exercise (incremental compilation)

program built from main.c + extra.c

main.c, extra.c both include extra.h, stdio.h

```
clang -c main.c                       # command 1
clang -c extra.c                      # command 2
clang -o program main.o extra.o # command 3
```

What commands need to be rerun if...

Question A: ...main.c changes?

Question B: ...extra.h changes?

make

`make` — Unix program for “making” things...

...by running commands based on what's changed

what commands? based on *rules* in *makefile*

make rules

```
main.o: main.c main.h extra.h
▶       clang -c main.c
```

before colon: target(s) (file(s) generated/updated)

after colon: prerequisite(s)

following lines prefixed by a tab character: command(s) to run

`make` will run the commands if any prerequisite is newer than the target

make rules

```
main.o: main.c main.h extra.h
	clang -c main.c
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main.o: main.c main.h extra.h
▶       clang -c main.c
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before colon: target(s) (file(s) generated/updated)

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`make` will run the commands if any prerequisite is newer than the target

make rules

```
main.o: main.c main.h extra.h
►           clang -c main.c
```

before colon: target(s) (file(s) generated/updated)

after colon: prerequisite(s)

following lines prefixed by a tab character: command(s) to run

`make` will run the commands if any prerequisite is newer than the target

...after making sure prerequisites up to date

make rule chains

```
program: main.o extra.o
►           clang -o program main.o extra.o

extra.o: extra.c extra.h
►           clang -c extra.c
main.o: main.c main.h extra.h

►           clang -c main.c
```

to *make* `program`, first...

update main.o and extra.o if they aren't

running make

"`make` *`target`*"

- look in `Makefile` in current directory for rules
- check if *`target`* is up-to-date
- if not, rebuild it (and dependencies, if needed) so it is

"`make` *`target1 target2`*"

- check if both target1 and target2 are up-to-date

"`make`"

- if "*`firstTarget`*" is the first rule in Makefile,
- same as '`make` *`firstTarget`*"

exercise: what will run?

```
W: X Y
▶     buildW
X: Q
▶     buildX
Y: X Z
▶     buildY
```

W	modified 1 minute ago
X	modified 2 hours ago
Y	does not exist
Z	modified 1 hour ago
Q	modified 3 hours ago

exercise: “make W” will run what commands?

A. none
B. `buildY` only
C. `buildW` then `buildY`
D. `buildY` then `buildW`
E. `buildX` then `buildY` then `buildW`
F. `buildX` then `buildW`
G. something else

'phony' targets (1)

common to have Makefile targets that aren't files

```
all: program1 program2 libfoo.a
```

"`make all`" effectively shorthand for "`make program1 program2 libfoo.a`"

no actual file called "all"

‘phony’ targets (2)

sometimes want targets that don’t actually build file

example: “`make clean`” to remove generated files

```
clean:
►           rm --force main.o extra.o
```

but what if I create...

```
clean:
▶           rm --force main.o extra.o

all: program1 program2 libfoo.a
```

Q: if I make a file called “all” and then “make all” what happens?

Q: same with “clean” and “make clean”?

marking phony targets

```
clean:
►           rm --force main.o extra.o

all: program1 program2 libfoo.a

.PHONY: all clean
```

special .PHONY rule says “ ‘all’ and ‘clean’ not real files”

(not required by POSIX, but in every `make` version I know)

conventional targets

common convention:

target name	purpose
(default), `all`	build everything
`install`	install to standard location
`test`	run tests
`clean`	remove generated files

redundancy (1)

```
program: main.o extra.o
▶        clang -o program main.o extra.o

extra.o: extra.c extra.h
▶        clang -o extra.o -c extra.c
main.o: main.c main.h extra.h

▶        clang -o main.o -c main.c
```

what if I want to run `clang` with `-Wall`?

what if I want to change to `gcc`?

variables (1)

```
CC = gcc
CFLAGS = -Wall -pedantic -std=c11 -fsanitize=addres
LDFLAGS = -Wall -pedantic -fsanitize=address

program: main.o extra.o
►        $(CC) $(LDFLAGS) -o program main.o extra.

extra.o: extra.c extra.h
►        $(CC) $(CFLAGS) -o extra.o -c extra.c

main.o: main.c main.h extra.h
►        $(CC) $(CFLAGS) -o main.o -c main.c
```

variables (2)

```
CC = gcc
CFLAGS = -Wall
LDFLAGS = -Wall

program: main.o extra.o
►          $(CC) $(LDFLAGS) -o $@ $^

extra.o: extra.c extra.h
►          $(CC) $(CFLAGS) -o $@ -c $<

main.o: main.c main.h extra.h
►          $(CC) $(CFLAGS) -o $@ -c $<
```

aside: `$^` works on GNU make (usual on Linux), but not portable.

suffix rules

```
CC = gcc
CFLAGS = -Wall
LDFLAGS = -Wall

program: main.o extra.o
►         $(CC) $(LDFLAGS) -o $@ $^

.c.o:
►         $(CC) $(CFLAGS) -o $@ -c $<

extra.o: extra.c extra.h
main.o: main.c main.h extra.h
```

aside: `$^` works on GNU make (usual on Linux), but not portable.

pattern rules

```
CC = gcc
CFLAGS = -Wall
LDFLAGS = -Wall

program: main.o extra.o
▶         $(CC) $(LDFLAGS) -o $@ $^

%.o: %.c
▶         $(CC) $(CFLAGS) -o $@ -c $<

extra.o: extra.c extra.h
main.o: main.c main.h extra.h
```

aside: these rules work on GNU make (usual on Linux), but less portable than suffix rules.

built-in rules

'make' has the 'make .o from .c' rule built-in already, so:

```
CC = gcc
CFLAGS = -Wall
LDFLAGS = -Wall

program: main.o extra.o
▶        $(CC) $(LDFLAGS) -o $@ $^

extra.o: extra.c extra.h
main.o: main.c main.h extra.h
```

(don't actually need to write supplied rule!)

writing Makefiles?

error-prone to automatically all .h dependencies

`-M` option to `gcc` or `clang`

- outputs Make rule
- ways of having make run this

Makefile generators

- other programs that write Makefiles

other build systems

alternatives to writing Makefiles:

other make-ish build systems

- ninja, scons, bazel, maven, xcodebuild, msbuild, …

tools that generate inputs for make-ish build systems

- cmake, autotools, qmake, …

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

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

privileged instructions

can't let any program run some instructions

example: talk to I/O device

allows machines to be shared between users (e.g. lab servers)

processor has two modes:

- kernel mode — privileged instructions work
- user mode — privileged instructions cause exception instead

only *trusted* OS code runs in kernel mode

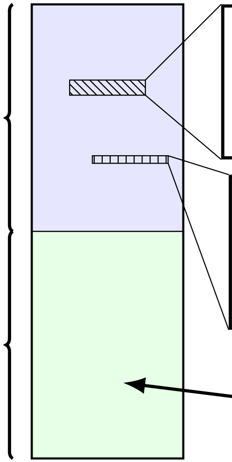
kernel mode

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

processor switches to kernel mode to run OS

OS switches processor back to use mode when running normal code

calling the OS?



```
void readFromDiskInto(int diskLocation, char *dest) {
    ...
    runPrivilegedInstruction(...);
    ...
}
```

```
void readFileSafely(const char *name, char *dest) {
    if (canCurrentProgramCanAccessFile(name)) {
        readFromDiskInto(lookupFile(name), dest)
    }
}
```

how do we let this code run `readFromSafely` in kernel mode but not `readFromDisk`?

controlled entry to kernel mode (1)

special instruction: “system call”

runs OS code in kernel mode at location specified earlier

OS sets up at boot

location can’t be changed without privilieged instrution

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

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

system call wrappers

can't write C code to generate syscall instruction

solution: call "wrapper" function written in assembly

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"],
        0x7ffeedafd0a0 /* 28 vars */) = 0
write(1, "Hello, World!\n\0", 15)       = 15
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?
- (file indicates whether to use ‘advanced’ processo features)

fstat: get information about open file

exit_group: variant of exit

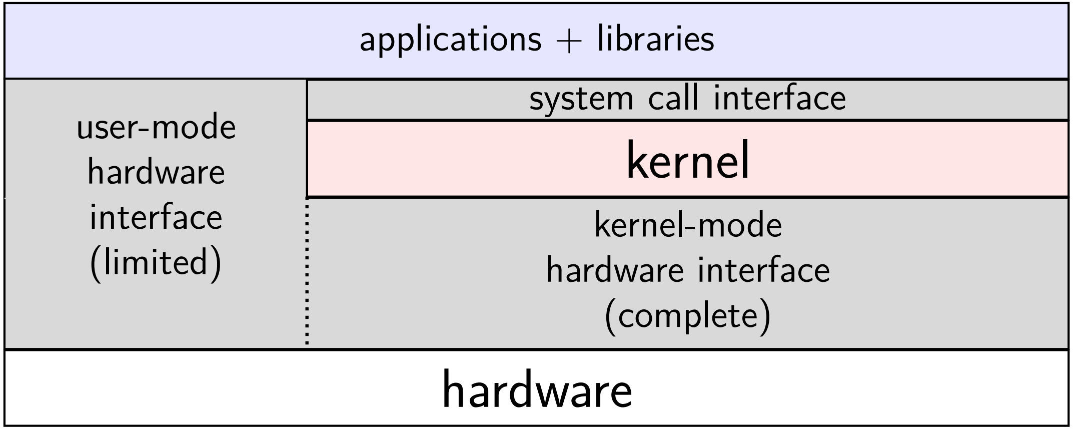
strace hello_world (2)

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

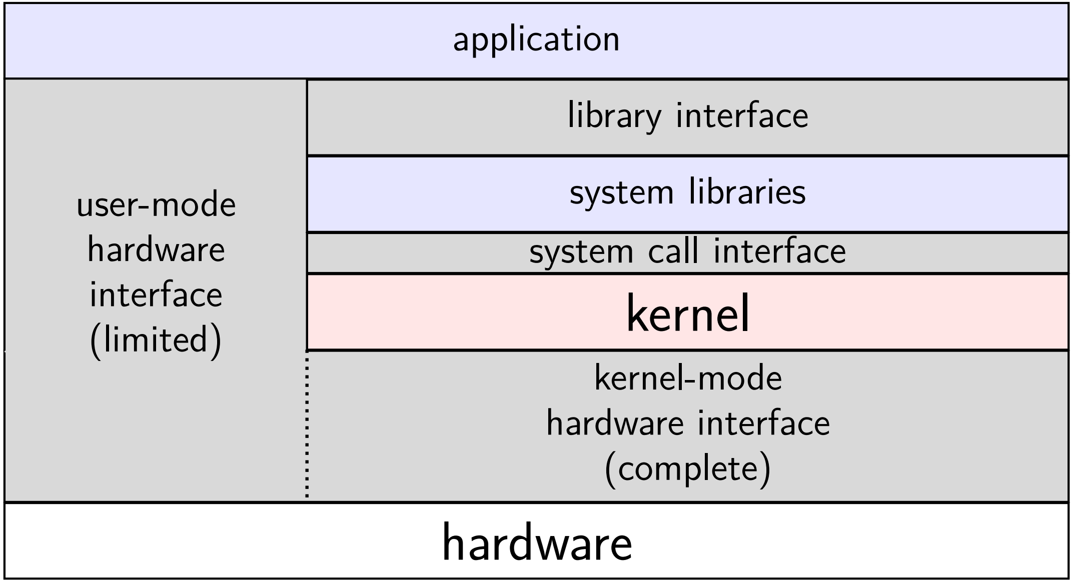
when dynamically linked:

```
execve("./hello_world", ["./hello_world"], 0x7ffcfe91d540 /* 28 vars */) = 0
brk(NULL)                               = 0x55d6c351b000
access("/etc/ld.so.nohwcap", F_OK)      = -1 ENOENT (No such file or directory)
access("/etc/ld.so.preload", R_OK)      = -1 ENOENT (No such file or directory)
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\3\0>\0\1\0\0\0\20\35\2\0\0\0\0\0"..., 832) = 832
...
close(3)                                = 0
write(1, "Hello, World!\n", 14)         = 14
exit_group(0)                           = ?
+++ exited with 0 +++
```

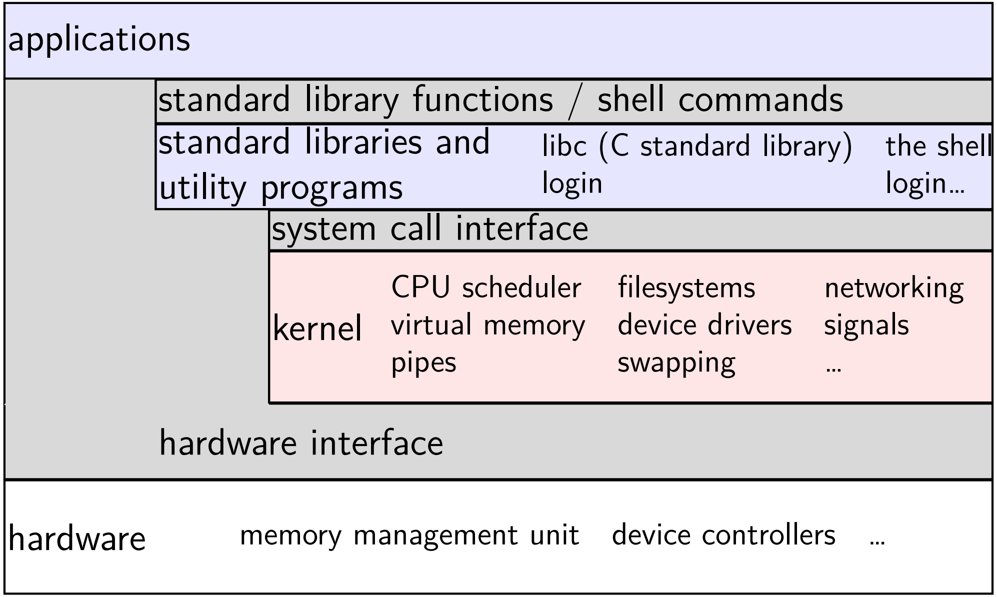
hardware + system call interface


applications + libraries
user-mode hardware interface (limited)
system call interface
kernel
kernel-mode hardware interface (complete)
hardware

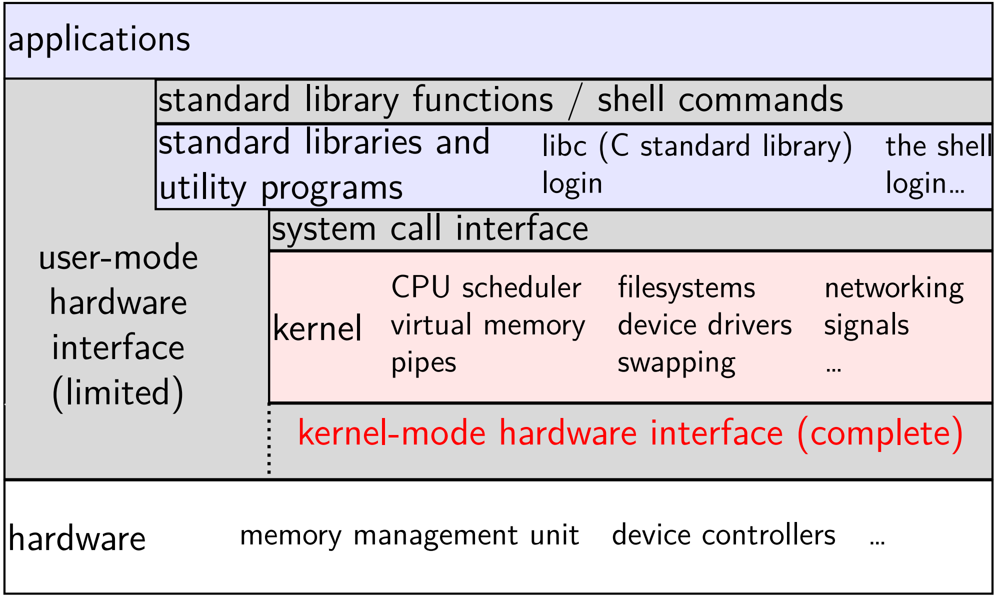
hardware + system call + library interface


application
library interface
system libraries
system call interface
kernel
user-mode hardware interface (limited)
kernel-mode hardware interface (complete)
hardware

the classic Unix design



the classic Unix design



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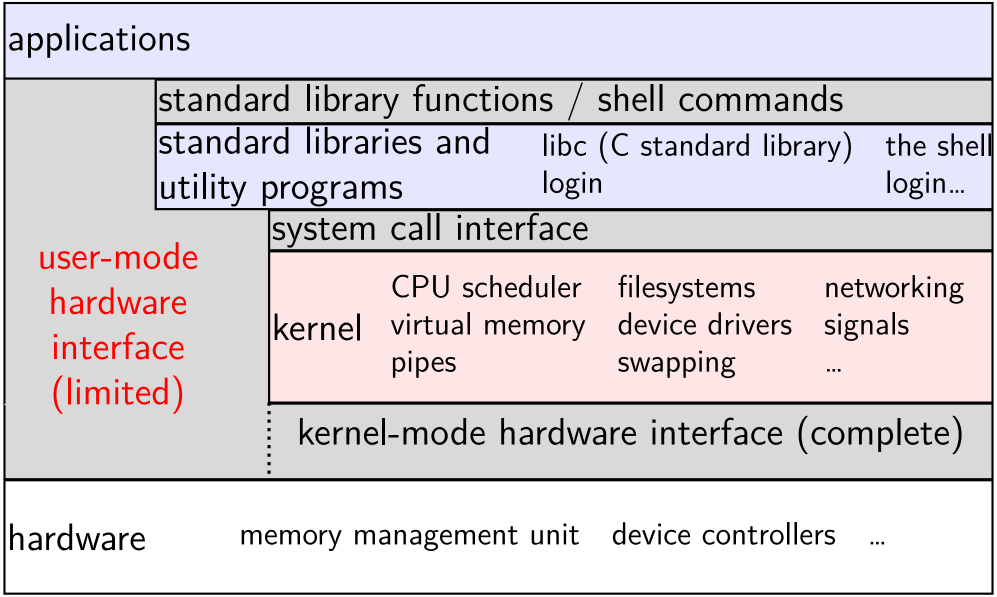
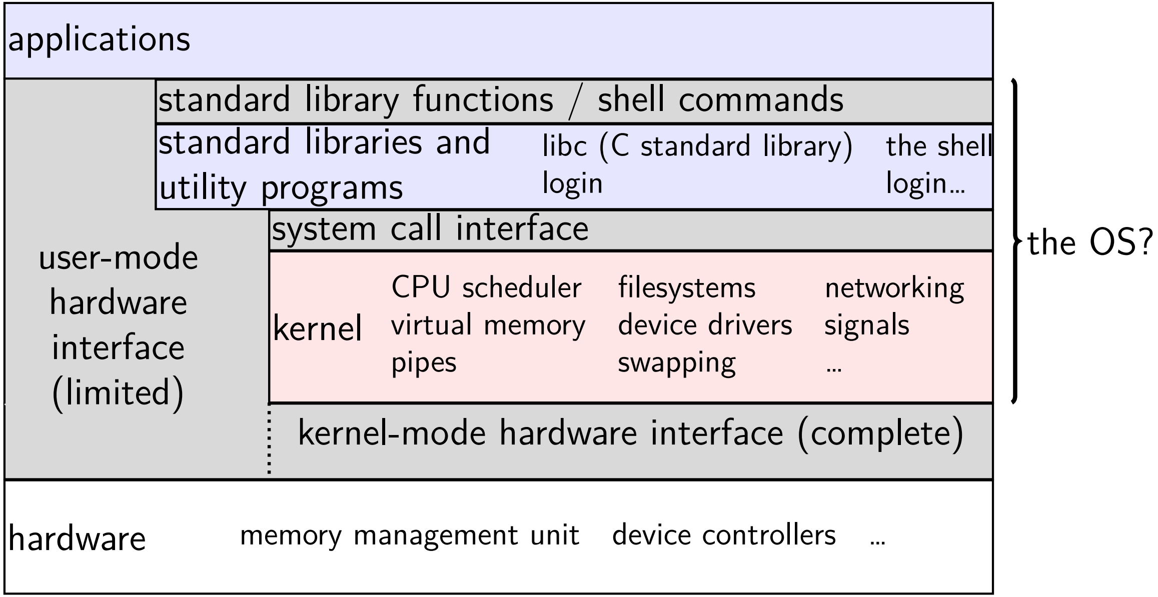


the classic Unix design



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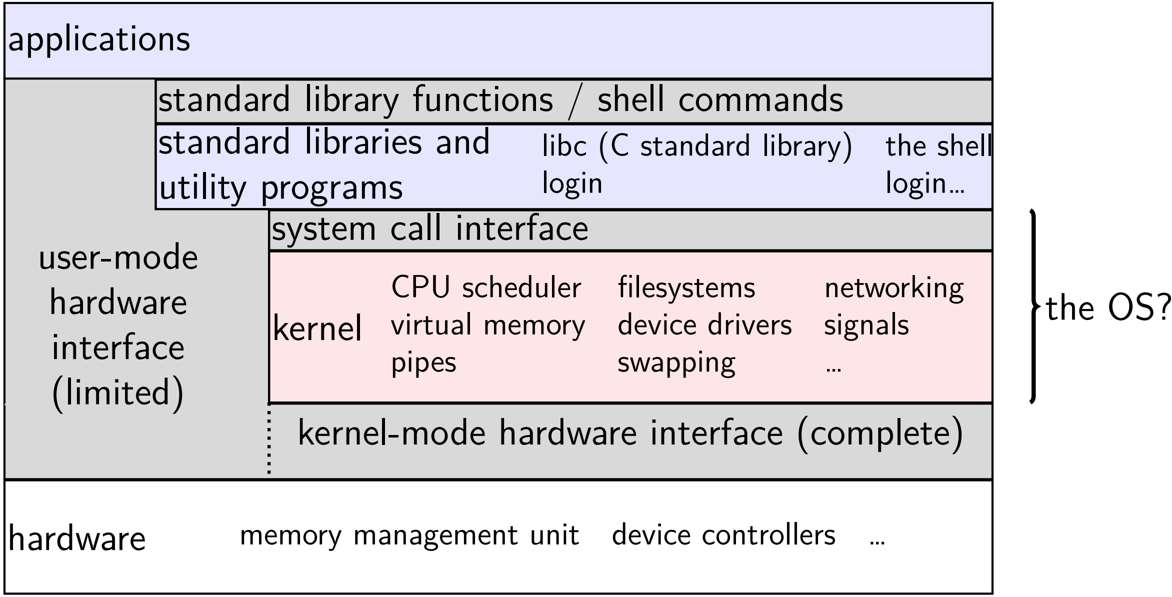


aside: is the OS the kernel?

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…

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

reading from another program's memory?

Program A

```
0x10000: .word 42
        // ...
        // do work
        // ...
        movq 0x10000, %rax
```

Program B

```
// while A is working:
movq $99, %rax
movq %rax, 0x10000
...
```

memory protection

reading from another program's memory?

Program A

```
0x10000: .word 42
     // ...
     // do work
     // ...
     movq 0x10000, %rax
```

Program B

```
// while A is working:
movq $99, %rax
movq %rax, 0x10000
...
```

result: `%rax` (in A) is ...

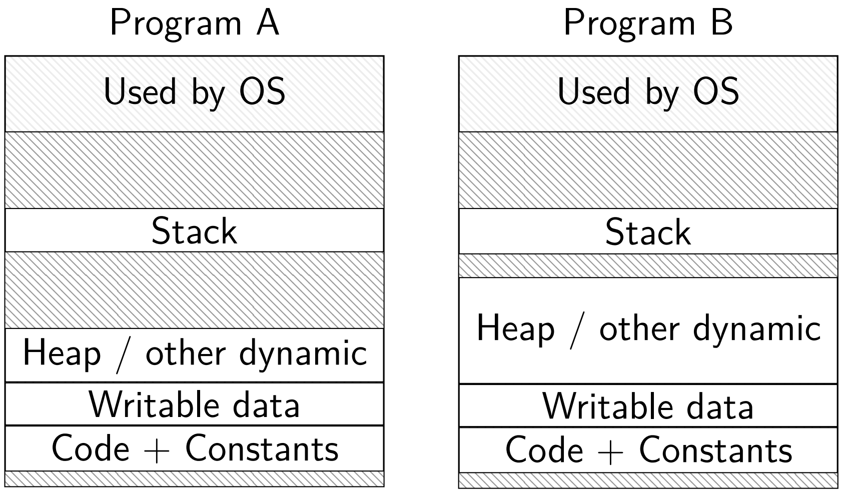
A. 42 B. 99 C. 0x10000

D. 42 or 99 (depending on timing/program layout/etc)

E. 42 or 99 or program might crash (depending on ...)

F. something else

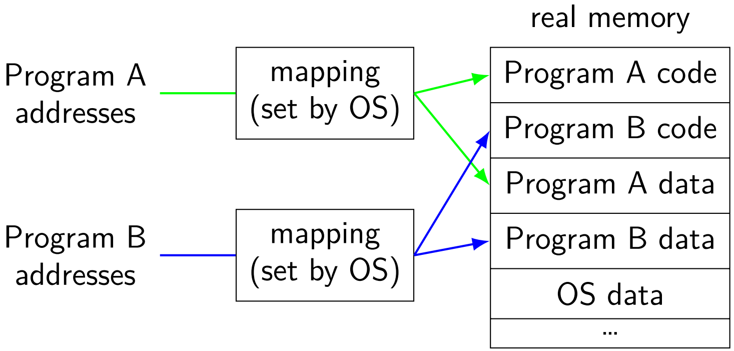
program memory (two programs)



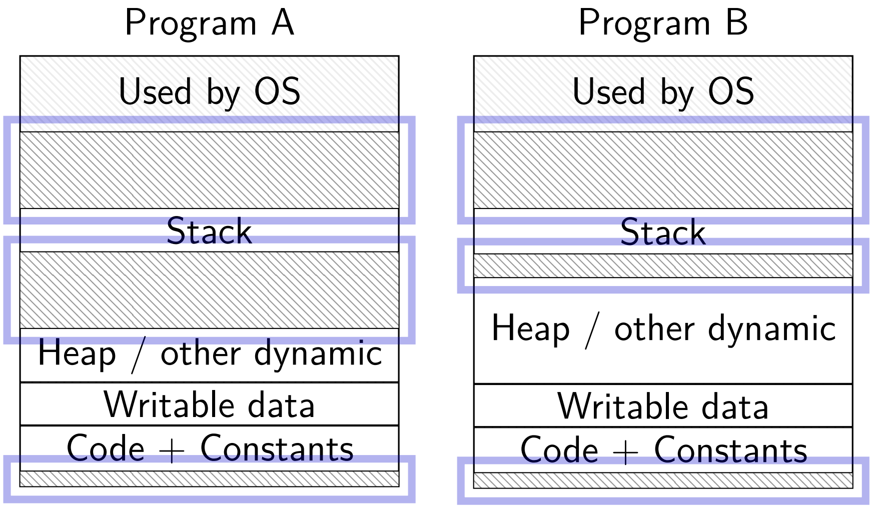
address space

programs have illusion of own memory

called a program's address space



program memory (two programs)



address space

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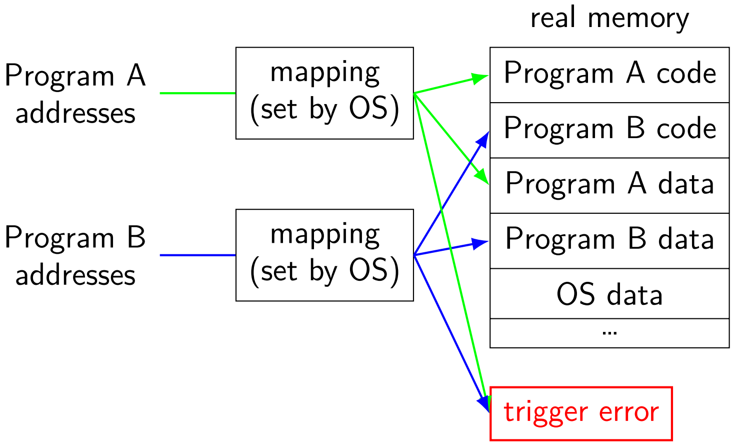


address space mechanisms

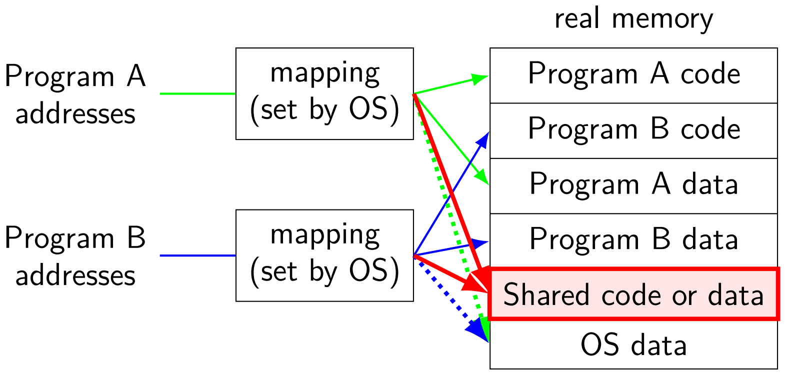
topic after exceptions

called virtual memory

mapping called page tables

mapping part of what is changed in context switch

shared memory



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

- if MAP_SHARED: same data for everyone mapping the file

will discuss a bit more when we talk about virtual memory

part of how Linux loads dynamically linked libraries

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

an infinite loop

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

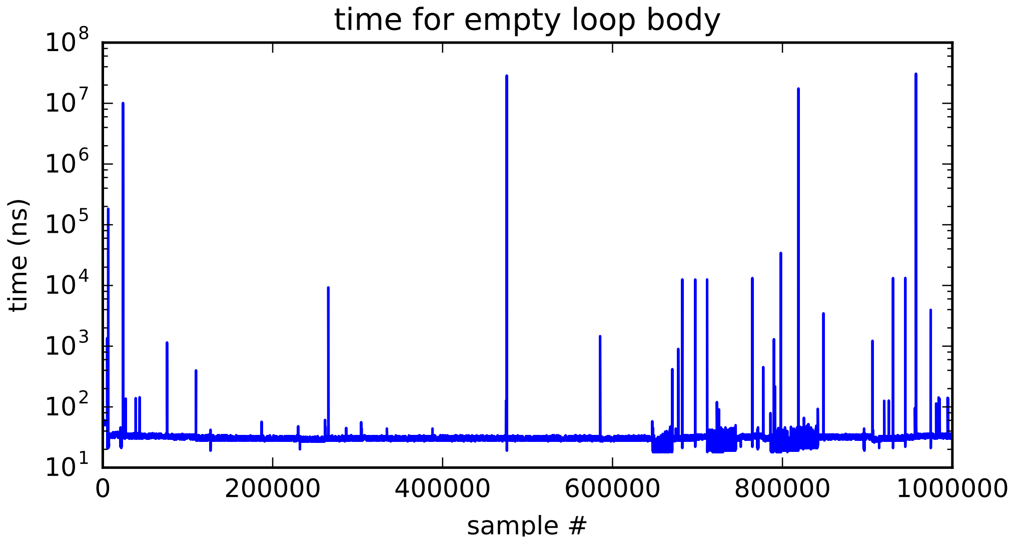
If I run this on a shared department machine, can you still use it?
...if the machine only has one core?

timing nothing

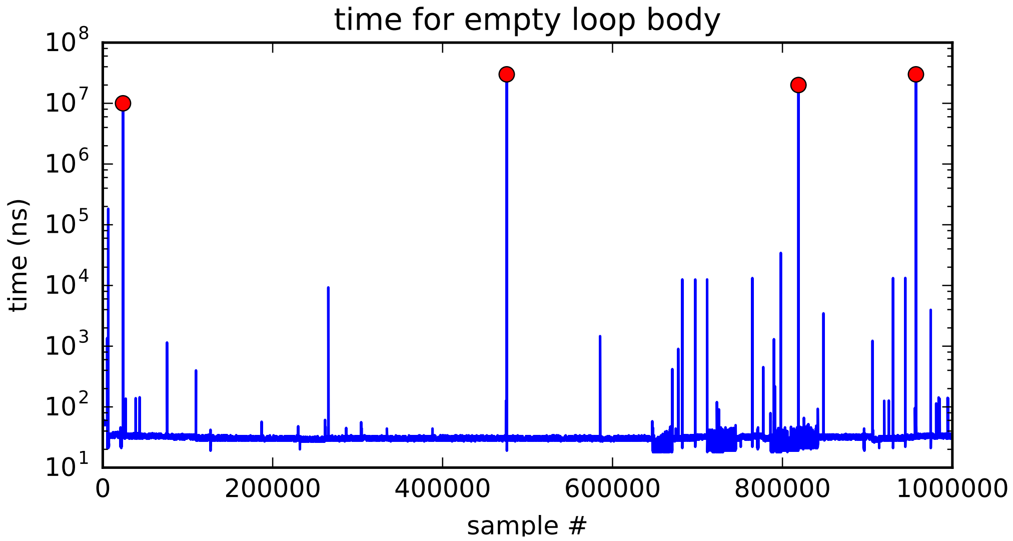
```
long times[NUM_TIMINGS];
int main(void) {
    for (int i = 0; i < N; ++i) {
        long start, end;
        start = get_time();
        /* do nothing */
        end = get_time();
        times[i] = end - start;
    }
    output_timings(times);
}
```

same instructions — same difference each time?

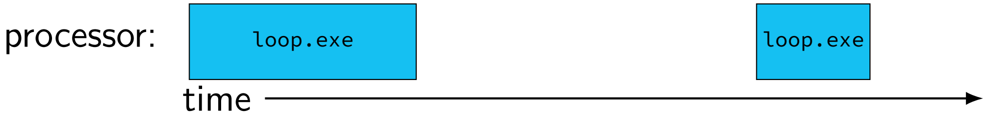
doing nothing on a busy system



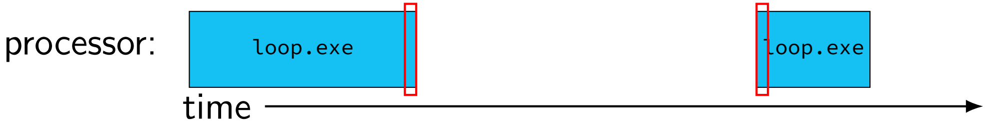
doing nothing on a busy system



time multiplexing



time multiplexing

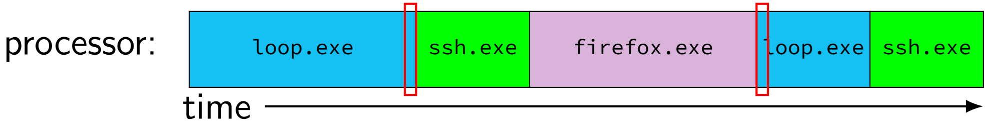


```
...
call get_time
    // whatever get_time does
movq %rax, %rbp
```

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
...
```

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

externally-triggered

- timer — keep program from hogging CPU
- I/O devices — key presses, hard drives, networks, ...
- hardware is broken (e.g. memory parity error)

} **asynchronous** not triggered by running program

intentionally triggered exceptions

- system calls — ask OS to do something

errors/events in programs

- memory not in address space ("Segmentation fault")
- privileged instruction
- divide by zero
- invalid instruction

} **synchronous** triggered by current program

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

exception implementation

detect condition (program error or external event)

save current value of PC somewhere

jump to exception handler (part of OS)

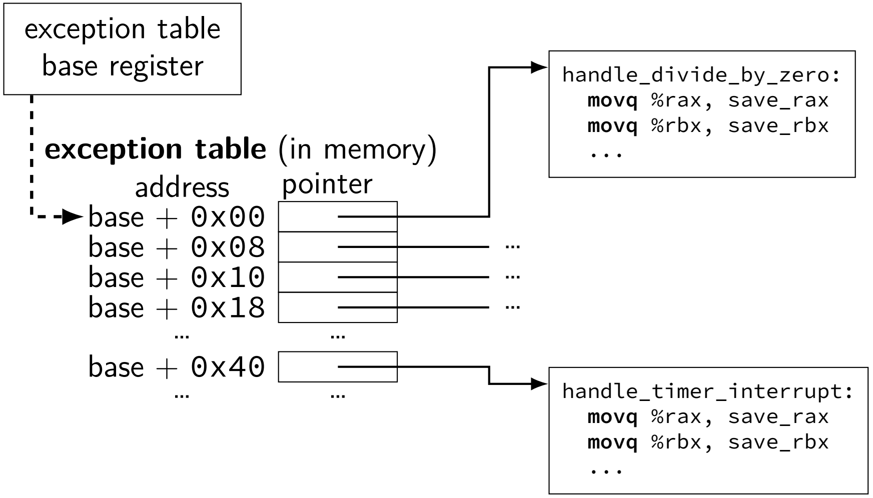
- jump done without program instruction to do so

exception implementation: notes

I describe a simplified version

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

locating exception handlers



```
handle_divide_by_zero:
  movq %rax, save_rax
  movq %rbx, save_rbx
  ...
```

```
handle_timer_interrupt:
  movq %rax, save_rax
  movq %rbx, save_rbx
  ...
```

running the exception handler

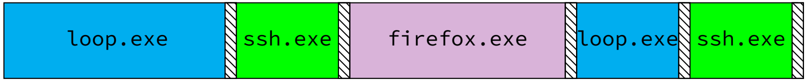
hardware saves the old program counter (and maybe more)

identifies location of exception handler via table

then jumps to that location

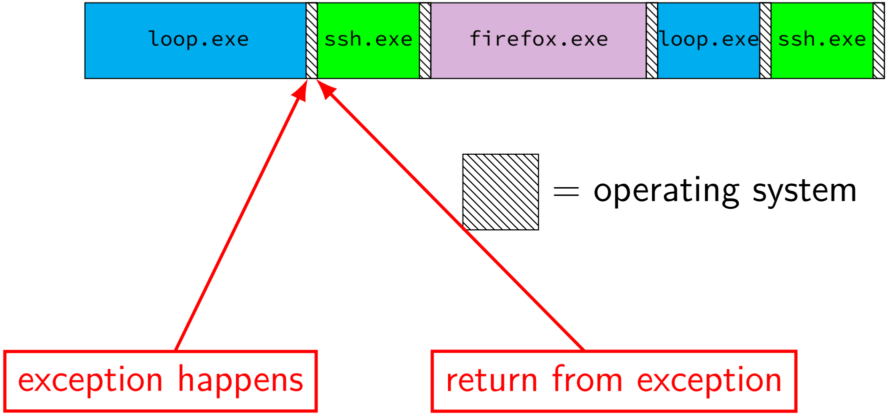
OS code can save anything else it wants to , etc.

time multiplexing really



▨ = operating system

time multiplexing really



OS and time multiplexing

starts running instead of normal program
- mechanism for this: exceptions (later)

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

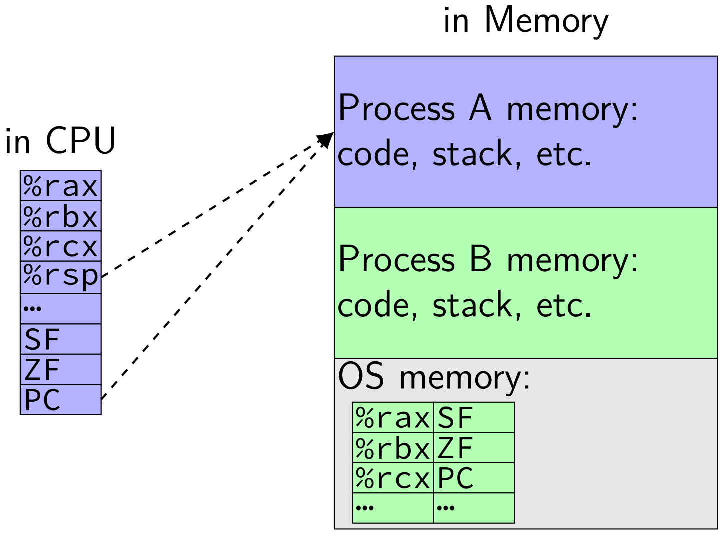
program counter

i.e. all visible state in your CPU except memory

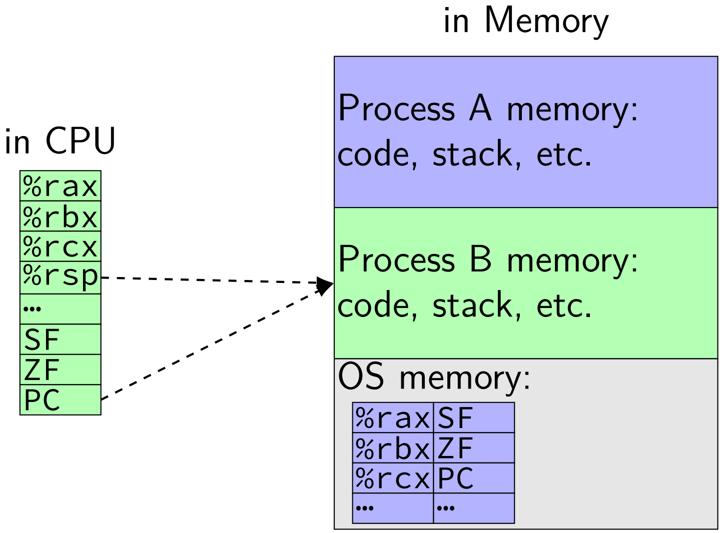
context switch pseudocode

```
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
```

contexts (A running)



contexts (B running)



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

The Process

process = thread(s) + address space

illusion of dedicated machine:

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