Architectural Support for Operating Systems

CS 4410, Operating Systems

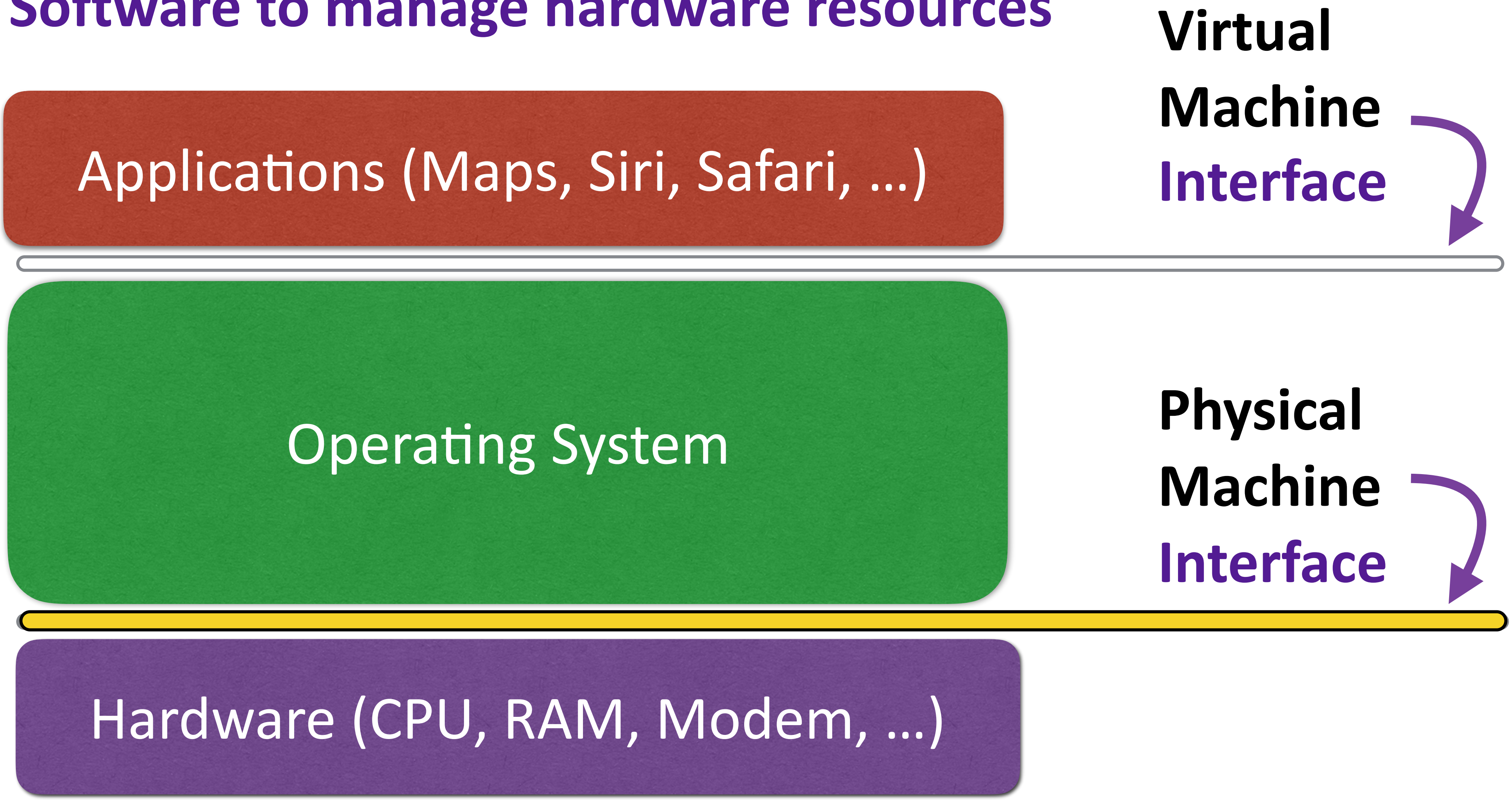
Fall 2016
Cornell University

Rachit Agarwal
Anne Bracy

See: Chapter 2 in OSPP textbook

What is an operating system?

Software to manage hardware resources



Virtual Machine Interface

Applications (Maps, Siri, Safari, …)

Operating System

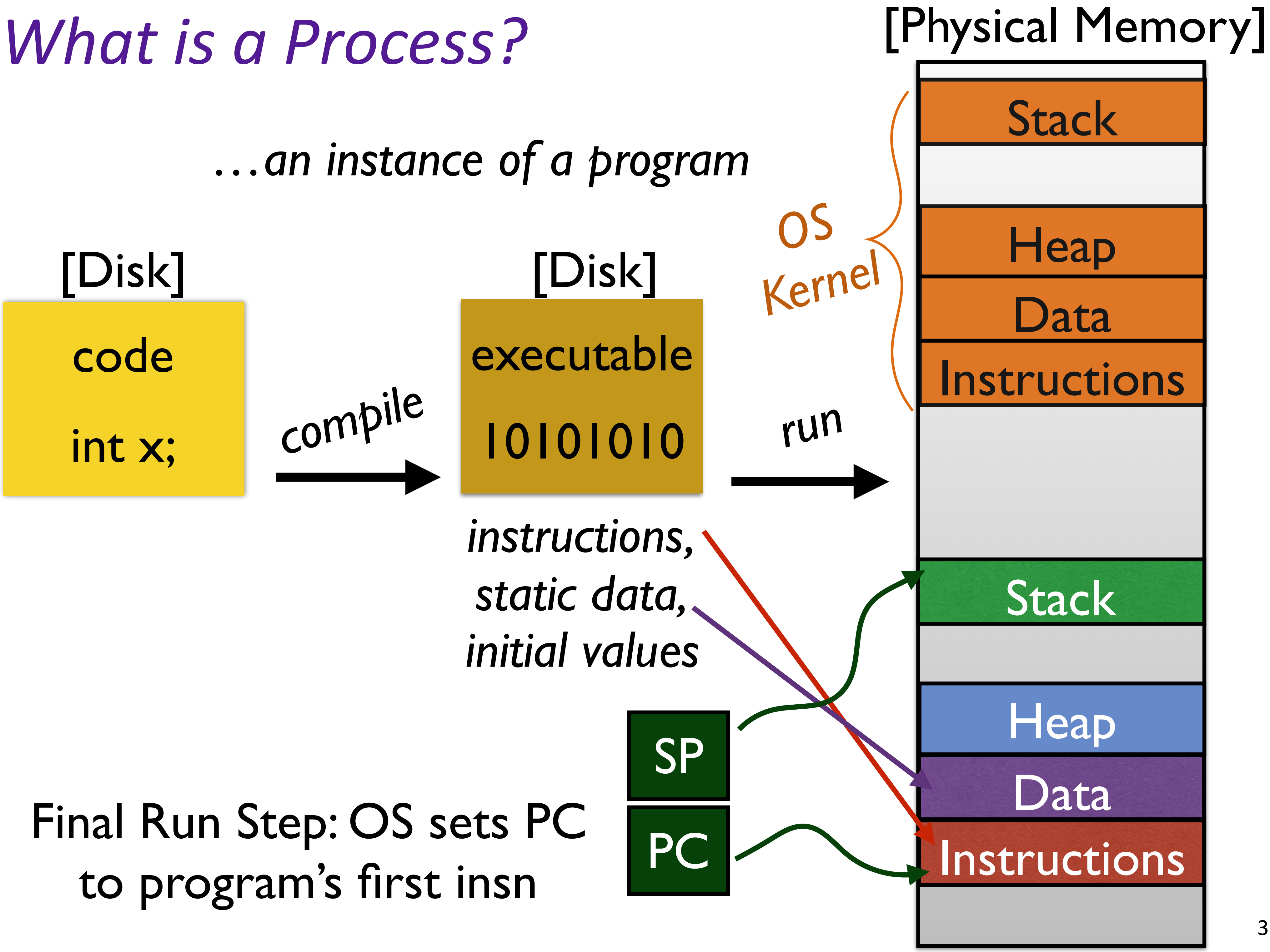
Physical Machine Interface

Hardware (CPU, RAM, Modem, …)

What hw is needed to help the OS do its job?

What is a Process?

…an instance of a program



[Physical Memory]

OS Kernel

Stack

Heap

Data

Instructions

[Disk]

code

int x;

compile

[Disk]

executable

10101010

run

instructions,
static data,
initial values

Stack

Heap

Data

Instructions

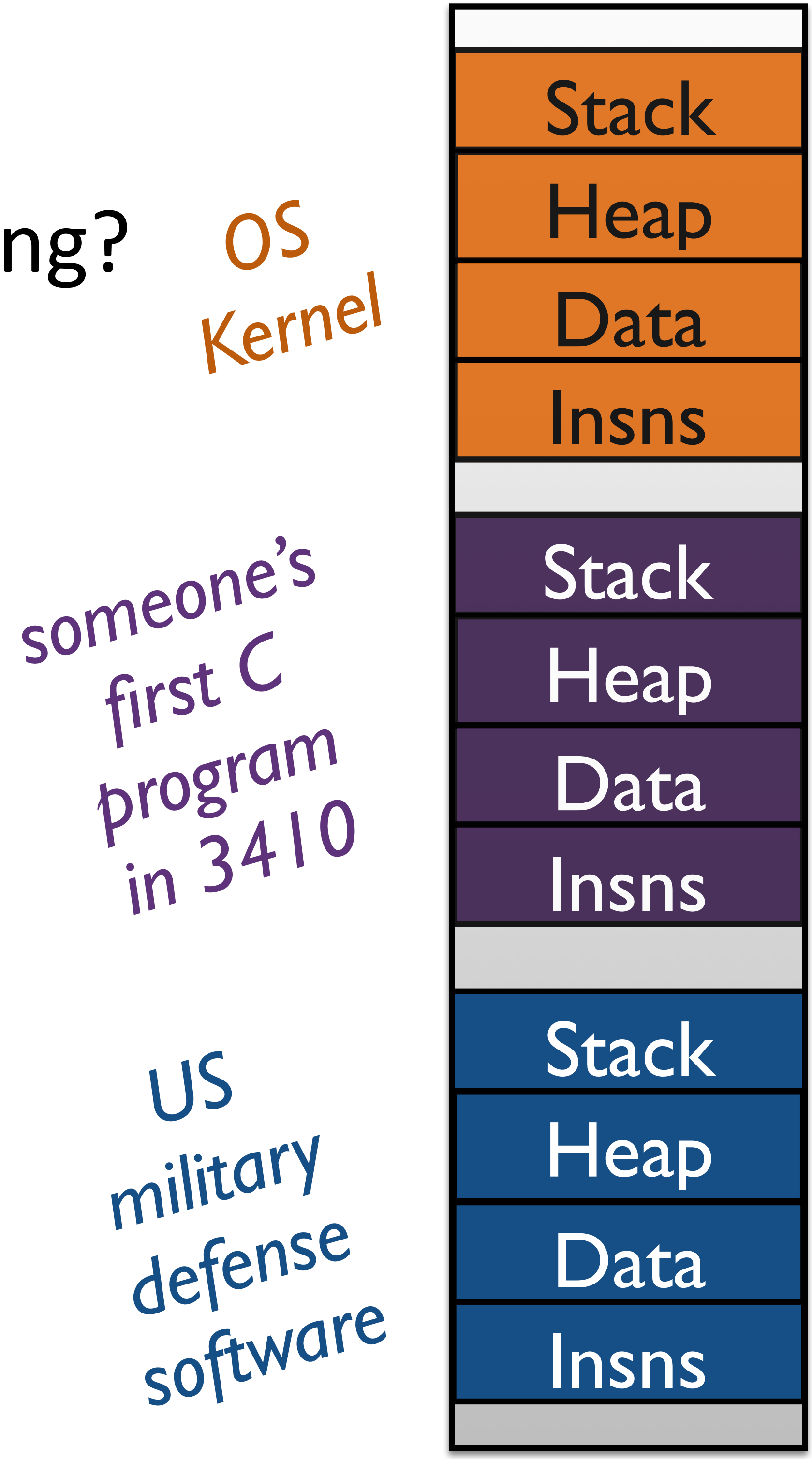
SP

PC

Final Run Step: OS sets PC to program's first insn

Protect who from what?

What could possibly go wrong?



OS Kernel

Stack

Heap

Data

Insns

someone's first C program in 3410

Stack

Heap

Data

Insns

US military defense software

Stack

Heap

Data

Insns

Privilege Levels

Some processor functionality cannot be made accessible to untrusted user applications

Operating System = the mediator between
untrusted/untrusting apps

Need to differentiate untrusted apps and OS code

Solution: "privilege mode" bit in the processor

0 = Untrusted = user   1 = Trusted = OS

Privileged Instructions

- changing the privilege mode
- writing to certain registers (page table base register)
- enabling a co-processor
- changing memory access permissions
- manipulate device settings
- signal other users' processes
- print character to screen
- send a packet on the network
- allocate a new page in memory

CPU knows which instructions are privileged.

`opcode == privileged && mode == 0` ➜ ***Exception!***

Context Switch/Mode Transfer

Hardware transfer to kernel:

1. save privilege mode, set mode to 1
2. mask interrupts *(see slide 14)*
3. save: SP, PC, eflags register (x86)
4. switches SP to the kernel stack
5. save values from #2 onto kernel stack
6. save error code
7. set PC to the interrupt vector table

Interrupt handler

1. saves all registers
2. examines the cause
3. performs operation required
4. restores all registers

why save the privilege mode?

why hardware support?

where is this address stored?

Performs "Return from Interrupt" insn (maybe)

- restores the privilege mode, SP and PC

Process Control Block (PCB)

For each process, the OS has a PCB containing:

- location in memory
- location of executable on disk
- which user is executing this process
- process privilege level
- process arguments
- register values
- PC, SP, eflags

… and more!

Usually lives on the kernel stack

Privileged Instructions

- changing the privilege mode
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- changing memory access permissions
- manipulate device settings
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- send a packet on the network
- allocate a new page in memory

is this really so bad?

CPU knows which instructions are privileged.

opcode == privileged && mode == 0 ➜ ***Exception!***

System Call (slight variation on standard context switch)

Hardware transfer to kernel:

1. save privilege mode, set mode to 1
2. mask interrupts *(see slide 14)*
3. save: SP, PC, eflags register (x86)
4. switches SP to the kernel stack
5. save values from #2 onto kernel stack
6. save error code ← sys call not an error
7. set PC to the interrupt vector table

Interrupt handler

1. saves all registers ← callee only
2. examines the cause ← which syscall was called, might have arguments
3. performs operation required
4. restores all registers ← callee only

Performs "Return from Interrupt" insn (maybe)

return to which insn?

- restores the privilege mode, SP and PC

Let's Start at the Very Beginning…

In the beginning… (when the system starts up)

- privilege mode set to 1
- PC contains address of boot code
- boot code loads kernel into memory
- kernel does some setup (devices, initializes MMU, creates interrupt vector table, etc.)
- picks an application, loads it
- resets privilege bit
- changes PC to starting instruction of the chosen application

Now what?

How does the OS re-take control?

Interrupts

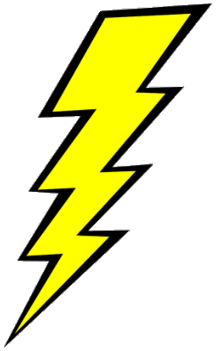
Timer Interrupts:

Process interrupted after certain period (number of instructions executed or time passed)

time →

More Generally: ***Hardware Interrupts***

External Event has happened.
OS needs to check it out.
Process stops what it's doing, invokes OS,
which handles the interrupt.

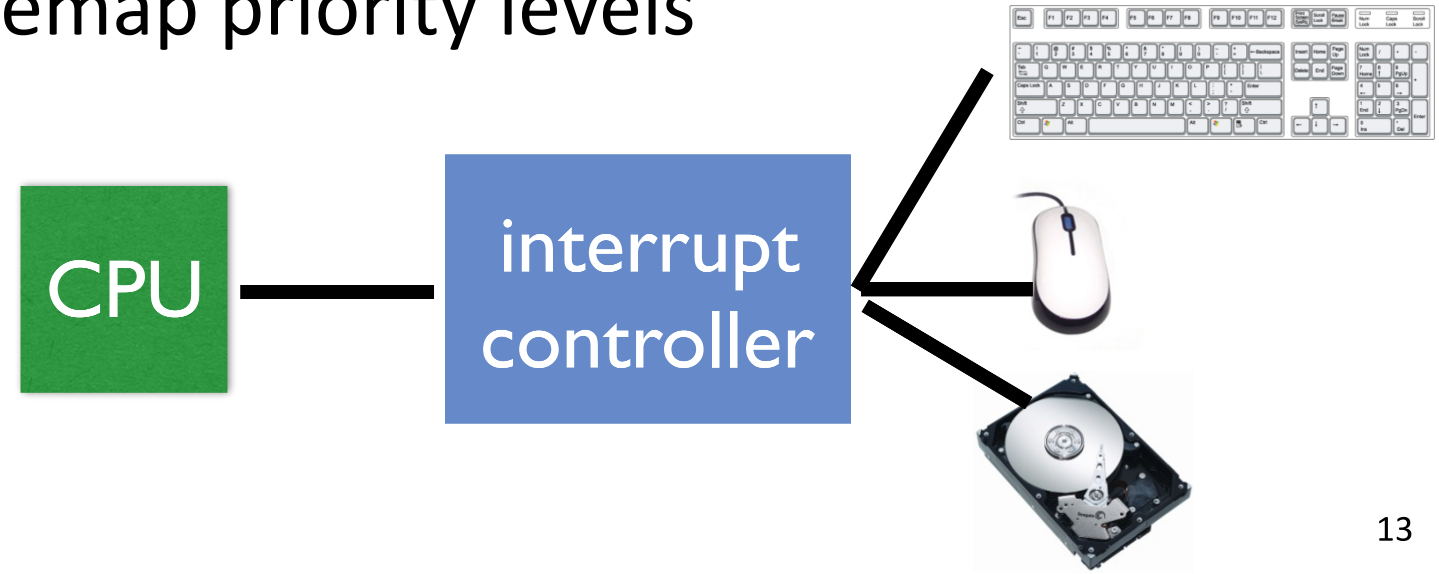


Interrupt Management

Interrupt controllers manage interrupts

Interrupts have descriptor of the interrupting device
Priority selector circuit examines all interrupting devices, reports highest level to the CPU

Interrupt controller implements interrupt priorities
Can optionally remap priority levels



CPU

interrupt controller

Masking Interrupts

Maskable interrupts: can be turned off by the CPU for critical processing (misnomer: *delayed*)

Nonmaskable interrupts: signifies serious errors (e.g., unrecoverable memory error, power out warning, etc)

Why would we want to mask interrupts?
(“discuss later” on slide 7)

Three ways for the OS to be invoked

1. Hardware interrupt
   - *some other entity trying to get CPU's attention*
   - Asynchronous = caused by an external event
   - Examples: keystroke, arrival of a packet from network
2. System Call
   - *process needs help from the OS*
   - Intentional, Synchronous = caused by the syscall insn
   - Examples: open, write, fork, exit
3. Exception
   - *something went wrong*
   - Unintentional, Synchronous = caused by executing insn
   - Examples: privileged insn in user mode, page fault

Terminology Chaos.

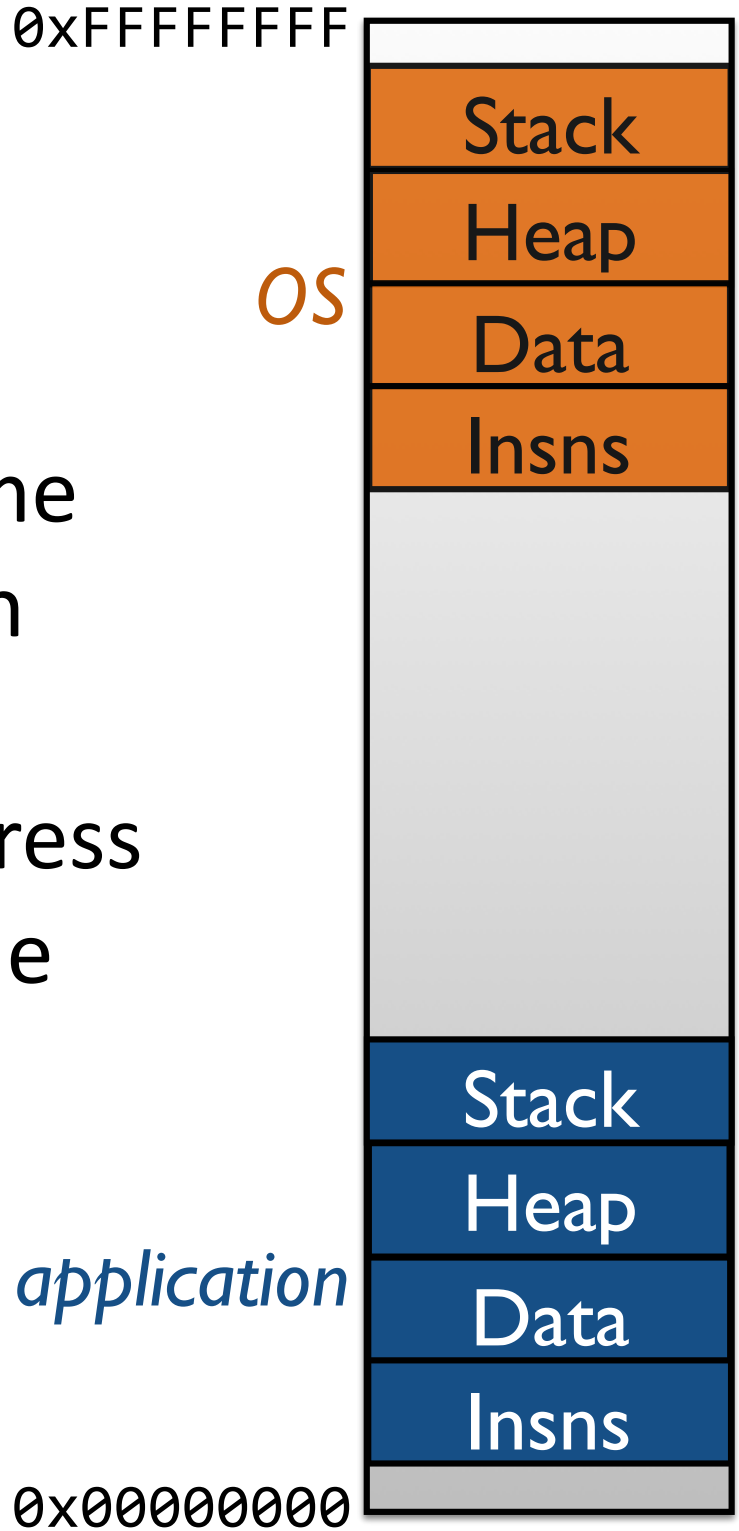
are we done yet?

Uniprogramming

No Translation or Protection

Application:

- Only one application at a time
- Always runs at same place in physical memory
- Can access any physical address
- Illusion of dedicated machine achieved by reality of a dedicated machine



Multiprogramming, V1

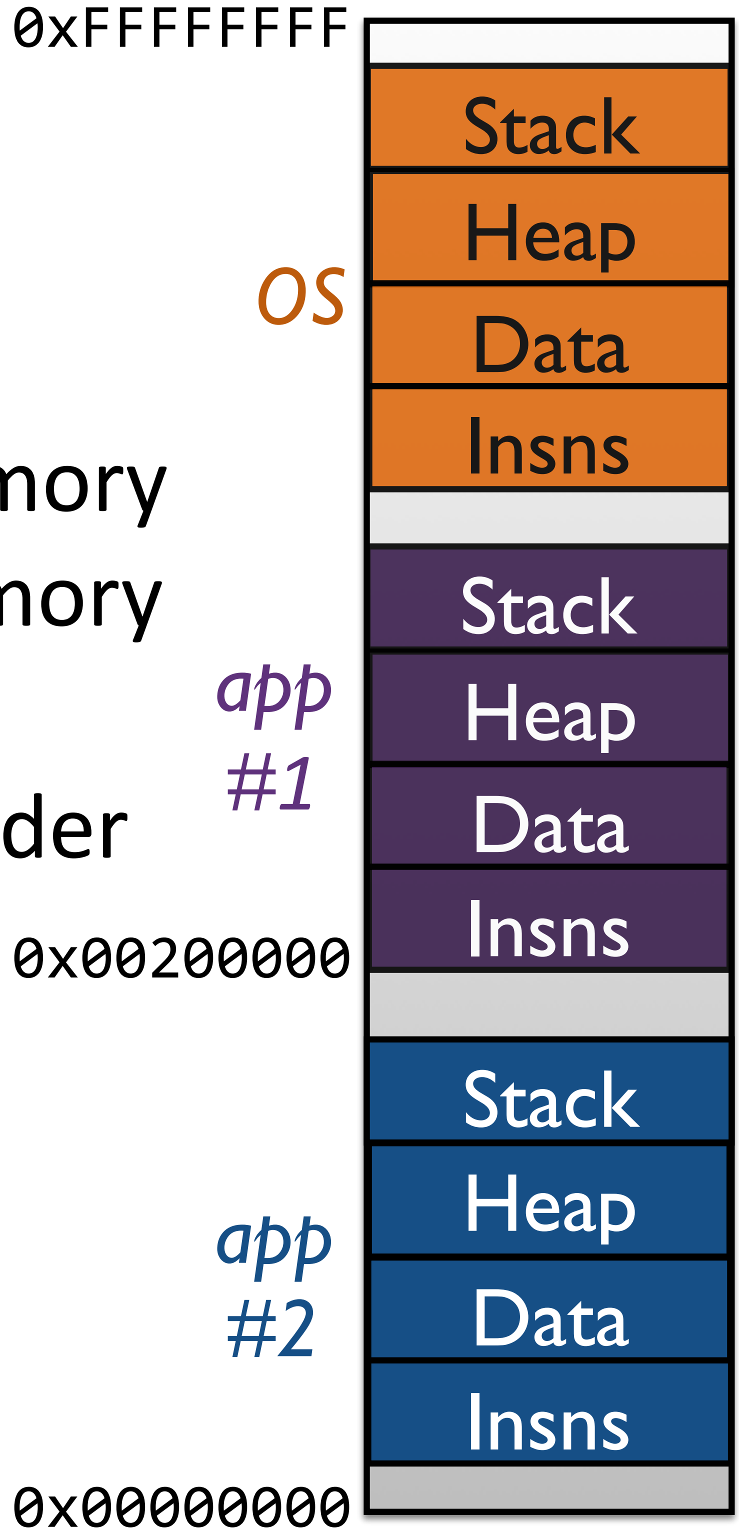
No Translation

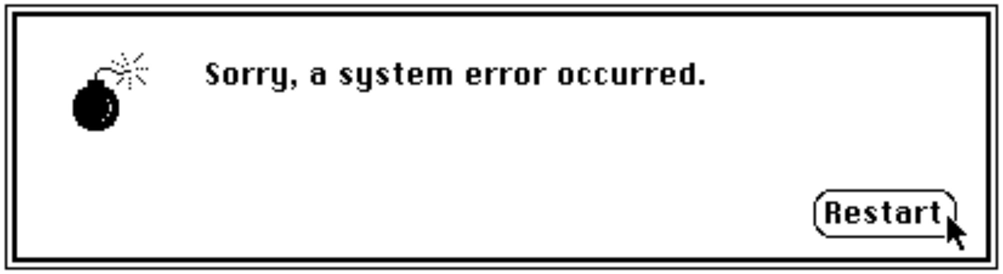
Adjust addresses (ld, st, jmps) when program loaded into memory

- Everything adjusted to memory location of program
- “Translation” by Linker/Loader
- Common in early days

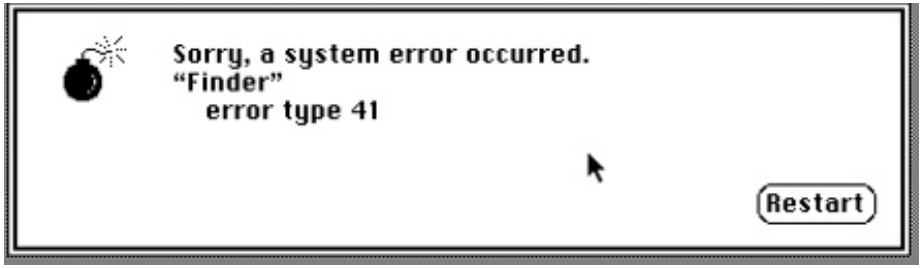
No protection

Any process can crash another (or the OS!)





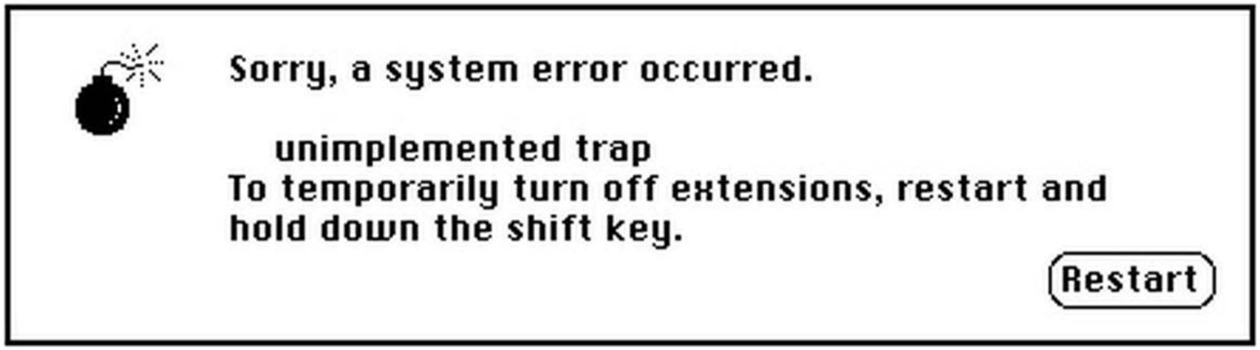
Sorry, a system error occurred.



Sorry, a system error occurred.
“Finder”
error type 41

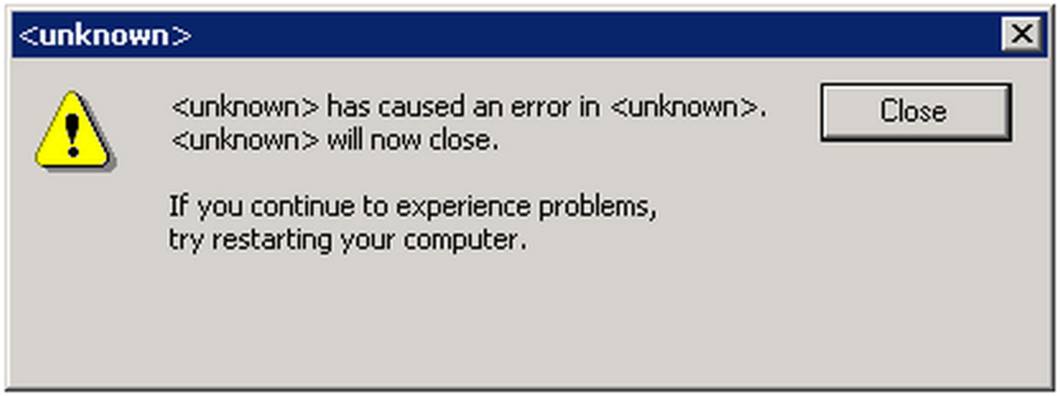
Sorry, a system error occurred.

ID = 03



Sorry, a system error occurred.

unimplemented trap
To temporarily turn off extensions, restart and hold down the shift key.



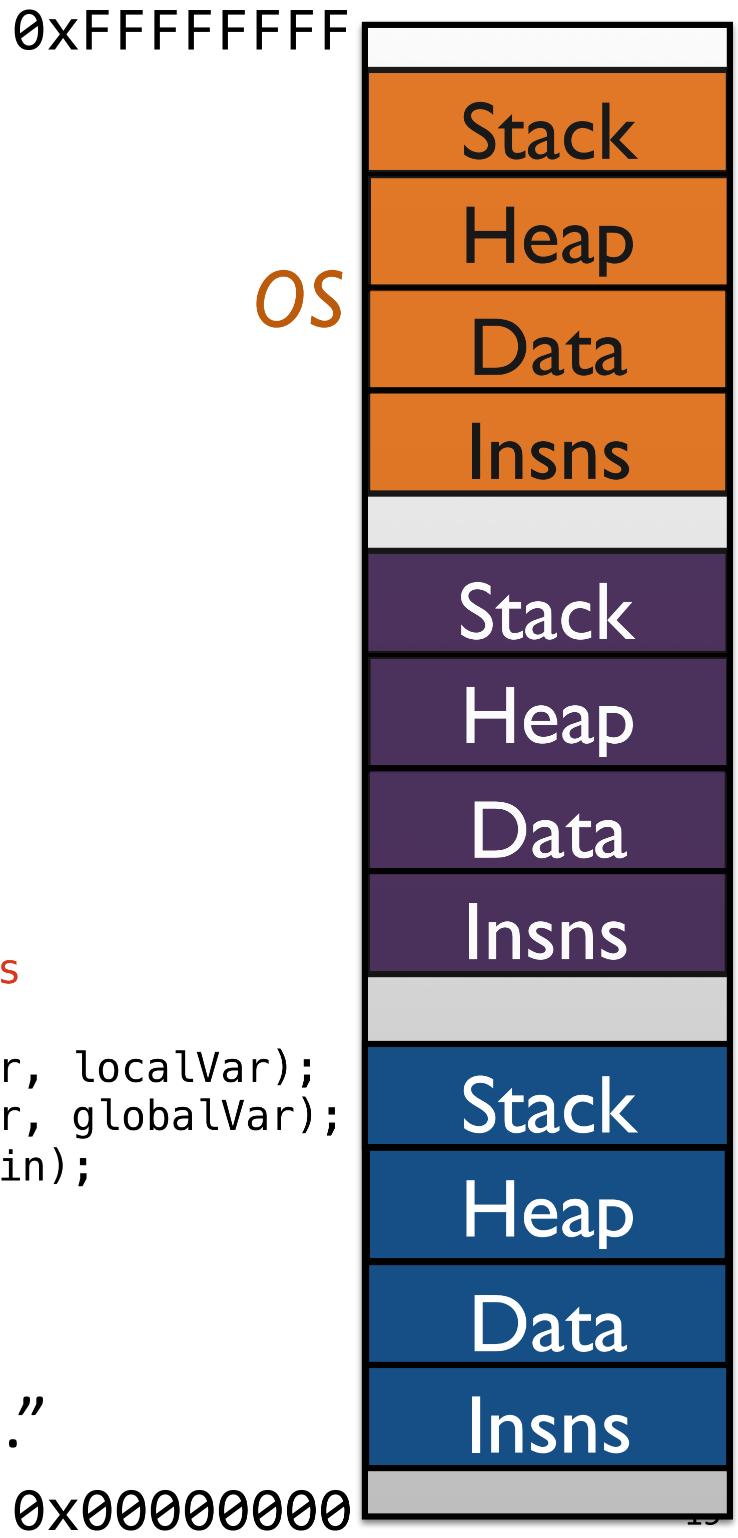
<unknown> has caused an error in <unknown>.
<unknown> will now close.

If you continue to experience problems,
try restarting your computer.

Code example

```
/*
 * Corresponds to Figure 2.7 in the textbook
 */

#include <stdio.h>
#include <unistd.h>

int globalVar = 0;      // a static variable

int main() {

    int localVar = 7;

    globalVar += 1;

    // sleep causes the program to wait for x seconds
    sleep(5);
    printf (“Loc Var: Addr: %p; Val: %d\n", &localVar, localVar);
    printf (“Gl Var: Addr: %p; Val: %d\n", &globalVar, globalVar);
    printf ("Location of Main: Address: \t%p\n", &main);
}
```

“When multiple copies of this program simultaneously, the output does not change.”



0xFFFFFFFF

OS

Stack
Heap
Data
Insns

Stack
Heap
Data
Insns

Stack
Heap
Data
Insns

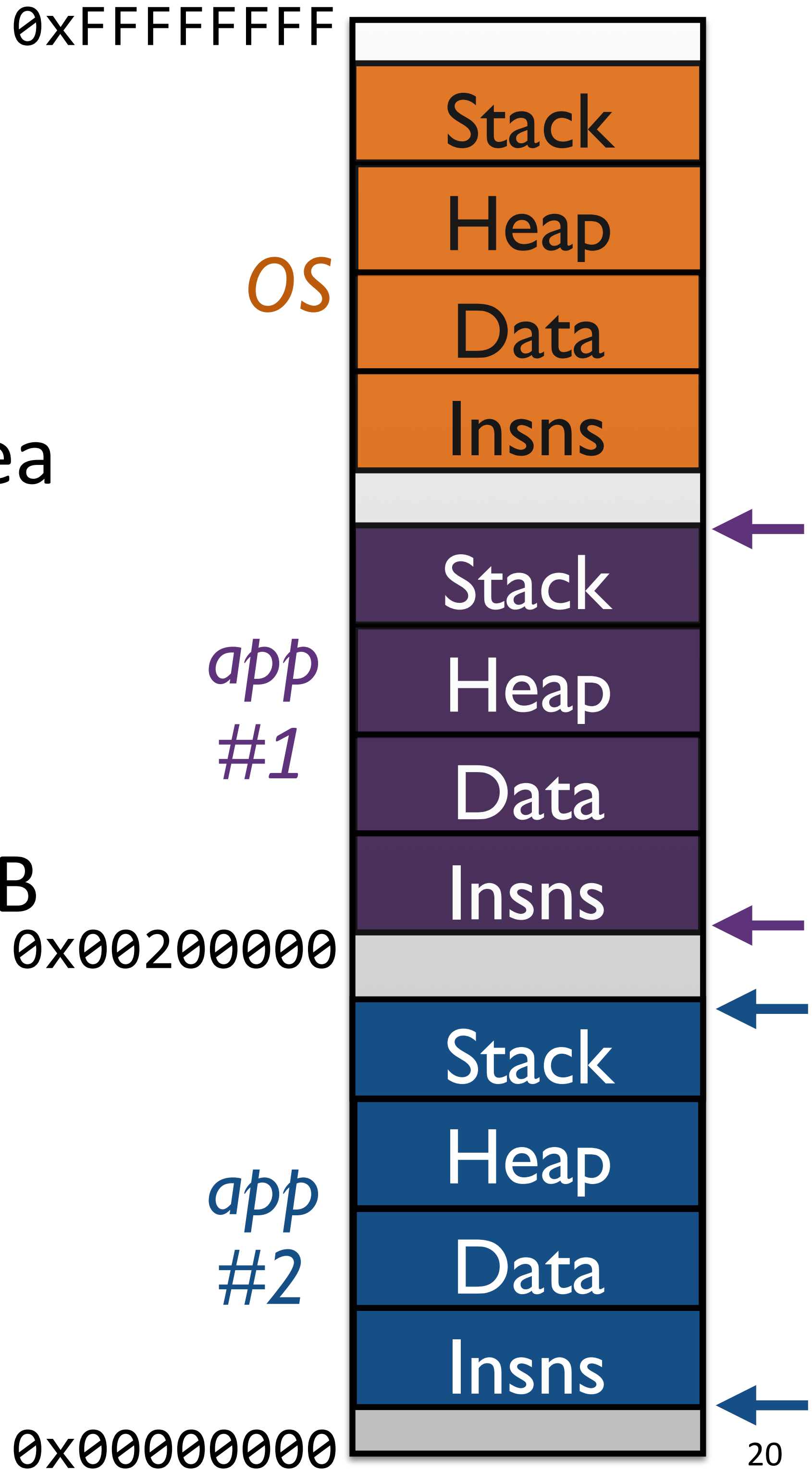
0x00000000

Multiprogramming, V1++

Add Protection

- Two registers (base and limit) keep user inside designated area
- Access illegal address → *error*

- During context switch, kernel saves/loads base/limit from PCB
- User not allowed to change base/limit registers



Dissatisfied?

Why is this a shame?

Don't worry, that's not the final version of how processors provide memory protection.

Minimum Hardware Requirements

- Privileged Instructions
- Timer Interrupts
- Memory Protection