exit_group`: variant of `exit`

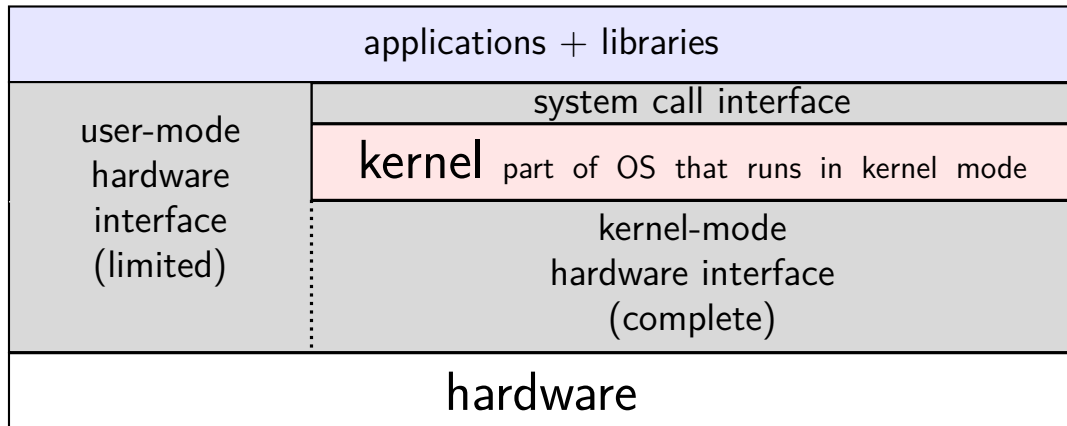
strace hello_world (2)

```
#include <stdio.h>
int main() { puts("Hello, World!"); }
```

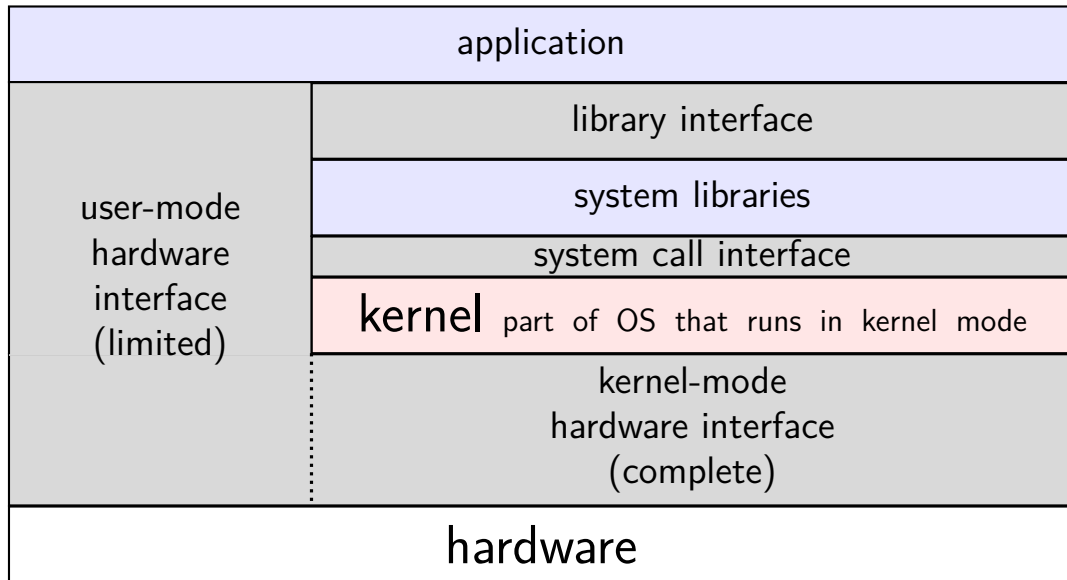
when dynamically linked:

```
execve("./hello_world", ["./hello_world"], 0x7ffcfe91d540 /* 28 vars */)
    = 0
brk(NULL)
    = 0x55d6c351b000
...
openat(AT_FDCWD, "/etc/ld.so.cache", O_RDONLY|O_CLOEXEC) = 3
fstat(3, {st_mode=S_IFREG|0644, st_size=196684, ...}) = 0
mmap(NULL, 196684, PROT_READ, MAP_PRIVATE, 3, 0) = 0x7f7a62dd3000
close(3)
    = 0
access("/etc/ld.so.nohwcap", F_OK)
    = -1 ENOENT (No such file or directory)
openat(AT_FDCWD, "/lib/x86_64-linux-gnu/libc.so.6", O_RDONLY|O_CLOEXEC) = 3
read(3, "\177ELF\2\1\1\3\0\0\0\0\0\0\0\0\0\0\3\0>\0\1\0\0\0"..., 832) = 832
...
close(3)
    = 0
write(1, "Hello, World!\n", 14)
    = 14
exit_group(0)
    = ?
+++ exited with 0 +++
```

hardware + system call interface



hardware + system call + library interface



things programs on portal shouldn't do

read other user's files

modify OS's memory

read other user's data in memory

hang the entire system

memory protection

modifying another program's memory?

Program A	Program B
<pre>0x10000: .long 42 // ... // do work // ... movq 0x10000, %rax</pre>	<pre><i>// while A is working:</i> movq \$99, %rax movq %rax, 0x10000 ...</pre>

memory protection

modifying another program's memory?

Program A	Program B
<pre>0x10000: .long 42 // ... // do work // ... movq 0x10000, %rax</pre>	<pre><i>// while A is working:</i> movq \$99, %rax movq %rax, 0x10000 ...</pre>
result: %rax (in A) is ...	

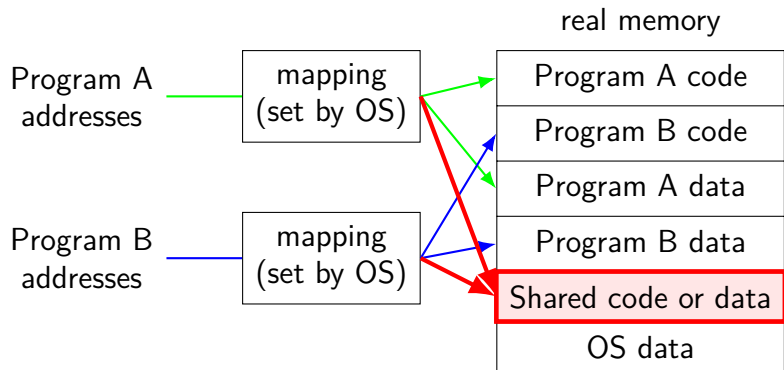
- A. 42
- B. 99
- C. 0x10000
- D. 42 or 99 (depending on timing/program layout/etc)
- E. 42 or 99 or program might crash (depending on ...)
- F. something else

shared memory

recall: dynamically linked libraries

would be nice not to duplicate code/data...

we can!



one way to set shared memory on Linux

```
/* regular file, OR: */
int fd = open("/tmp/somefile.dat", O_RDWR);
/* special in-memory file */
int fd = shm_open("/name", O_RDWR);
...
/* make file's data accessible as memory */
void *memory = mmap(NULL, size, PROT_READ | PROT_WRITE,
                    MAP_SHARED, fd, 0);
```

mmap: “map” a file’s data into your memory

will discuss a bit more when we talk about virtual memory

part of how Linux loads dynamically linked libraries

memory protection

modifying another program's memory?

Program A	Program B
<pre>0x10000: .long 42 // ... // do work // ... movq 0x10000, %rax</pre>	<pre><i>// while A is working:</i> movq \$99, %rax movq %rax, 0x10000 ...</pre>
<p>result: %rax (in A) is 42 (always with 'normal' multiuser OSes)</p> <p>A. 42 B. 99 C. 0x10000 D. 42 or 99 (depending on timing/program layout/etc) E. 42 or 99 or program might crash (depending on ...) F. something else</p>	<p>result: might crash</p>

program crashing?

what happens on processor when program crashes?

other program informed of crash to display message

use processor to run some other program

program crashing?

what happens on processor when program crashes?

other program informed of crash to display message

use processor to run some other program

how does hardware do this?

would be complicated to tell about other programs, etc.

instead: hardware runs designated OS routine

exceptions

recall: system calls — software asks OS for help

also cases where hardware asks OS for help

different triggers than system calls

but same mechanism as system calls:

- switch to kernel mode (if not already)

- call OS-designated function

exceptions

recall: system calls — software asks OS for help

also cases where hardware asks OS for help

different triggers than system calls

but **same mechanism as system calls**:

- switch to kernel mode (if not already)

- call OS-designated function

types of exceptions

- system calls

 - intentional — ask OS to do something

- errors/events in programs

 - memory not in address space (“Segmentation fault”)

 - privileged instruction

 - divide by zero, invalid instruction

 - ...

- (and more we'll talk about later)

types of exceptions

system calls

intentional — ask OS to do something

errors/events in programs

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(and more we'll talk about later)

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synchronous

triggered by
current program

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triggered by
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external — I/O, etc.

timer — configured by OS to run OS at certain time

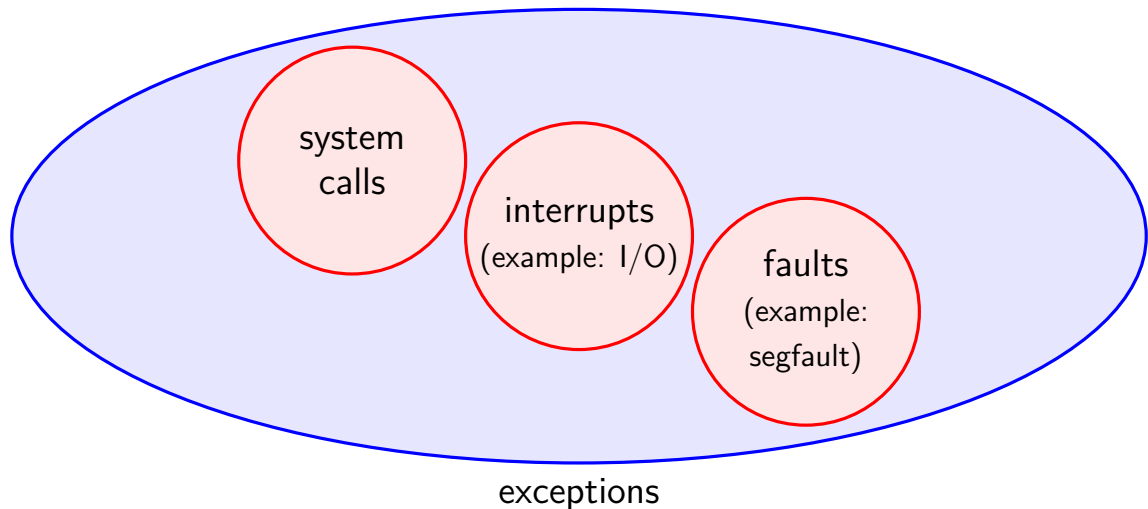
I/O devices — key presses, hard drives, networks, ...

hardware is broken (e.g. memory parity error)

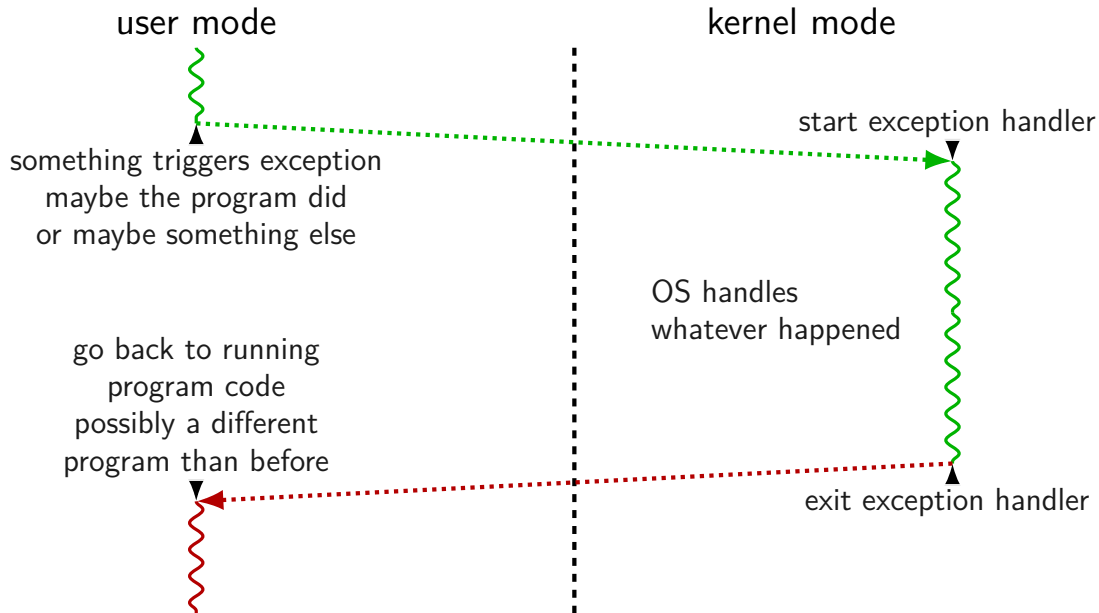
asynchronous

not triggered by
running program

exceptions [Venn diagram]



general exception process

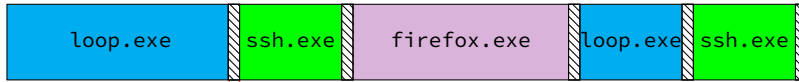


time multiplexing



= operating system

time multiplexing



= operating system

exception happens

return from exception

switching programs

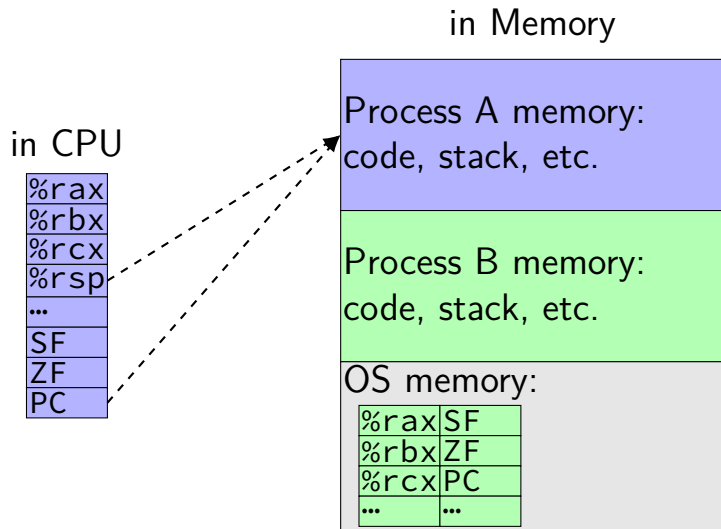
OS starts running somehow
some sort of exception

saves old registers + program counter + address mapping
(optimization: could omit when program crashing/exiting)

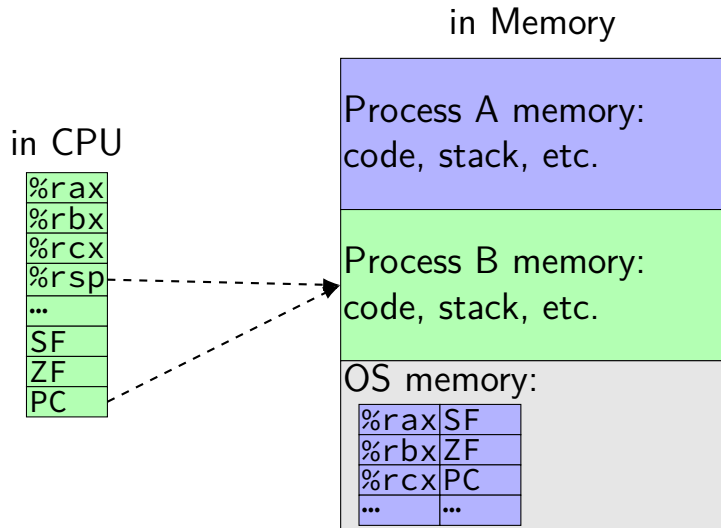
sets new registers + address mapping, jumps to new program counter

called **context switch**
saved information called **context**

contexts (A running)



contexts (B running)



threads

thread = illusion of own processor

own register values

own program counter value

threads

thread = illusion of own processor

own register values

own program counter value

actual implementation:

many threads sharing one processor

problem: where are register/program counter values
when thread not active on processor?

types of exceptions

system calls

intentional — ask OS to do something

errors/events in programs

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...

external — I/O, etc.

timer — configured by OS to run OS at certain time

I/O devices — key presses, hard drives, networks, ...

hardware is broken (e.g. memory parity error)

synchronous

triggered by
current program

asynchronous

not triggered by
running program

exception patterns with I/O (1)

input — available now:

- exception: device says “I have input now”

- handler: OS stores input for later

- exception (syscall): program says “I want to read input”

- handler: OS returns that input

input — not available now:

- exception (syscall): program says “I want to read input”

- handler: OS runs other things (context switch)

- exception: device says “I have input now”

- handler: OS retrieves input

- handler: (possibly) OS switches back to program that wanted it

exception patterns with I/O (2)

output — ready now:

exception (syscall): program says “I want to output this”

handler: OS sends output to device

output — not ready now

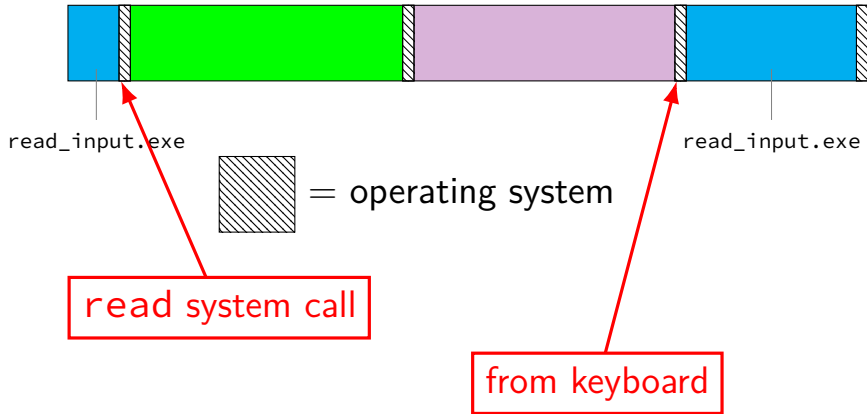
exception (syscall): program says “I want to output”

handler: OS realizes device can't accept output yet
(other things happen)

exception: device says “I'm ready for output now”

handler: OS sends output requested earlier

keyboard input timeline



review: definitions

exception: hardware calls OS specified routine

- many possible reasons

- system calls: type of exception

context switch: OS switches to another thread

- by saving old register values + loading new ones

- part of OS routine run by exception

which of these require exceptions? context switches?

- A. program calls a function in the standard library
- B. program writes a file to disk
- C. program A goes to sleep, letting program B run
- D. program exits
- E. program returns from one function to another function
- F. program pops a value from the stack

terms for exceptions

terms for exceptions aren't standardized

our readings use one set of terms

- interrupts = externally-triggered

- faults = error/event in program

- trap = intentionally triggered

all these terms appear differently elsewhere

The Process

process = thread(s) + address space

illusion of **dedicated machine**:

- thread = illusion of own CPU

- (process could have multiple threads — with independent registers)

- address space = illusion of own memory

backup slides

authorization v authentication

authentication — who is who

authorization v authentication

authentication — who is who

authorization — who can do what
probably need authentication first...

authentication

password

hardware token

...

some security tasks (1)

helping students collaborate in ad-hoc small groups on shared server?

Q1: what to allow/prevent?

Q2: how to use POSIX mechanisms to do this?

some security tasks (2)

letting students assignment files to faculty on shared server?

Q1: what to allow/prevent?

Q2: how to use POSIX mechanisms to do this?

some security tasks (3)

running untrusted game program from Internet?

Q1: what to allow/prevent?

Q2: how to use POSIX mechanisms to do this?

set-user ID gates

set-user ID program: gate to higher privilege

controlled access to extra functionality

make authorization/authentication decisions *outside the kernel*

way to allow normal users to do *one thing that needs privileges*

- write program that does that one thing — nothing else!

- make it owned by user that can do it (e.g. root)

- mark it set-user-ID

want to allow only some user to do the thing

- make program check which user ran it

set-user-ID program v syscalls

hardware decision: some things only for kernel

system calls: *controlled* access to things kernel can do

decision about how can do it: in the kernel

kernel decision: some things only for root (or other user)

set-user-ID programs: controlled access to things root/... can do

decision about how can do it: made by root/...

a broken setuid program: setup

suppose I have a directory all-grades on shared server

in it I have a folder for each assignment

and within that a text file for each user's grade + other info

say I don't have flexible ACLs and want to give each user access

a broken setuid program: setup

suppose I have a directory all-grades on shared server

in it I have a folder for each assignment

and within that a text file for each user's grade + other info

say I don't have flexible ACLs and want to give each user access

one (bad?) idea: setuid program to read grade for assignment

```
./print_grade assignment
```

outputs grade from all-grades/assignment/USER.txt

a very broken setuid program

print_grade.c:

```
int main(int argc, char **argv) {
    char filename[500];
    sprintf(filename, "all-grades/%s/%s.txt",
            argv[1], getenv("USER"));
    int fd = open(filename, O_RDWR);
    char buffer[1024];
    read(fd, buffer, 1024);
    printf("%s: %s\n", argv[1], buffer);
}
```

HUGE amount of stuff can go wrong

examples?

other privileged escalation issues

sudo problem: trusted code that's supposed to enforce restriction can be fooled into not really enforcing it

also can occur in other contexts:

system call letting program access things it shouldn't?

browser letting web page javascript access things it shouldn't?

web application giving users access to files they shouldn't have?

mobile phone OS allowing location access without location permission?

...

another very broken setuid program (setup)

allow users to print files, but only if less than 1KB

another very broken setuid program

print_short_file.c:

```
int main(int argc, char **argv) {
    struct stat st;
    if (stat(argv[1], &st) == -1) abort();
    // make sure argv[1] is owned by user running this
    if (st.st_uid != getuid()) abort();
    // and that it's less than 1 KB
    if (st.st_size >= 1024) abort();
    char command[1024];
    sprintf(command, "print_%1000s", argv[1]);
    system(command);
    return EXIT_SUCCESS;
}
```

a delegation problem

consider printing program marked `setuid` to access printer

- decision: no accessing printer directly

- printing program enforces page limits, etc.

command line: file to print

can printing program just call `open()`?

a broken solution

```
if (original user can read file from argument) {  
    open(file from argument);  
    read contents of file;  
    write contents of file to printer  
    close(file from argument);  
}
```

hope: this prevents users from printing files than can't read

problem: race condition!

a broken solution / why

setuid program

check: can user access? (yes)

open("toprint.txt")

read ...

other user program

create normal file toprint.txt

—

unlink("toprint.txt")

link("/secret", "toprint.txt")

—

—

link: create new directory entry for file

another option: rename, symlink ("symbolic link" — alias for file/directory)

another possibility: run a program that creates secret file (e.g. temporary file used by password-changing program)

time-to-check-to-time-of-use vulnerability

TOCTTOU solution

temporarily 'become' original user

then open

then turn back into set-uid user

this is why POSIX processes have multiple user IDs

can swap out effective user ID temporarily

practical TOCTTOU races?

can use symlinks *maze* to make check slower

symlink toprint.txt → a/b/c/d/e/f/g/normal.txt

symlink a/b → ../a

symlink a/c → ../a

...

lots of time spent following symbolic links when program opening toprint.txt

gives more time to sneak in unlink/link or (more likely) rename

exercise

which (if any) of the following would fix for a TOCTTOU vulnerability in our setuid printing application? (assume the Unix-permissions without ACLs are in use)

[A] **both before and after** opening the path passed in for reading, check that the path is accessible to the user who ran our application

[B] after opening the path passed in for reading, using `fstat` with the file descriptor opened to check the permissions on the file

[C] before opening the path, verify that the user controls the file referred to by the path **and** the directory containing it

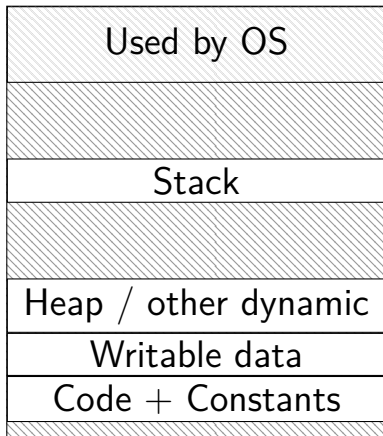
keeping permissions?

which of the following would still be secure?

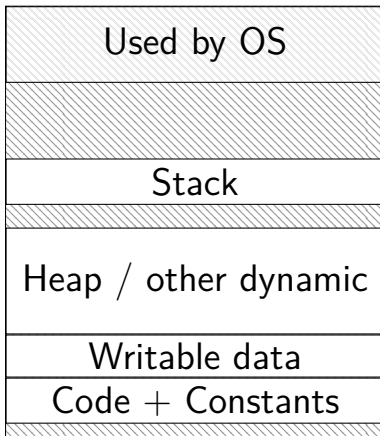
- A. performing authorization checks in the standard library in addition to system call handlers
- B. performing authorization checks in the standard library instead of system call handlers
- C. making the user ID a system call argument rather than storing it persistently in the OS's memory

program memory (two programs)

Program A



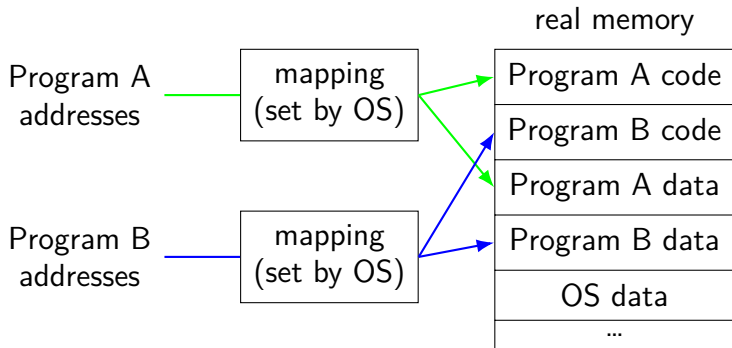
Program B



address space

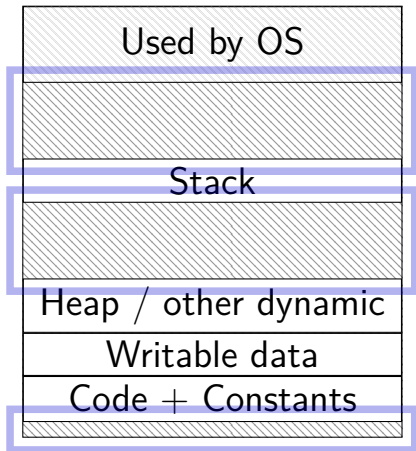
programs have **illusion of own memory**

called a program's **address space**

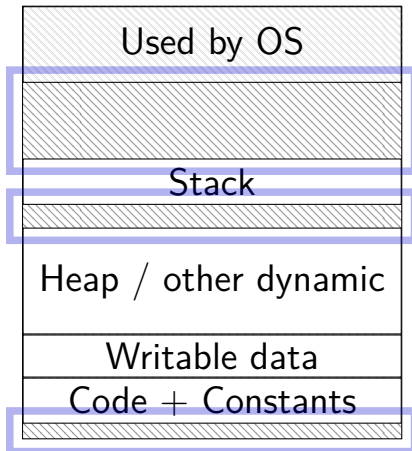


program memory (two programs)

Program A



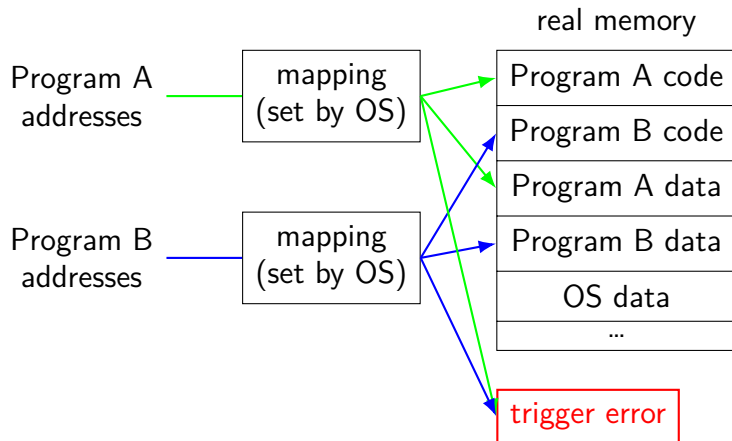
Program B



address space

programs have **illusion of own memory**

called a program's **address space**



address space mechanisms

topic after exceptions

called **virtual memory**

mapping called **page tables**

mapping part of what is changed in context switch

an infinite loop

```
int main(void) {  
    while (1) {  
        /* waste CPU time */  
    }  
}
```

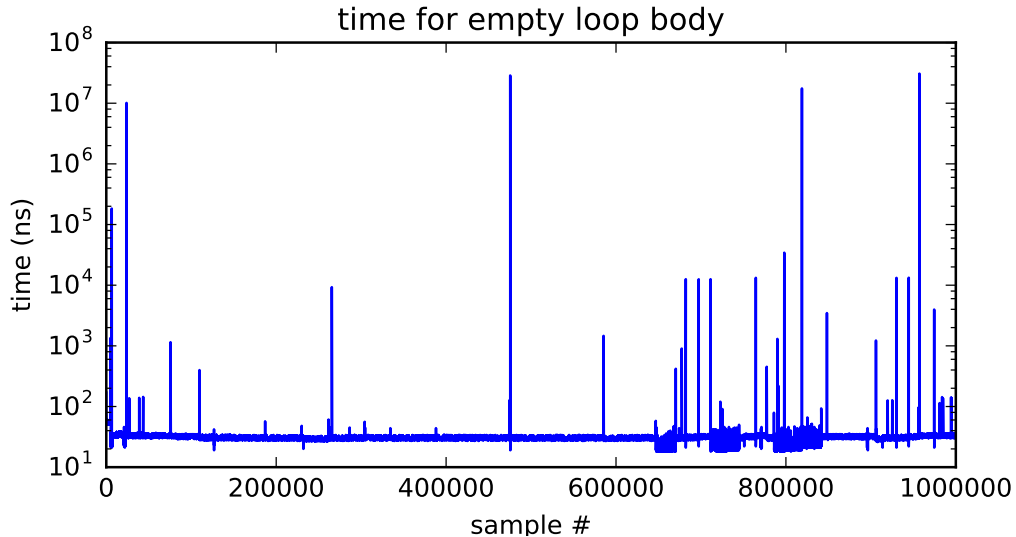
If I run this on a shared department machine, can you still use it?
...if the machine only has one core?

timing nothing

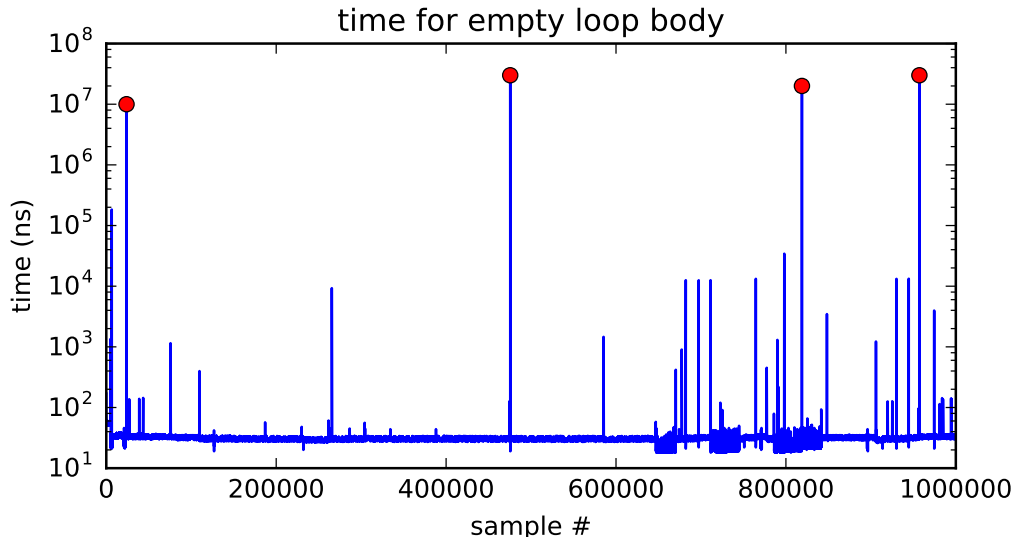
```
long times[NUM_TIMINGS];
int main(void) {
    for (int i = 0; i < N; ++i) {
        long start, end;
        start = get_time();
        /* do nothing */
        end = get_time();
        times[i] = end - start;
    }
    output_timings(times);
}
```

same instructions — *same difference* each time?

doing nothing on a busy system

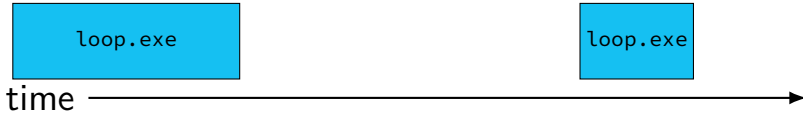


doing nothing on a busy system



time multiplexing

processor:



time multiplexing

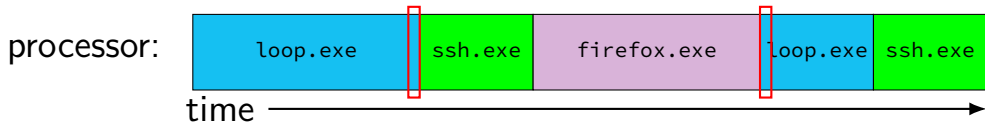


```
...  
call get_time  
    // whatever get_time does  
movq %rax, %rbp
```

———— million cycle delay ————

```
call get_time  
    // whatever get_time does  
subq %rbp, %rax  
...
```

time multiplexing



...

```
call get_time
```

// whatever get_time does

```
movq %rax, %rbp
```

———— million cycle delay ————

```
call get_time
```

// whatever get_time does

```
subq %rbp, %rax
```

...

crash timeline timeline



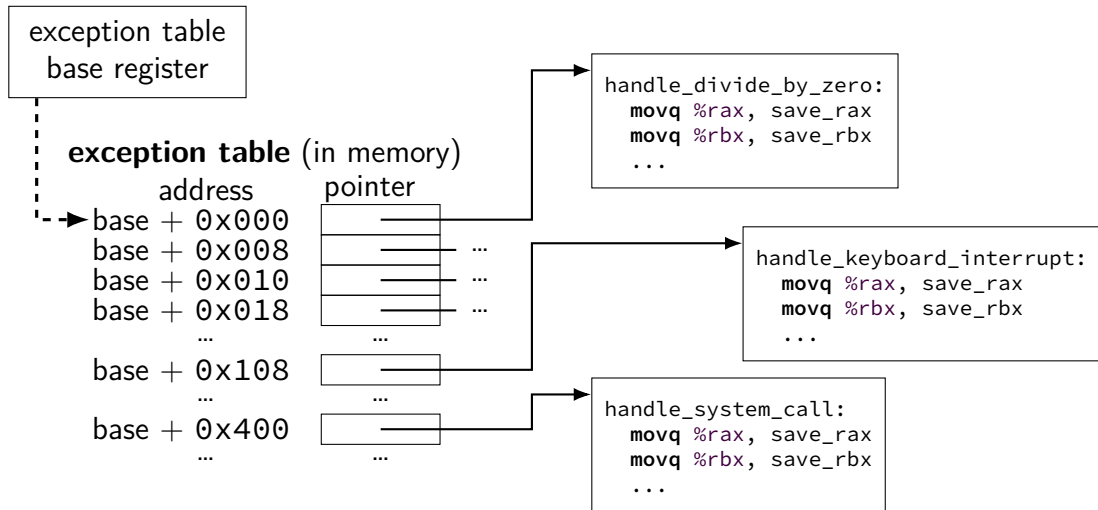
segfault.exe



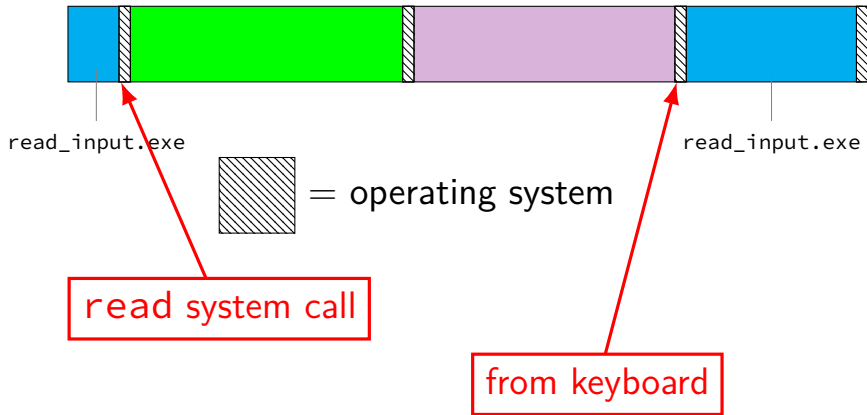
= operating system

out of bounds memory access

locating exception handlers (one strategy)



keyboard input timeline



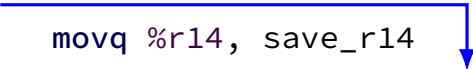
exceptions in exceptions

```
handle_timer_interrupt:  
    save_old_pc save_pc  
    movq %r15, save_r15  
    /* key press here */  
  
    movq %r14, save_r14  
    ...
```

exceptions in exceptions

```
handle_timer_interrupt:  
    save_old_pc save_pc  
    movq %r15, save_r15  
    /* key press here */
```

```
    movq %r14, save_r14  
    ...
```



```
handle_keyboard_interrupt:  
    save_old_pc save_pc  
    movq %r15, save_r15  
    movq %r14, save_r14  
    movq %r13, save_r13  
    ...
```

exceptions in exceptions

```
handle_timer_interrupt:  
    save_old_pc save_pc  
    movq %r15, save_r15  
    /* key press here */
```

```
    movq %r14, save_r14  
    ...
```

oops, overwrote saved values?

```
handle_keyboard_interrupt:  
    save_old_pc save_pc  
    movq %r15, save_r15  
    movq %r14, save_r14  
    movq %r13, save_r13  
    ...
```

interrupt disabling

CPU supports **disabling** (most) interrupts

interrupts will **wait** until it is reenabled

CPU has extra state:

- are interrupts enabled?

- is keyboard interrupt pending?

- is timer interrupt pending?

exceptions in exceptions

```
handle_timer_interrupt:
```

```
/* interrupts automatically disabled here */
```

```
movq %rsp, save_rsp
```

```
save_old_pc save_pc
```

```
/* key press here */
```

```
jmpIfFromKernelMode skip_exception_stack
```

```
movq current_exception_stack, %rsp
```

```
skip_set_kernel_stack:
```

```
pushq save_rsp
```

```
pushq save_pc
```

```
enable_intterrupts2
```

```
pushq %r15
```

```
...
```

```
/* interrupt happens here! */
```

```
...
```

exceptions in exceptions

```
handle_timer_interrupt:
```

```
    /* interrupts automatically disabled here */
```

```
    movq %rsp, save_rsp
```

```
    save_old_pc save_pc
```

```
    /* key press here */
```

```
    jmpIfFromKernelMode skip_exception_stack
```

```
    movq current_exception_stack, %rsp
```

```
skip_set_kernel_stack:
```

```
    pushq save_rsp
```

```
    pushq save_pc
```

```
    enable_intterrupts2
```

```
    pushq %r15
```

```
    ...
```

```
    /* interrupt happens here! */
```

```
    ...
```

exceptions in exceptions

handle_timer_interrupt:

/ interrupts automatically disabled here */*

movq %rsp, save_rsp

save_old_pc save_pc

/ key press here */*

jmpIfFromKernelMode skip_exception_stack

movq current_exception_stack, %rsp

skip_set_kernel_stack:

pushq save_rsp

pushq save_pc

enable_intterrupts2

pushq %r15

...

/ interrupt happens here! */*

...

handle_keyboard_interrupt:

movq %rsp, save_rsp

disabling interrupts

automatically disabled when exception handler starts

also can be done with privileged instruction:

```
change_keyboard_parameters:
```

```
    disable_interrupts
```

```
    ...
```

```
    /* change things used by  
       handle_keyboard_interrupt here */
```

```
    ...
```

```
    enable_interrupts
```

exception implementation

detect condition (program error or external event)

save current value of PC somewhere

jump to **exception handler** (part of OS)

jump done without program instruction to do so

exception implementation: notes

I describe a **simplified** version

real x86/x86-64 is a bit more complicated
(mostly for historical reasons)

context

all registers values

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

condition codes

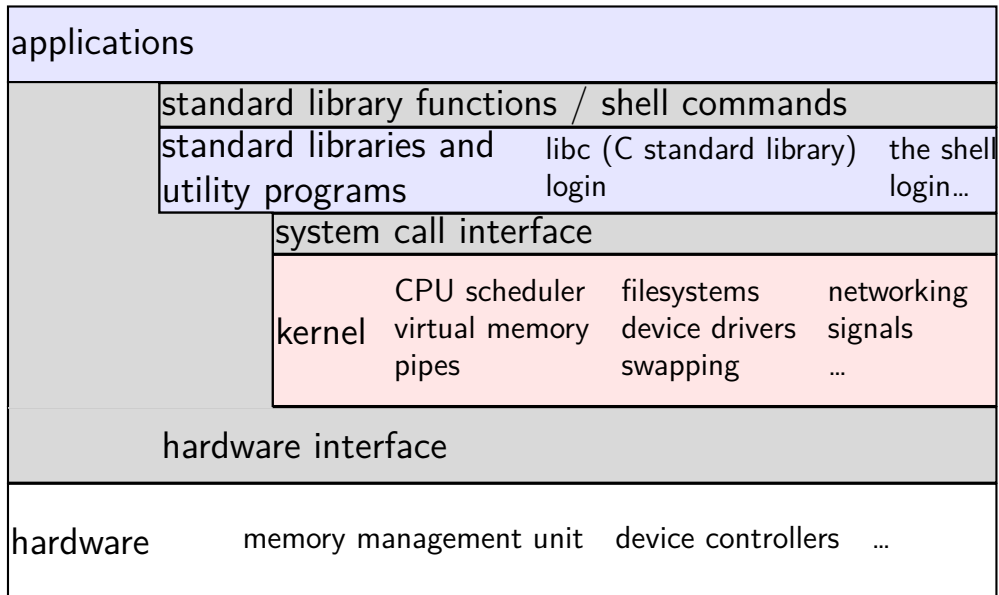
program counter

address space (map from program to real addresses)

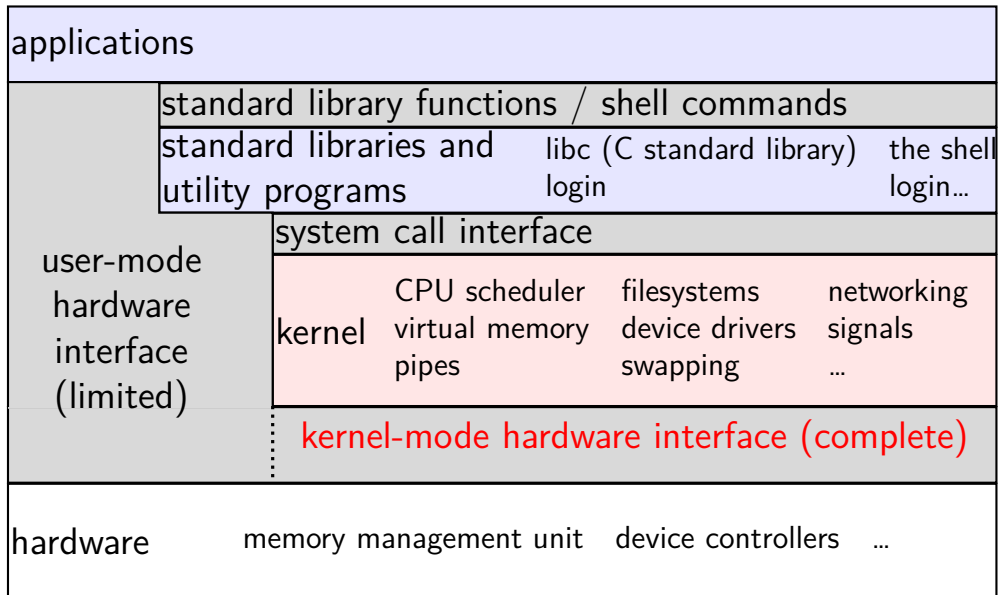
context switch pseudocode

```
context_switch(last, next):  
    copy_preexception_pc last->pc  
    mov rax, last->rax  
    mov rcx, last->rcx  
    mov rdx, last->rdx  
    ...  
    mov next->rdx, rdx  
    mov next->rcx, rcx  
    mov next->rax, rax  
    jmp next->pc
```

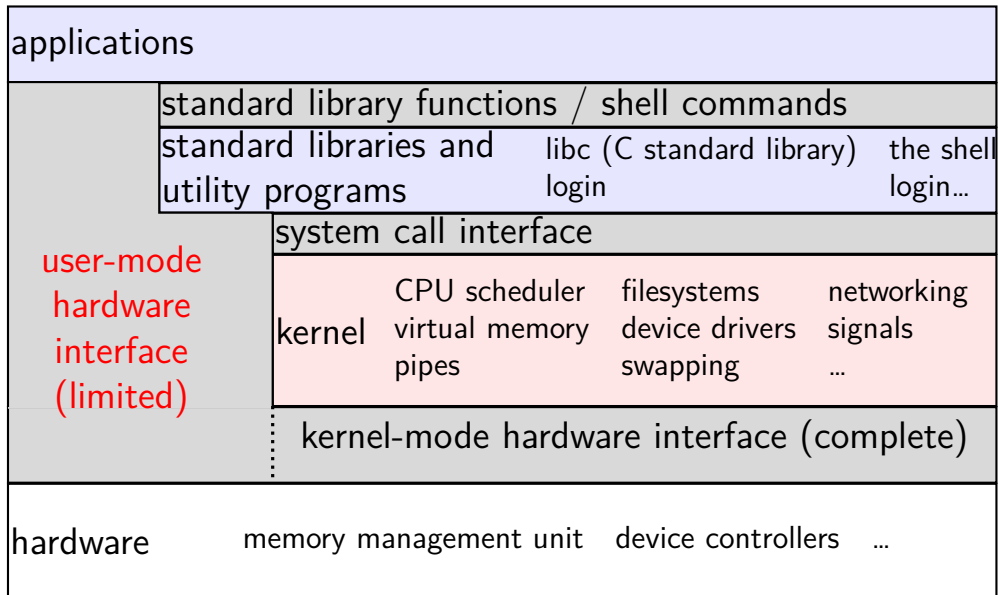
the classic Unix design



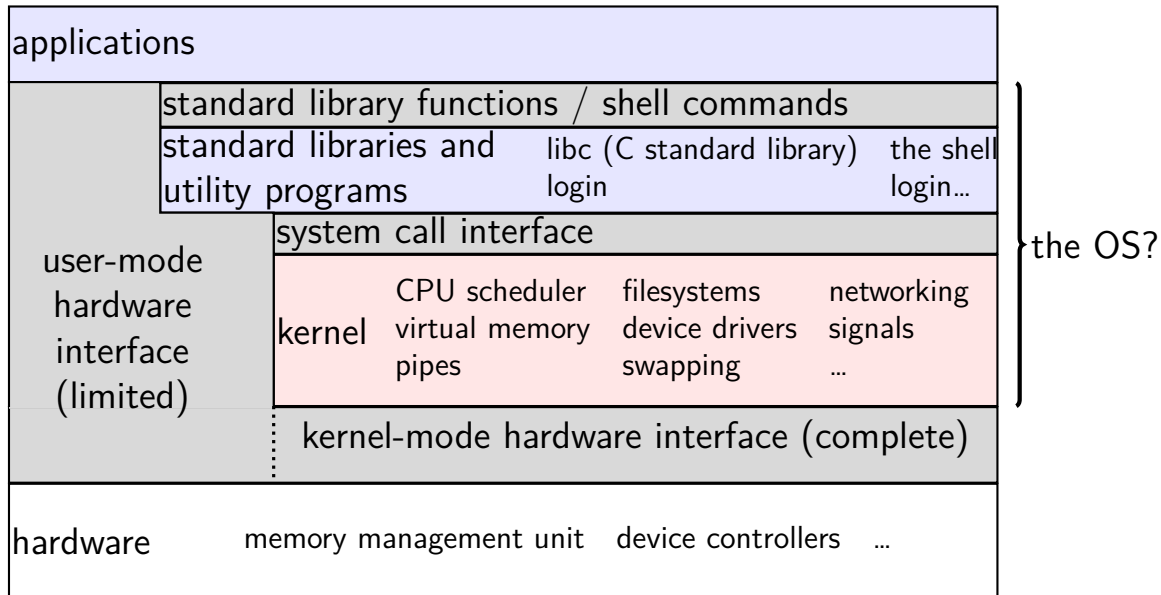
the classic Unix design



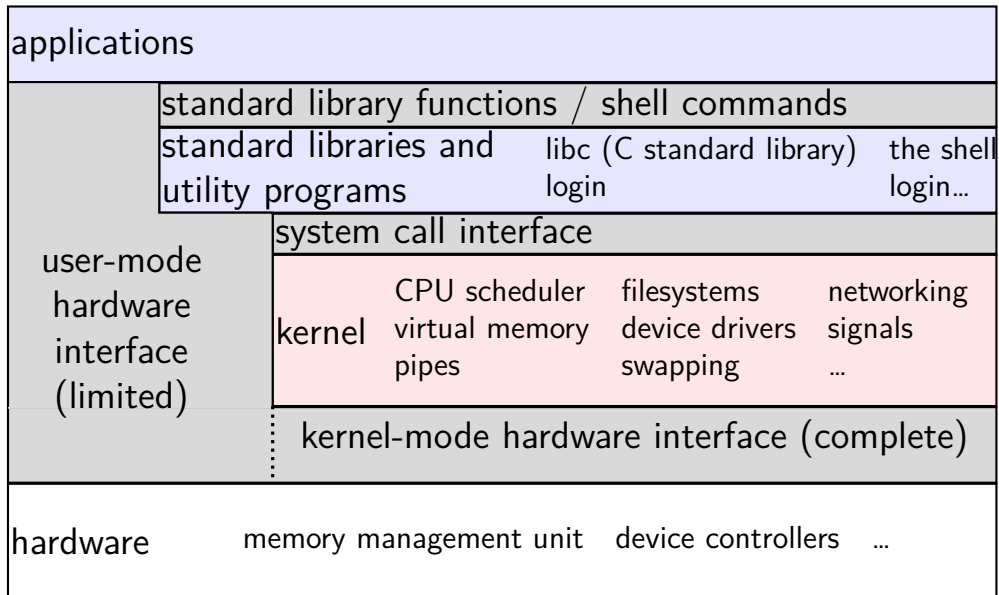
the classic Unix design



the classic Unix design



the classic Unix design



} 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...

exception implementation

detect condition (program error or external event)

save current value of PC somewhere

jump to **exception handler** (part of OS)

jump done without program instruction to do so

exception implementation: notes

I describe a **simplified** version

real x86/x86-64 is a bit more complicated
(mostly for historical reasons)

running the exception handler

hardware saves the **old program counter** (and maybe more)

identifies location of exception handler via table

then jumps to that location

OS code can save anything else it wants to , etc.