CS162
Operating Systems and Systems Programming
Lecture 2

Four Fundamental OS Concepts

September 3rd , 2024

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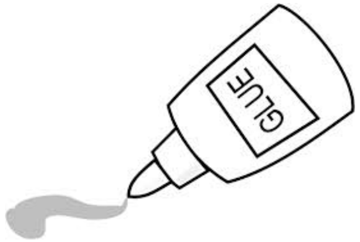
http://cs162.eecs.Berkeley.edu

Slides courtesy of David Culler, Natacha Crooks, Anthony D. Joseph, John Kubiatowicz, AJ Shankar, Alex Aiken, Eric Brewer, Ras Bodik, Doug Tygar, and David Wagner.

Recall: What is an Operating System?

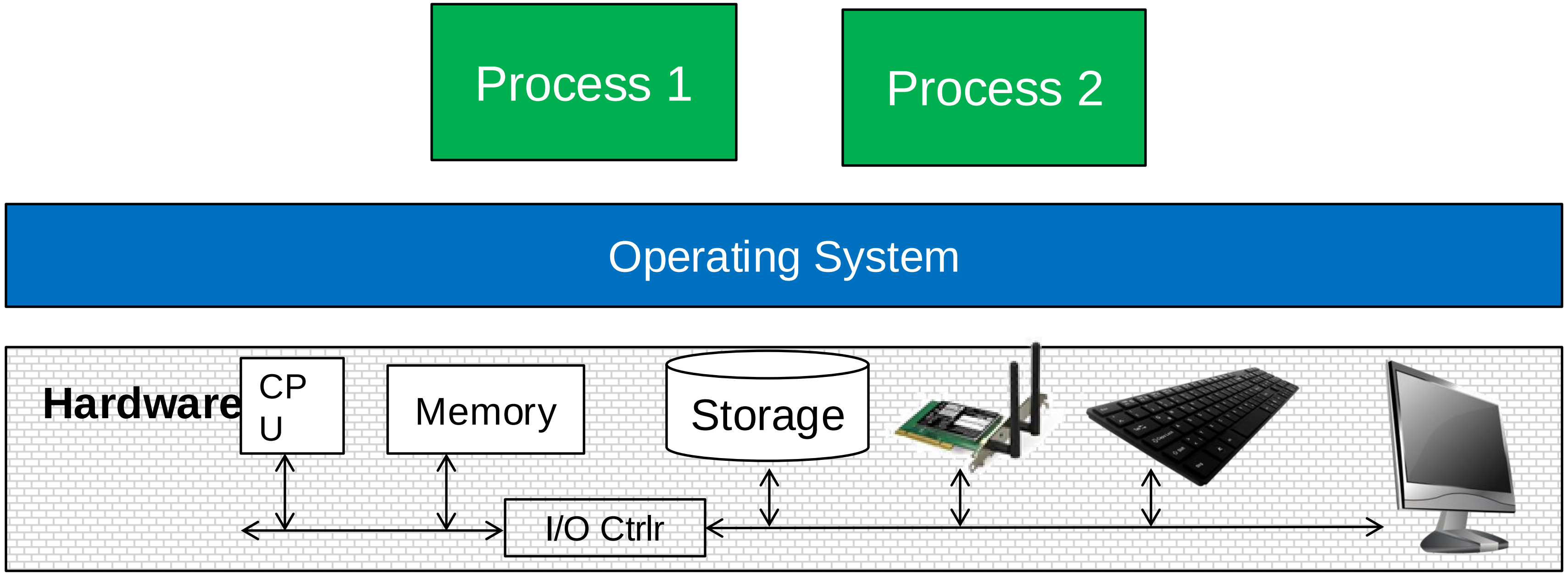
- Referee
  - Manage protection, isolation, and sharing of resources
    - » Resource allocation and communication

- Illusionist
  - Provide clean, easy-to-use abstractions of physical resources
    - » Infinite memory, dedicated machine
    - » Higher level objects: files, users, messages
    - » Masking limitations, virtualization



- Glue
  - Common services
    - » Storage, Window system, Networking
    - » Sharing, Authorization
    - » Look and feel

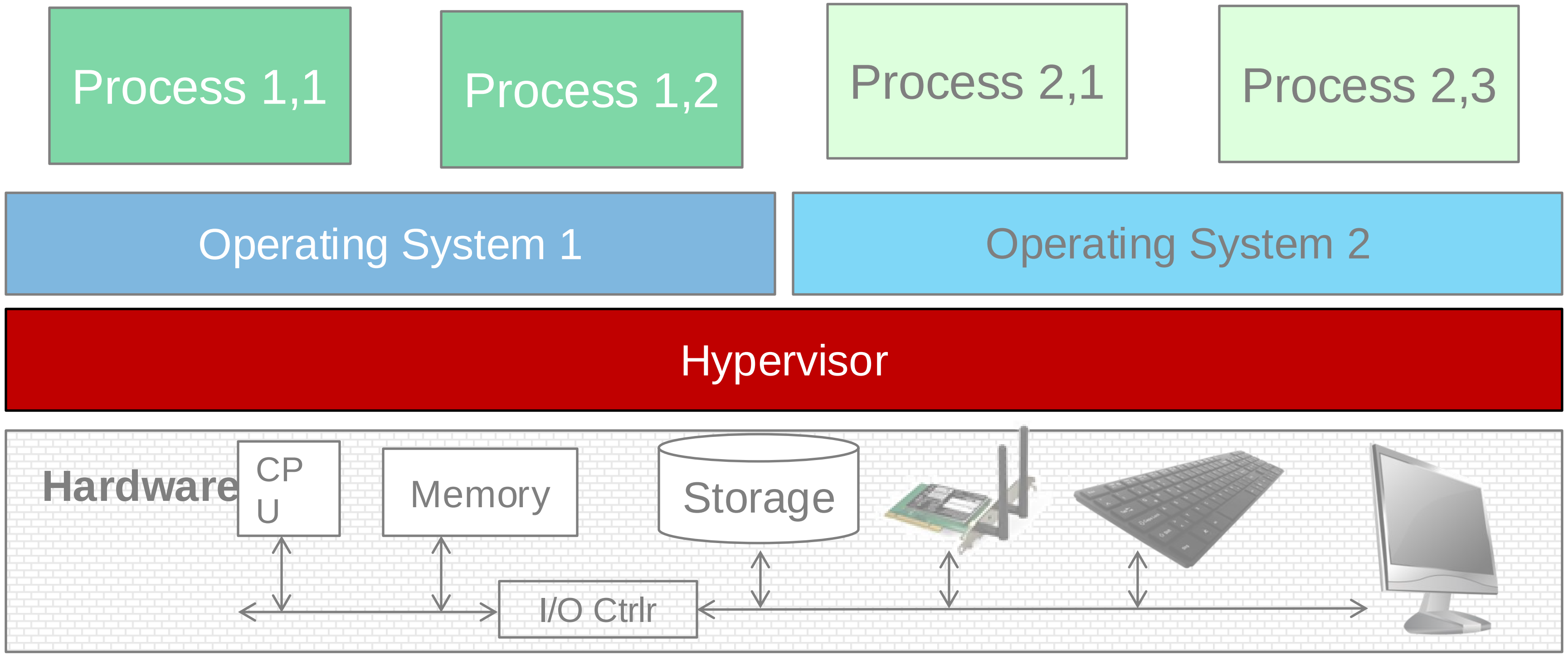
Virtualization: Operating System



Operating System virtualizes* hardware to applications providing high-level abstractions (e.g., processes, thread, sockets, etc)

***virtualization: provides the illusion that each process uses its own machine; also provides illusion if infinite memory and processor (though there will be hit in performance)**

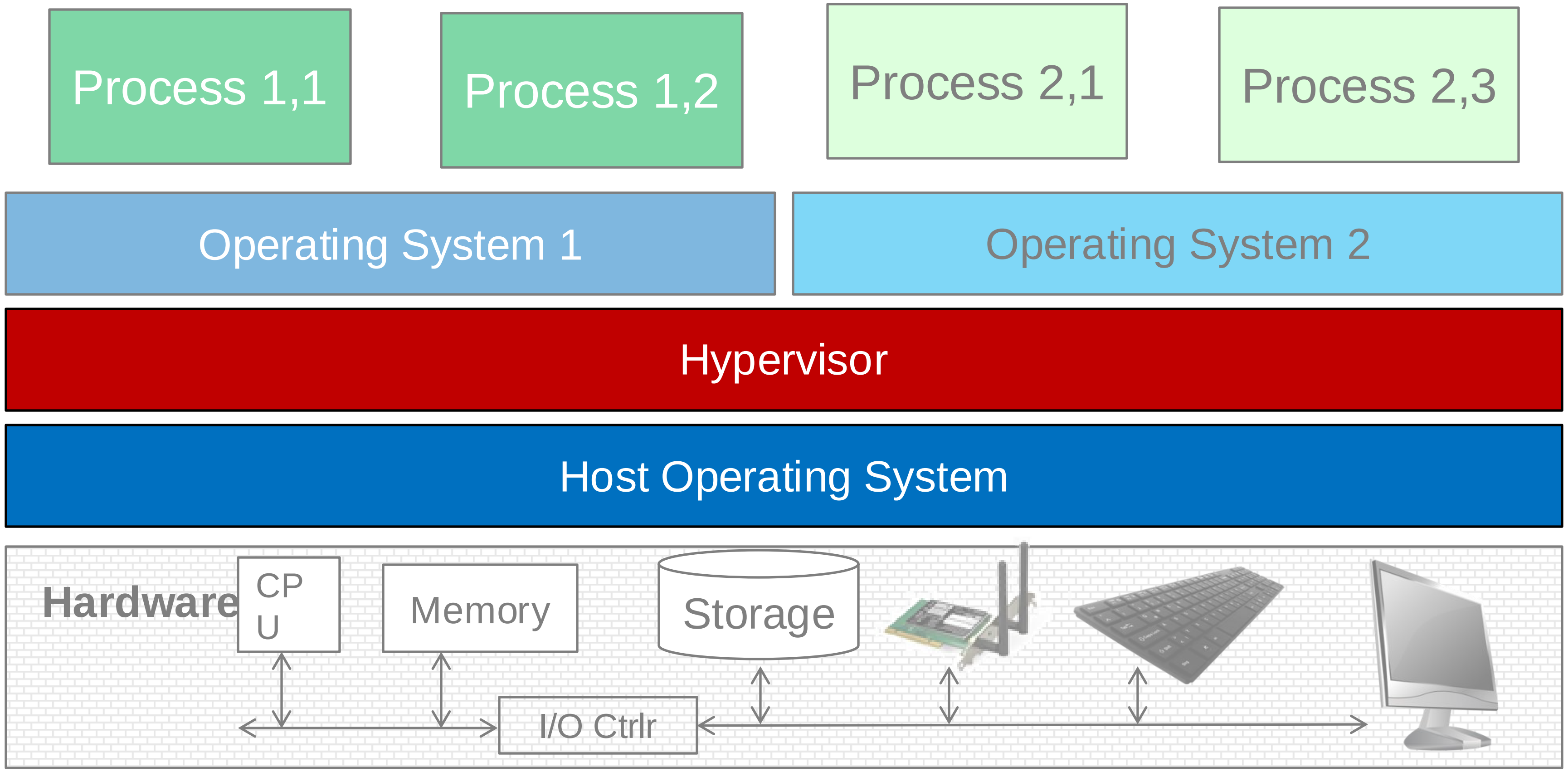
Virtualization: Virtual Machine



Hypervisor creates virtual machines.
A virtual machine virtualizes* hardware to Operating System providing same hardware abstraction

***virtualization: provides the illusion that each operating system is using the same physical machine; It provides fault isolation; if an OS crashes wont affect other OSes**

Virtualization: Virtual Machine



Virtual machines can be implemented on top of an existing OS as well (easier to deploy; provide OS isolation; it makes developing and testing for different OSes easier)

OS *Abstracts* Underlying Hardware to help Tame Complexity

- Processor → Thread
- Memory → Address Space
- Disks, SSDs, … → Files
- Networks → Sockets
- Machines → Processes

Application

Abstract Machine Interface

Operating System

Physical Machine Interface

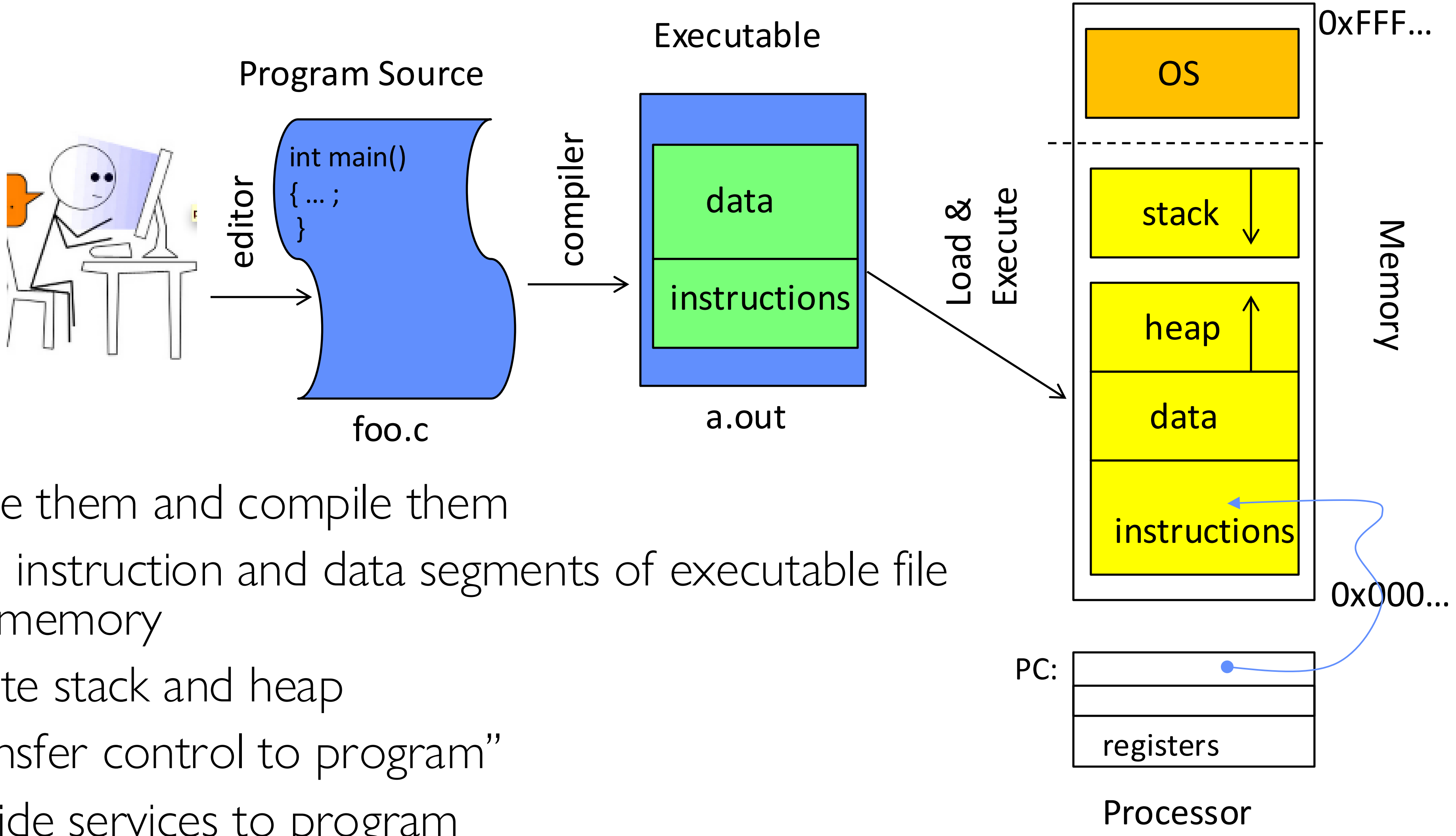
Hardware

- OS as an *Illusionist*:
  - Remove software/hardware quirks (*fight complexity)*
  - Optimize for convenience, utilization, reliability, … *(help the programmer)*
- For any OS area (e.g. file systems, virtual memory, networking, scheduling):
  - What hardware interface to handle? (physical reality)
  - What's software interface to provide? (nicer abstraction)

Today: Four Fundamental OS Concepts

- Thread: Execution Context
  - Fully describes program state
  - Program Counter, Registers, Execution Flags, Stack
- **Address space** (with or w/o **translation**)
  - Set of memory addresses accessible to program (for read or write)
  - May be distinct from memory space of the physical machine (in which case programs operate in a virtual address space)
- **Process: an instance of a running program**
  - Protected Address Space + One or more Threads
- **Dual mode operation / Protection**
  - Only the "system" has the ability to access certain resources
  - Combined with translation, isolates programs from each other and the OS from programs

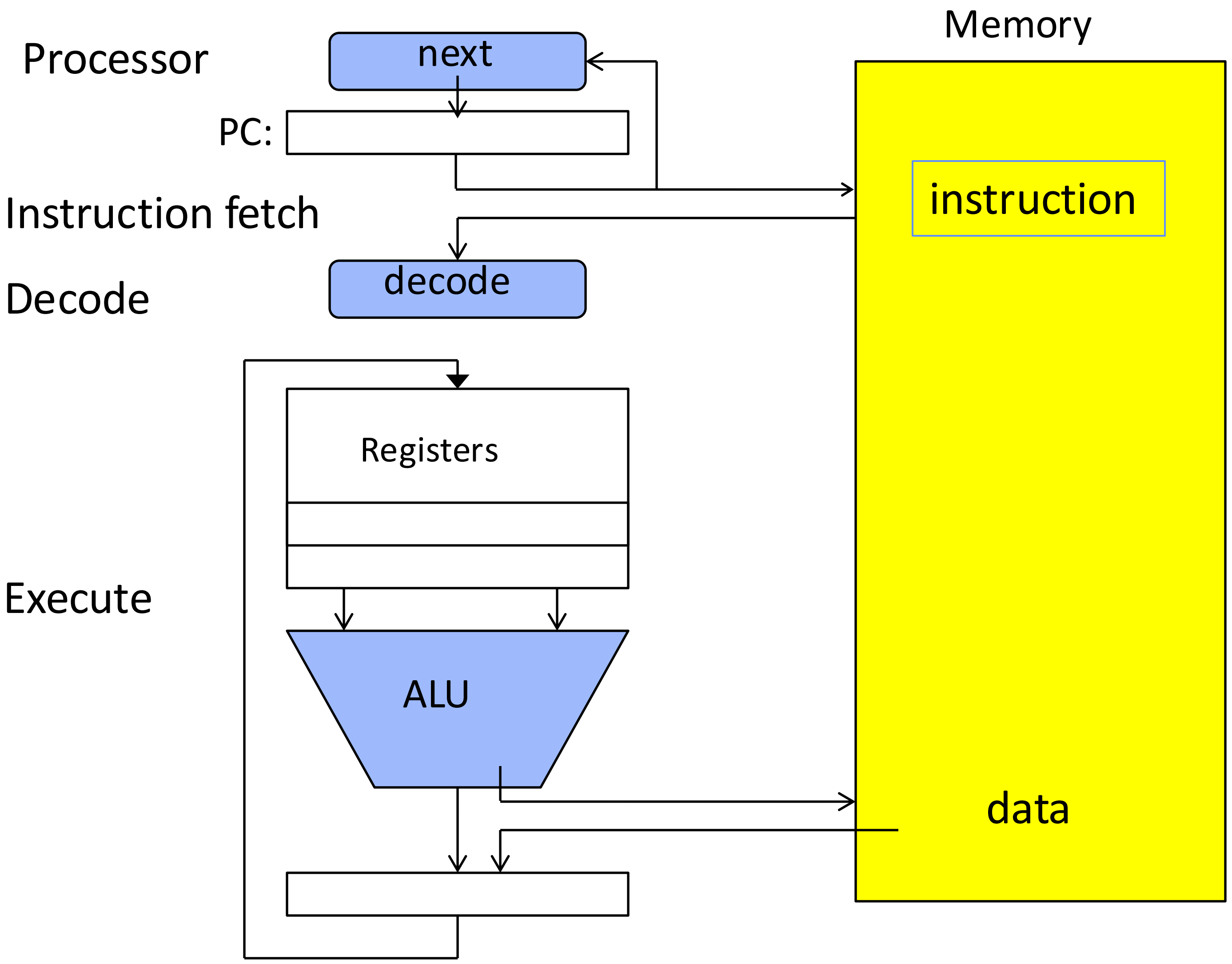
OS Bottom Line: Run Programs



- Write them and compile them
- Load instruction and data segments of executable file into memory
- Create stack and heap
- "Transfer control to program"
- Provide services to program
- While protecting OS and program

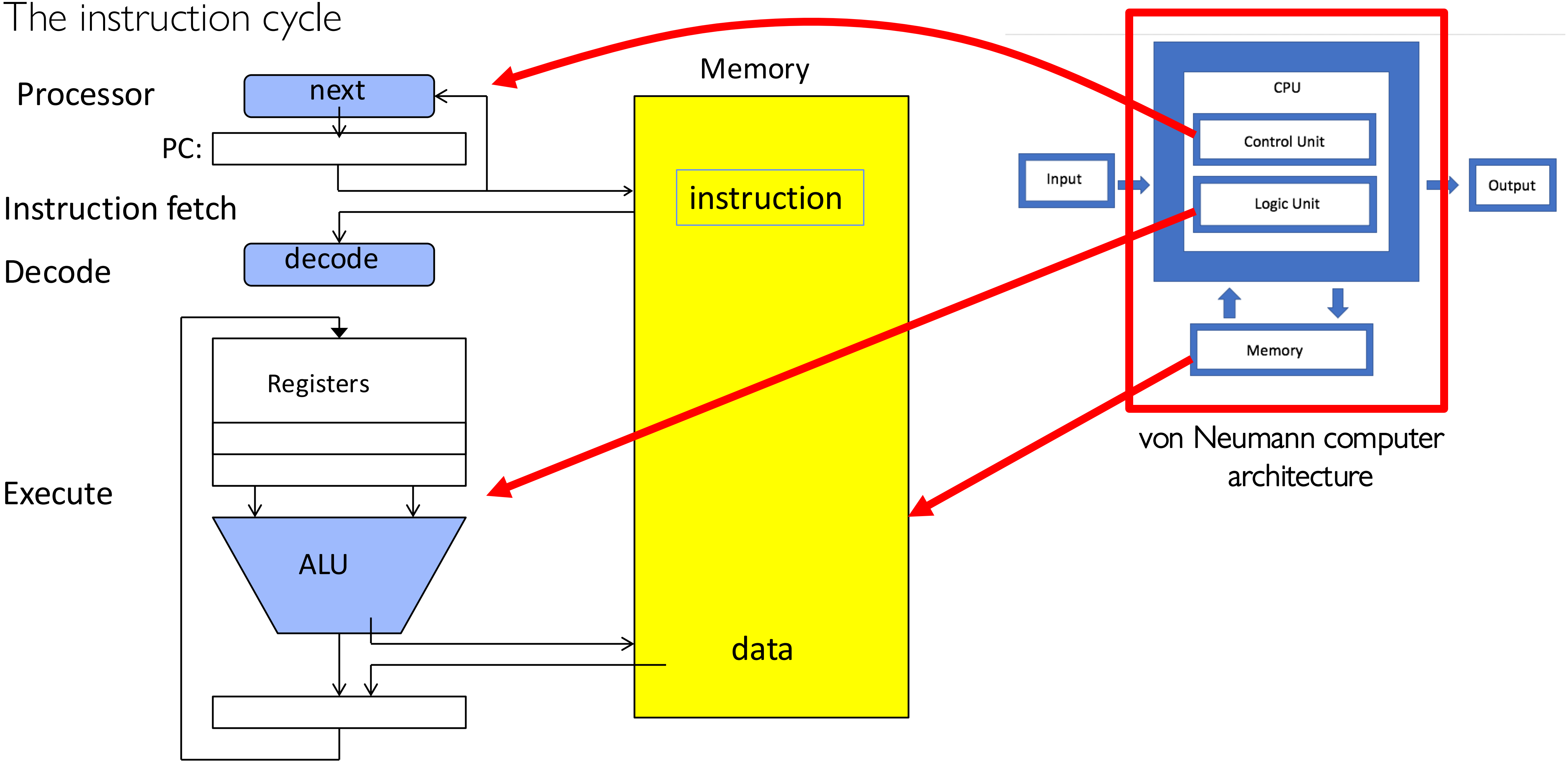
Recall (61C): Instruction Fetch/Decode/Execute

The instruction cycle



Recall (61C): Instruction Fetch/Decode/Execute

The instruction cycle

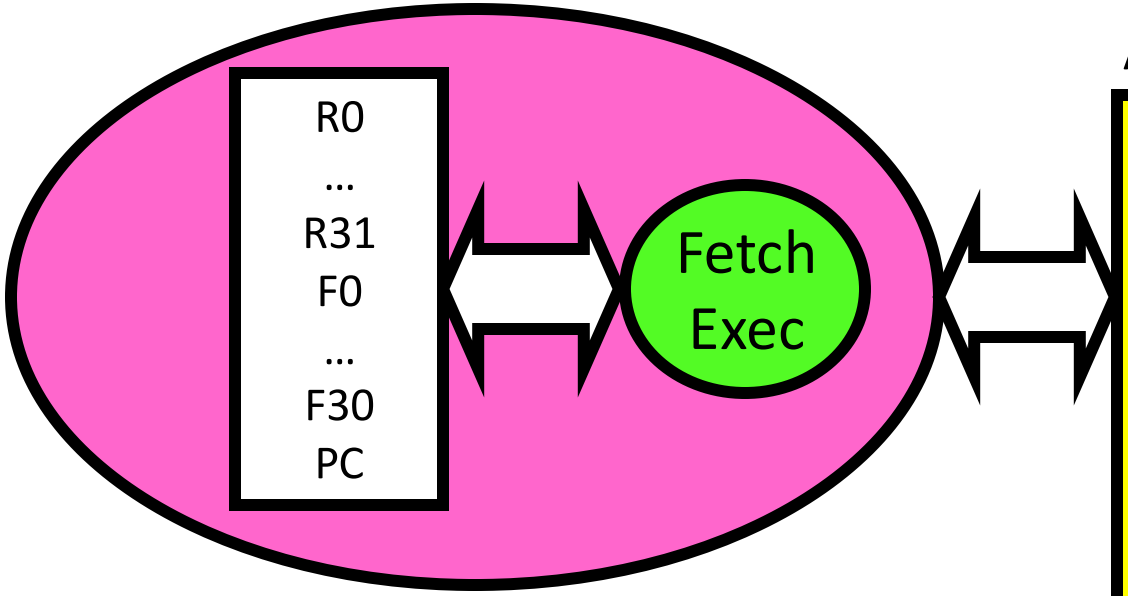


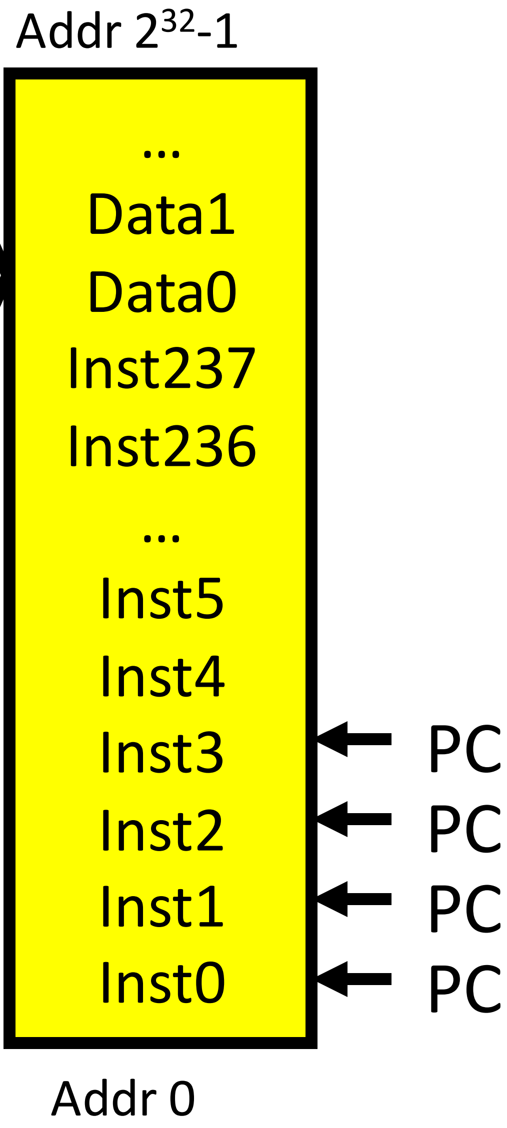
von Neumann computer architecture

First OS Concept: Thread of Control

- **Thread**: Single unique execution context
  - Program Counter, Registers, Execution Flags, Stack, Memory State
- A thread is *executing* on a processor (core) when it is *resident* in the processor registers
- Resident means: Registers hold the root state (context) of the thread:
  - Including program counter (PC) register & currently executing instruction
    - PC points at next instruction in memory
    - Instructions stored in memory
  - Including intermediate values for ongoing computations
    - Can include actual values (like integers) or pointers to values in memory
  - Stack pointer holds the address of the top of stack (which is in memory)
  - The rest is "in memory"
- A thread is *suspended* (not *executing*) when its state *is not* loaded (resident) into the processor
  - Processor state pointing at some other thread
  - Program counter register *is not* pointing at next instruction from this thread
  - Often: a copy of the last value for each register stored in memory

Recall (61C): What happens during program execution?



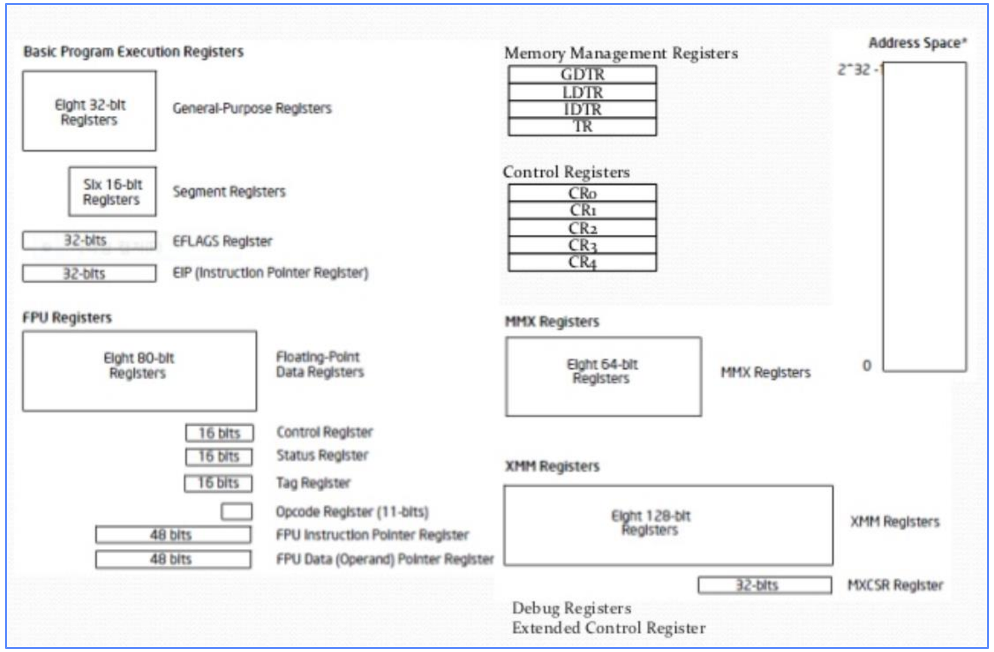


- Execution sequence:
  - Fetch Instruction at PC
  - Decode
  - Execute (possibly using registers)
  - Write results to registers/mem
  - PC = Next Instruction(PC)
  - Repeat

Registers: RISC-V ⇒ x86

Register	ABI Name	Description	Saver
x0	zero	Hard-wired zero	—
x1	ra	Return address	Caller
x2	sp	Stack pointer	Callee
x3	gp	Global pointer	—
x4	tp	Thread pointer	—
x5	t0	Temporary/alternate link register	Caller
x6–7	t1–2	Temporaries	Caller
x8	s0/fp	Saved register/frame pointer	Callee
x9	s1	Saved register	Callee
x10–11	a0–1	Function arguments/return values	Caller
x12–17	a2–7	Function arguments	Caller
x18–27	s2–11	Saved registers	Callee
x28–31	t3–6	Temporaries	Caller

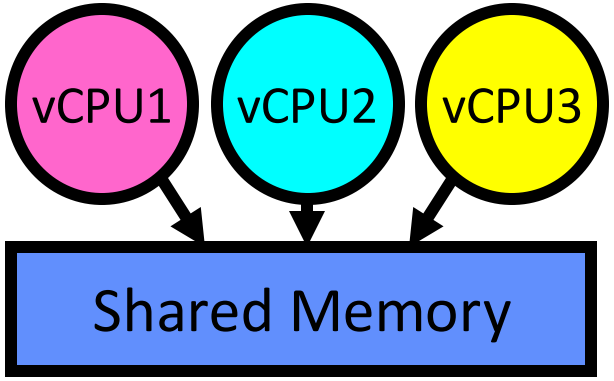
Load/Store Arch (RISC-V) with software conventions



Complex mem-mem arch (x86) with specialized registers and "segments"

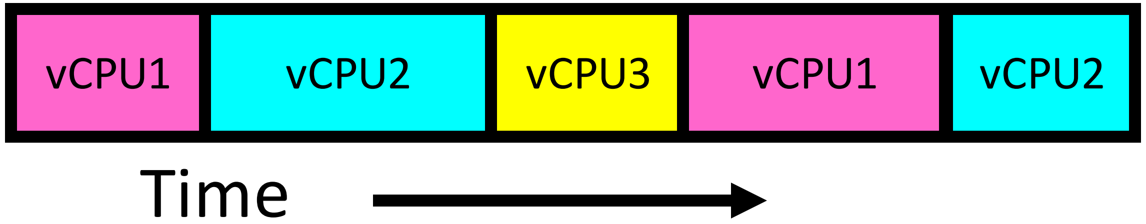
- CS61C does RISC-V. Will need to learn x86…
- Section will cover this architecture

Illusion of Multiple Processors with single core



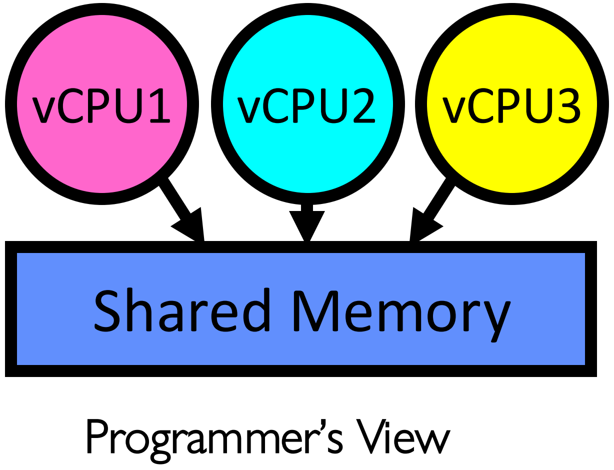
Programmer's View

- Assume a single processor (core). How do we provide the illusion of multiple processors?
  – Multiplex in time!
- Threads are *virtual cores*

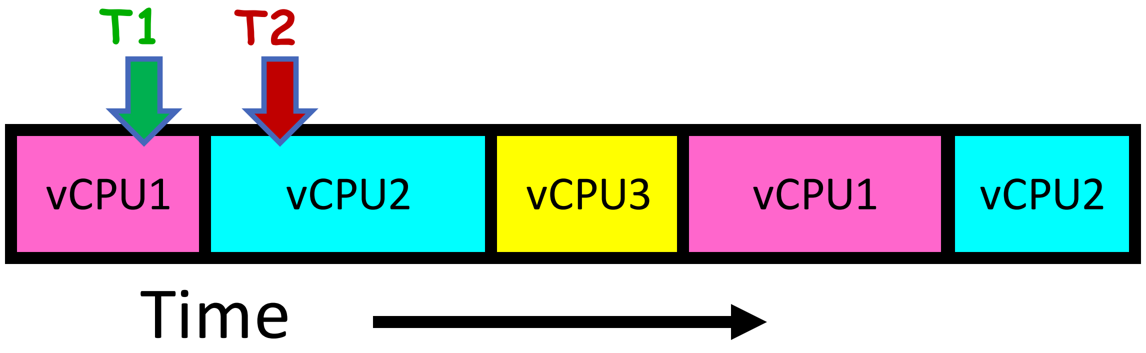


- Contents of virtual core (thread):
  – Program counter, stack pointer
  – Registers
- Where is "it" (the thread)?
  – On the real (physical) core, or
  – Saved in chunk of memory – called the *Thread Control Block (TCB)*

Illusion of Multiple Processors (Continued)

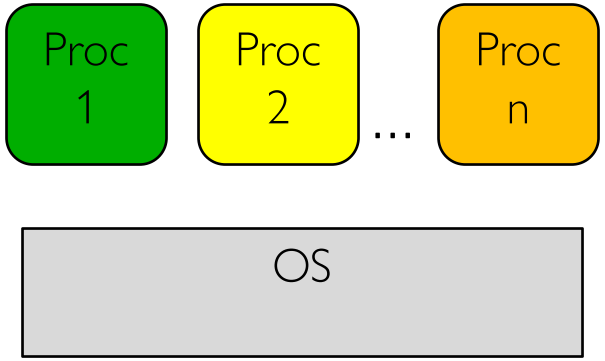


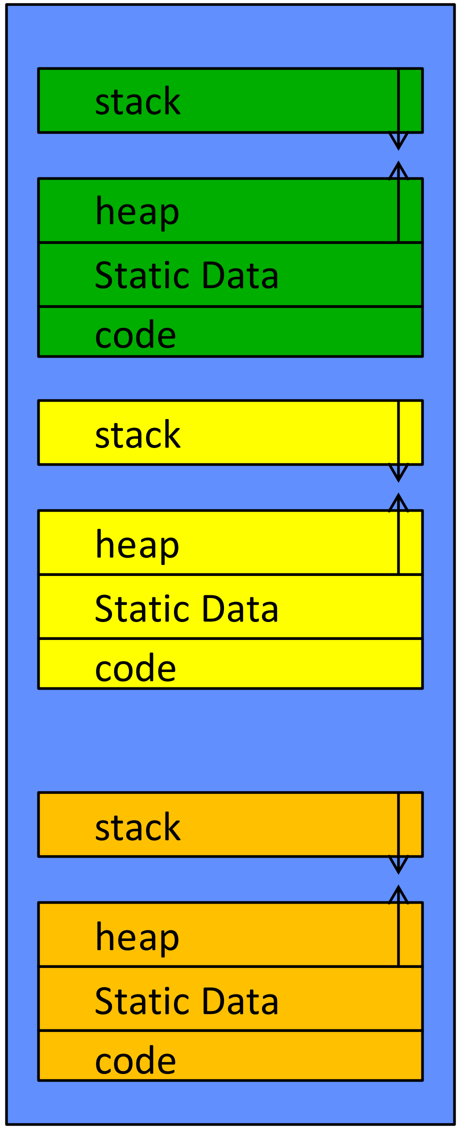
- Consider:
  - At T1: vCPU1 on real core, vCPU2 in memory
  - At T2: vCPU2 on real core, vCPU1 in memory



- What happened?
  - OS Ran [how?]
  - Saved PC, SP, … in vCPU1's thread control block (memory)
  - Loaded PC, SP, … from vCPU2's TCB, jumped to PC
- What triggered this switch?
  - Timer, voluntary yield, I/O, other things we will discuss

Multiprogramming - Multiple Threads of Control





- Thread Control Block (TCB)
  – Holds contents of registers when thread not running
  – What other information?
- Where are TCBs stored?
  – For now, in the kernel
- PINTOS? – read thread.h and thread.c

Administrivia: Getting started

- Should be working on Homework 0 already! ⇒ Due Friday (9/6)
  - cs162-xx account, Github account, registration survey
  - VM environment for the course
  - Get familiar with all the cs162 tools, submitting to autograder via git
- Start Project 0 Monday!
  - To be done on your own – like a homework
- Reminder of Resources for you (look at Resources tab on homepage!)
  - Quick tutorial about C: Ladder
  - Oreilly Books on: C language, Git environment, Rust (for later)
- Class size is fixed at 305 students, 10 sections
  - Will be moving more students from waitlist ⇒ class as students drop
  - If you are on waitlist, *assume you could get into the class at any time in next week or so!*
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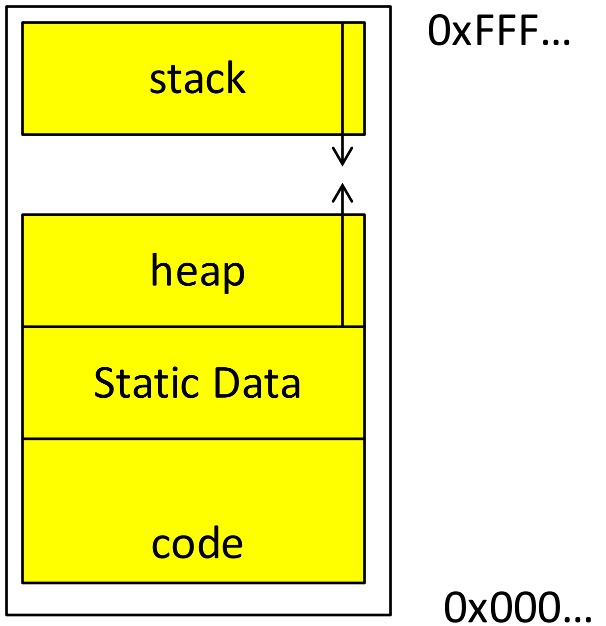
  - Very hard to drop afterwards…
  - Please drop sooner if you are going to anyway ⇒ Let someone else in!

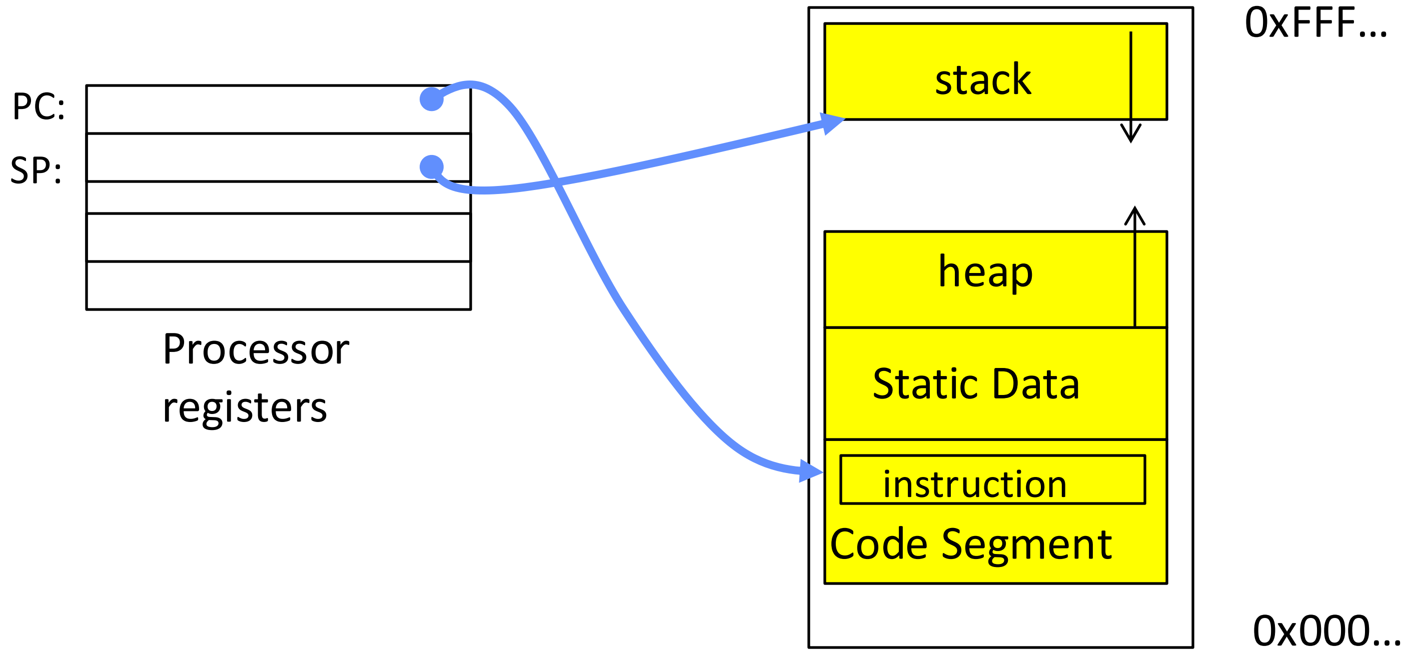
Second OS Concept: Address Space

- Address space ⇒ the set of accessible addresses + state associated with them:
  – For 32-bit processor: 2^{32} = 4 billion (10^9) addresses
  – For 64-bit processor: 2^{64} = 18 quintillion (10^{18}) addresses



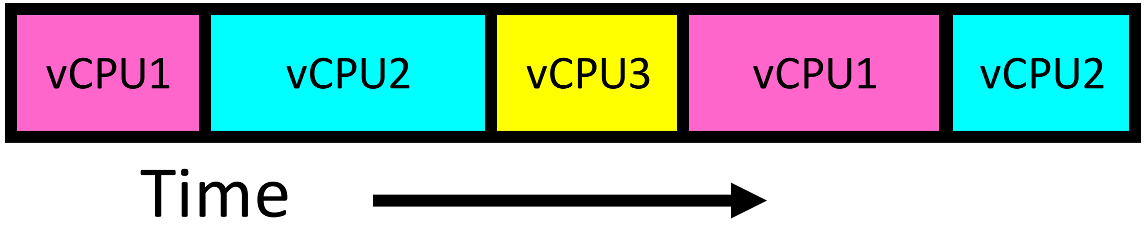
- What happens when you read or write to an address?
  – Perhaps acts like regular memory
  – Perhaps ignores writes
  – Perhaps causes I/O operation
    » (Memory-mapped I/O)
  – Perhaps causes exception (fault)
  – Communicates with another program
  – ….

Address Space: In a Picture



- What's in the code segment? Static data segment?
- What's in the Stack Segment?
  - How is it allocated? How big is it?
- What's in the Heap Segment?
  - How is it allocated? How big?

Previous discussion of threads: Very Simple Multiprogramming



- All vCPU's share non-CPU resources
  - Memory, I/O Devices
- Each thread can read/write memory
  - Perhaps data of others
  - can overwrite OS ?
- Unusable?
- This approach is used in
  - Very early days of computing
  - Embedded applications
  - MacOS 1-9/Windows 3.1 (switch only with voluntary yield)
- However it is risky…

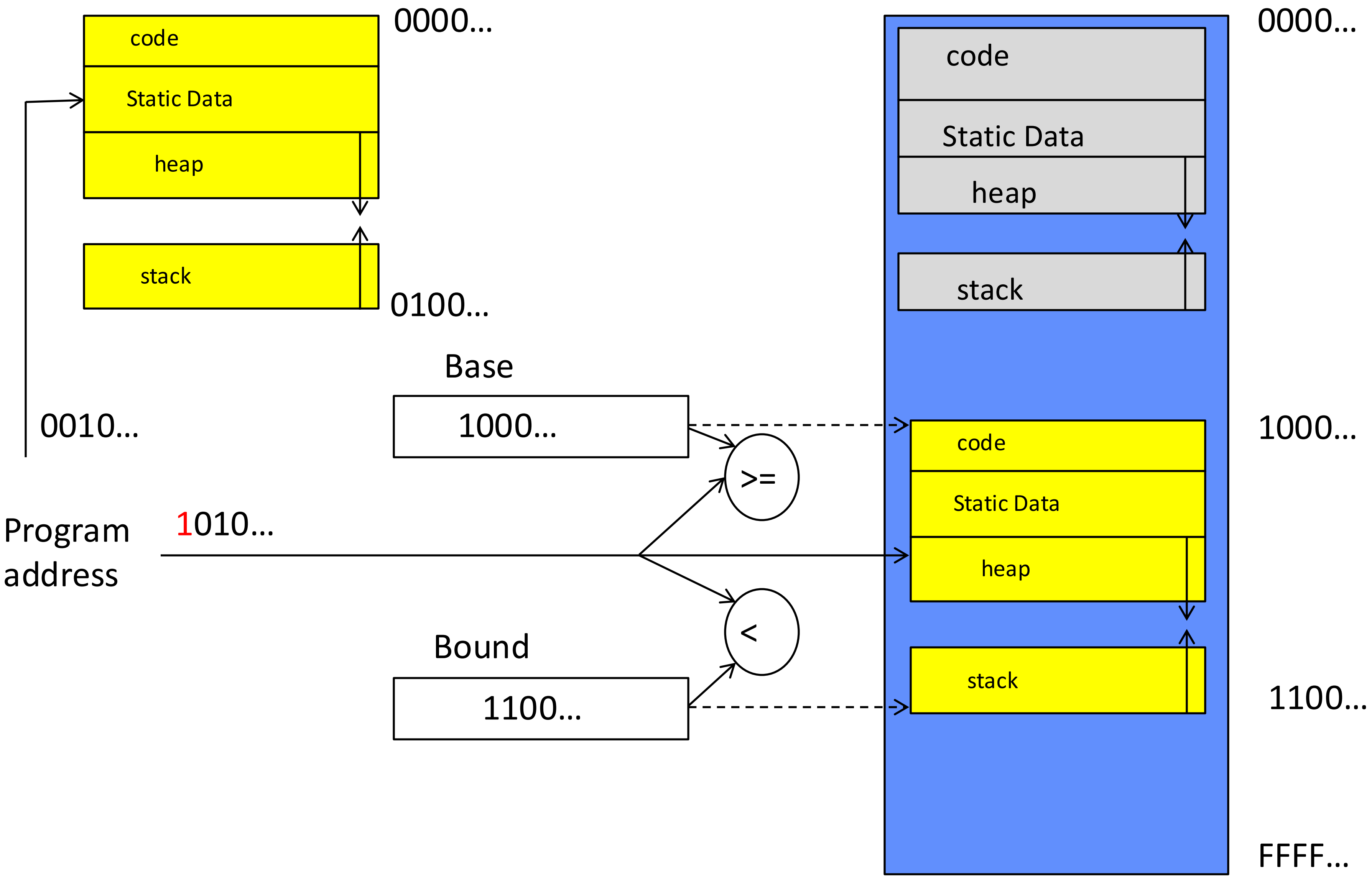
Simple Multiplexing has no Protection!

- Operating System must protect itself from user programs
  - Reliability: compromising the operating system generally causes it to crash
  - Security: limit the scope of what threads can do
  - Privacy: limit each thread to the data it is permitted to access
  - Fairness: each thread should be limited to its appropriate share of system resources (CPU time, memory, I/O, etc)
- OS must protect User programs from one another
  - Prevent threads owned by one user from impacting threads owned by another user
  - Example: prevent one user from stealing secret information from another user

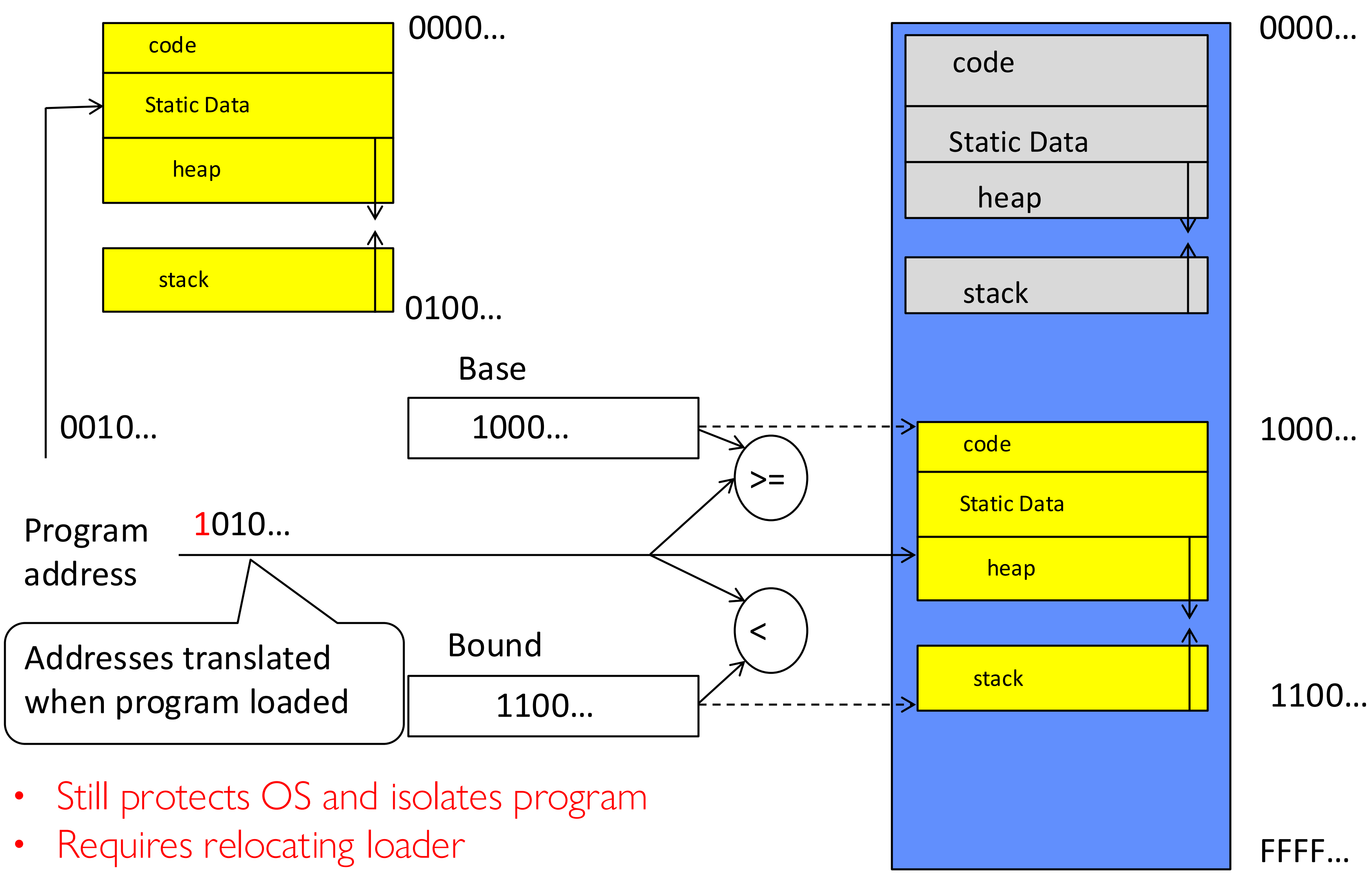
What can the hardware do to help the OS protect itself from programs???

How about: Limit the *ACCESS* that threads have to memory

Simple Protection: Base and Bound (B&B)

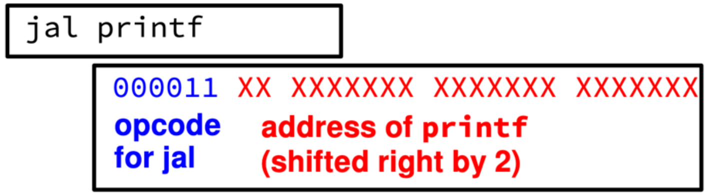


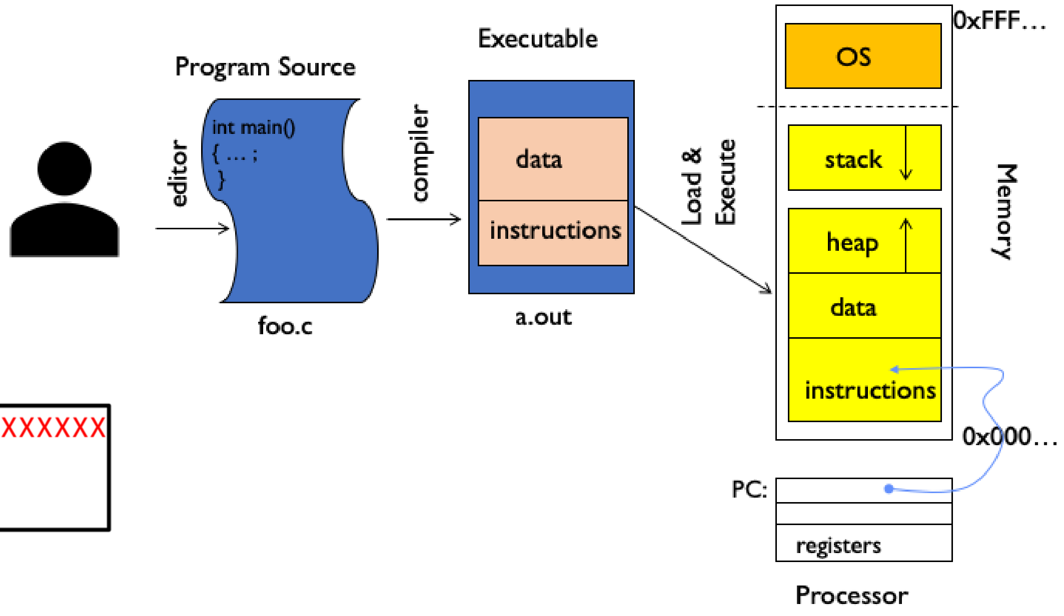
Simple Protection: Base and Bound (B&B)



- Still protects OS and isolates program
- Requires relocating loader
- No addition on address path

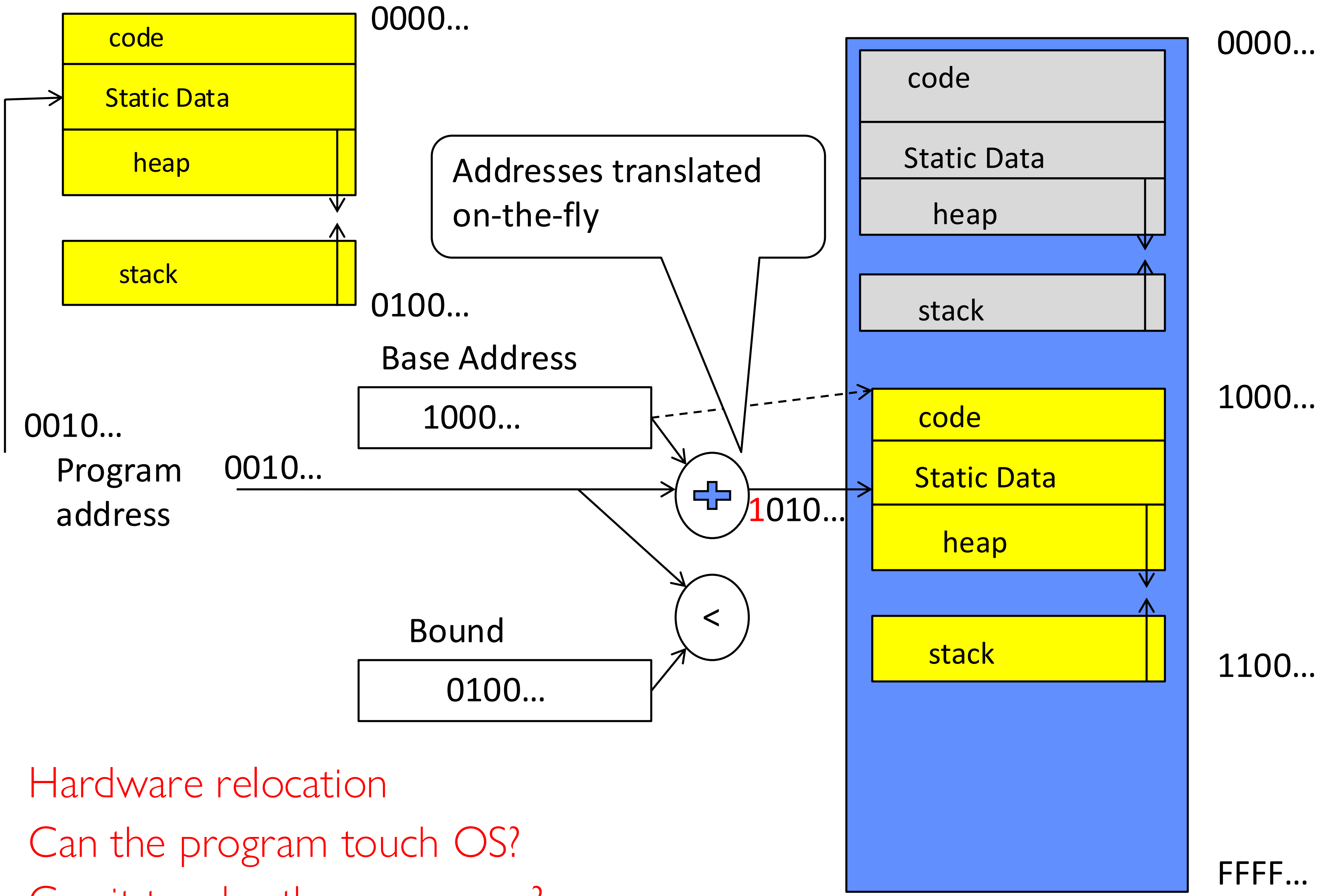
61C Review: Relocation





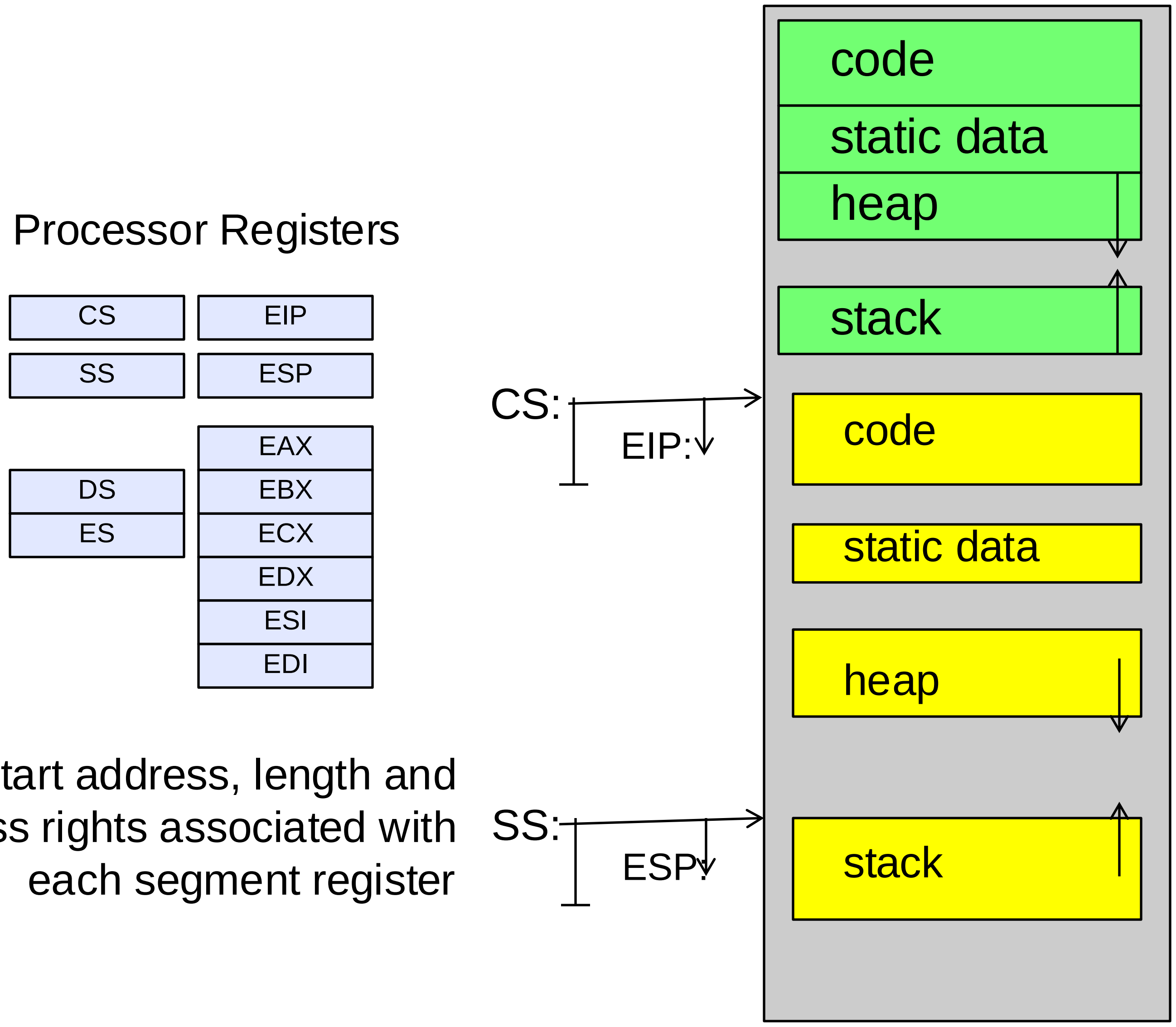
- Compiled .obj file linked together in an .exe
- All address in the .exe are as if it were loaded at memory address 00000000
- File contains a list of all the addresses that need to be adjusted when it is “relocated” to somewhere else.

Simple address translation with Base and Bound



- Hardware relocation
- Can the program touch OS?
- Can it touch other programs?

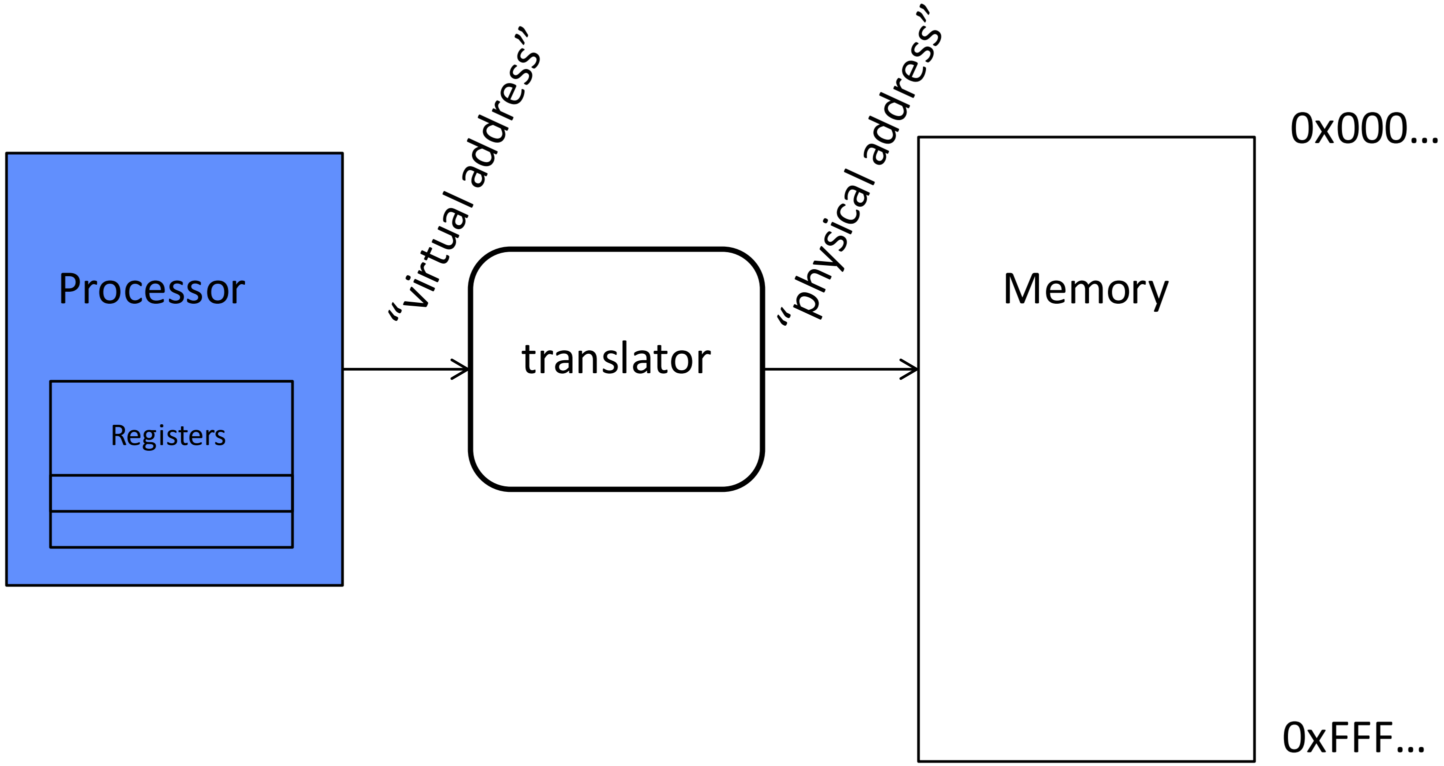
x86 – segments and stacks



Start address, length and access rights associated with each segment register

Another idea: Address Space Translation

- Program operates in an address space that is distinct from the physical memory space of the machine

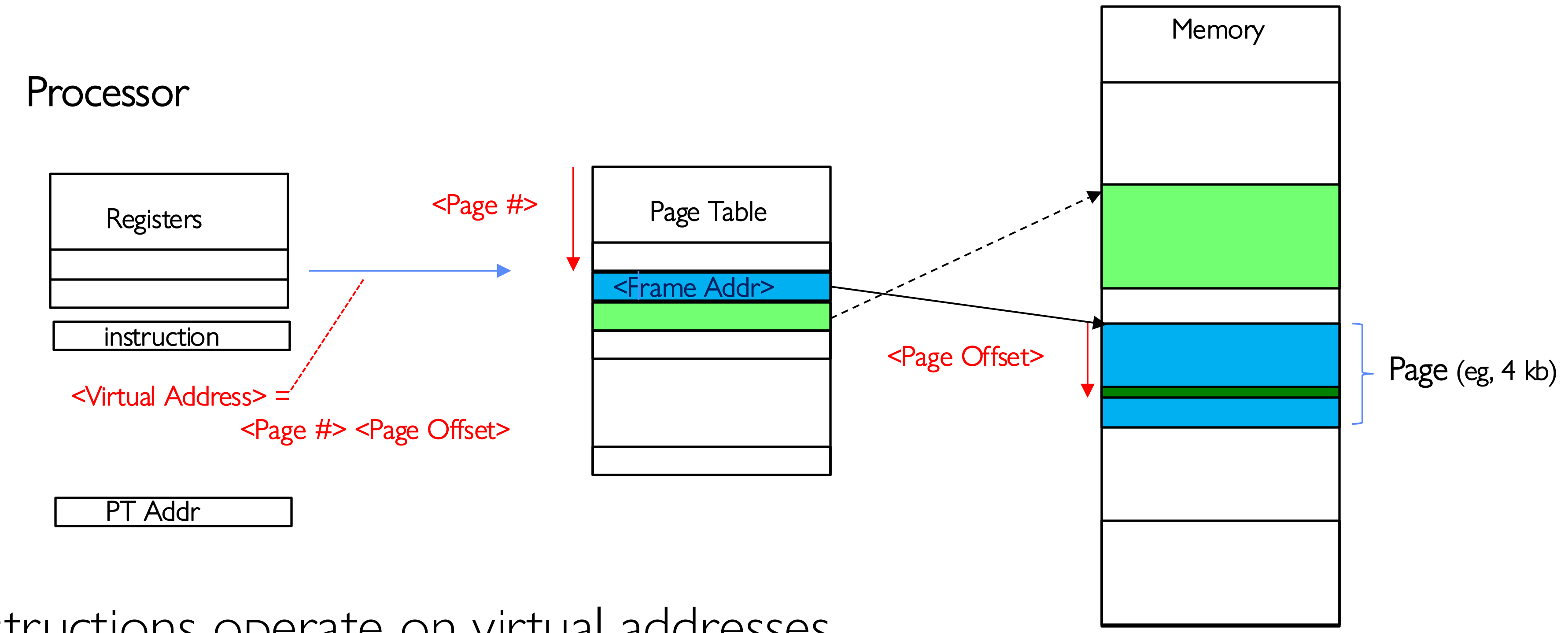


Paged Virtual Address Space

- What if we break the entire virtual address space into equal size chunks (i.e., pages) have a base for each?
- All pages same size, so easy to place each page in memory!
- Hardware translates address using a **page table**
  - Each page has a separate base
  - The "bound" is the page size
  - Special hardware register stores pointer to page table
  - Treat memory as page size frames and put any page into any frame …

- Another cs61C review…

Paged Virtual Address (from 61C)



- Instructions operate on virtual addresses
  – Instruction address, load/store data address
- Translated to a physical address through a Page Table by the hardware
- Any Page of address space can be in any (page sized) frame in memory
  – Or not-present (access generates a page fault)
- Special register holds page table base address (of the process)

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- Reminder of Resources for you (look at Resources tab on homepage!)
  - Quick tutorial about C: Ladder
  - Oreilly Books on: C language, Git environment, Rust (for later)
- Slip days: I'd bank these and not spend them right away!
  - You have 6 slip days for homework
  - You have 7 slip days for projects
  - (Very) Limited credit when late and run out of slip days
- Please don't use slip days on Homework 0 / Project 0!
  - You will start off on wrong foot!

Administrivia (Con't)

- Monday is an optional REVIEW session for C
  - Time and location/Zoom link TBA
  - May be recorded
- Class size is fixed at 316 students; 10 discussion sections
  - Will be moving more students from waitlist ⇒ class as students drop
  - If you are on waitlist, *assume you could get into the class at any time in next week or so!*
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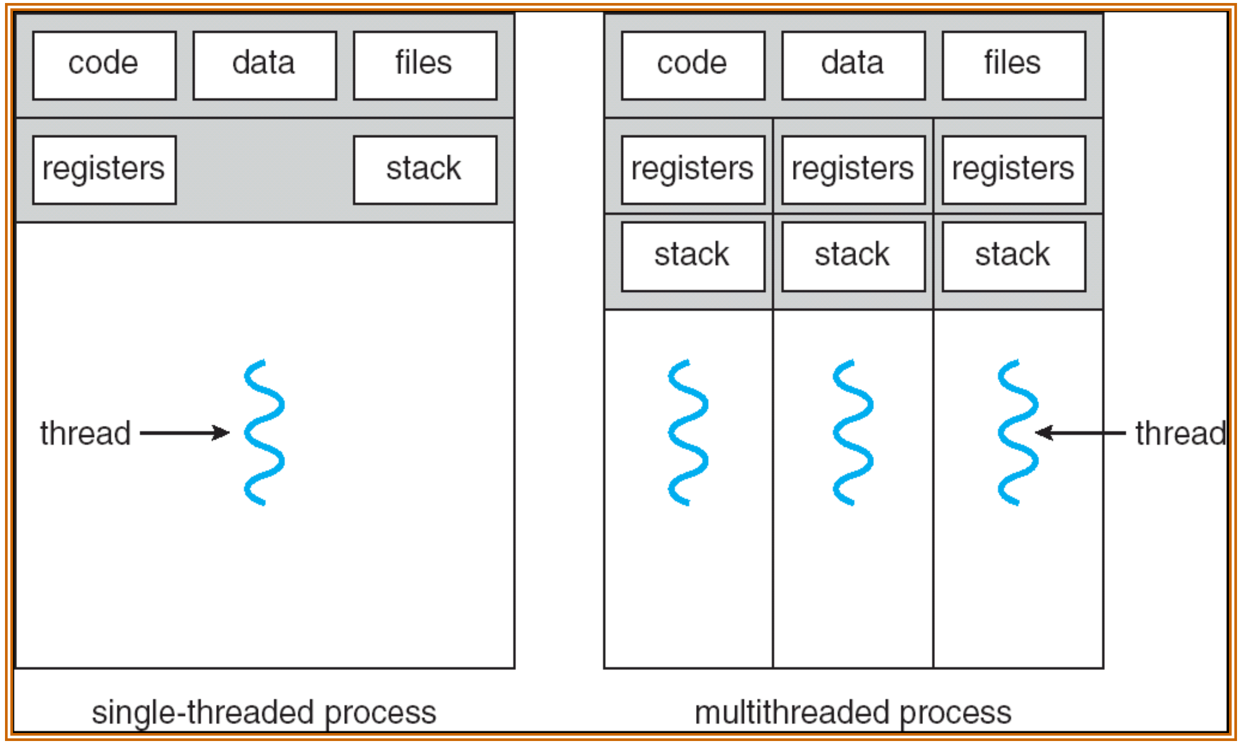
Third OS Concept: Process

- **Definition:** execution environment with Restricted Rights
  - **(Protected) Address Space with One or More Threads**
  - Owns memory (address space)
  - Owns file descriptors, file system context, …
  - Encapsulate one or more threads sharing process resources
- Application program executes as a process
  - Complex applications can fork/exec child processes [later!]
- Why **processes**?
  - Protected from each other!
  - OS Protected from them
  - Processes provides memory protection
- Fundamental tradeoff between protection and efficiency
  - Communication easier *within* a process
  - Communication harder *between* processes

Single and Multithreaded Processes



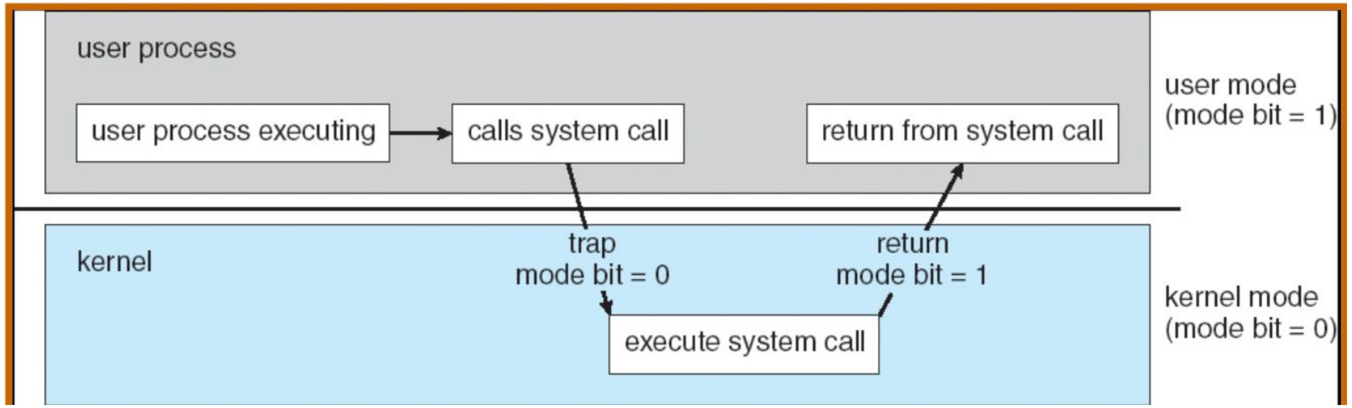
- Threads encapsulate concurrency:
  - "Active" component
- Address spaces encapsulate protection:
  - "Passive" component
  - Keeps buggy programs from crashing the system
- Why have multiple threads per address space?
  - Parallelism: take advantage of actual hardware parallelism (e.g. multicore)
  - Concurrency: ease of handling I/O and other simultaneous events

Protection and Isolation

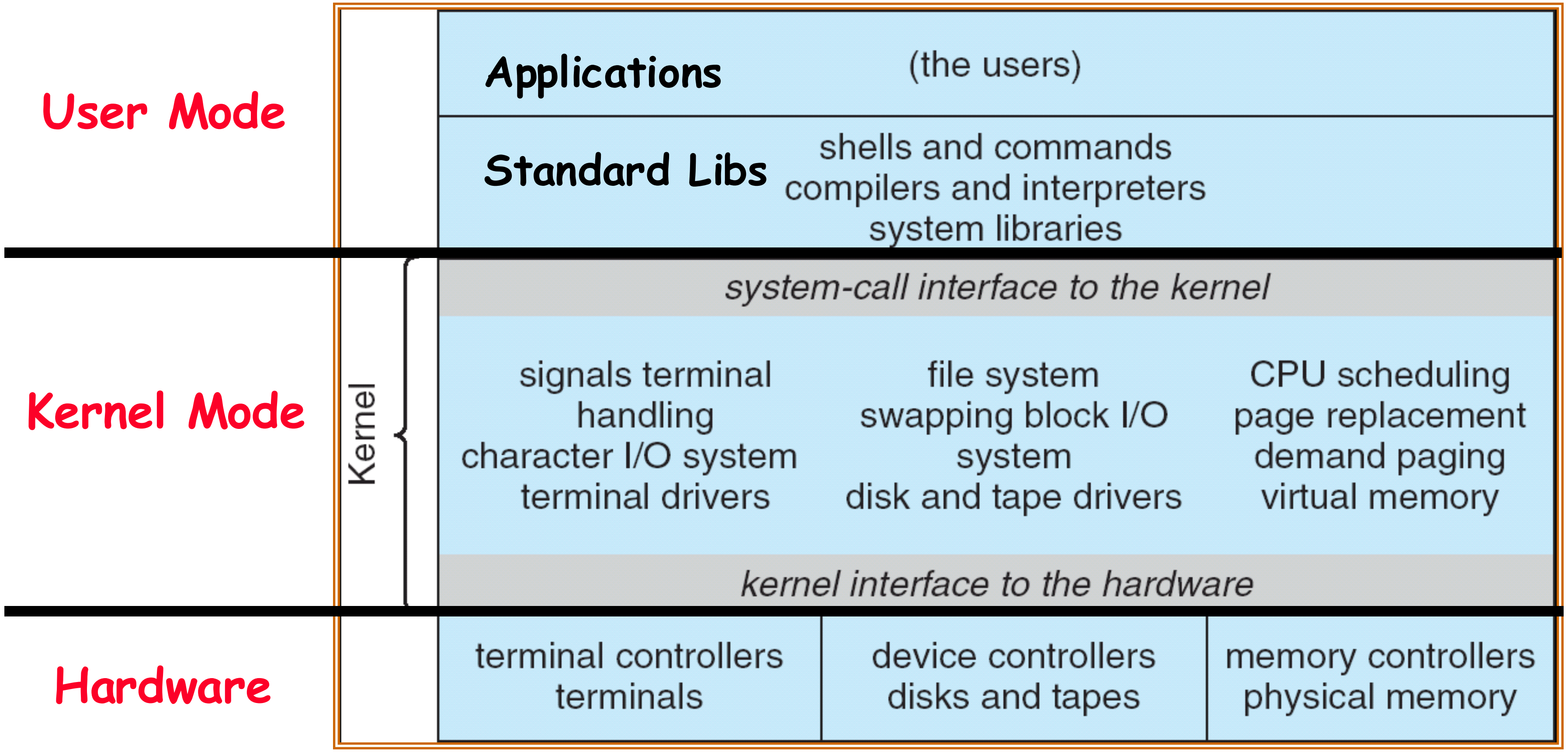
- Why Do We Need Processes??
  – Reliability: bugs can only overwrite memory of process they are in
  – Security and privacy: malicious or compromised process can't read or write other process' data
  – (to some degree) Fairness: enforce shares of disk, CPU
- Mechanisms:
  – Address translation: address space only contains its own data
  – BUT: why can't a process change the page table pointer?
    » Or use I/O instructions to bypass the system?
  – Hardware must support **privilege levels**

Fourth OS Concept: Dual Mode Operation

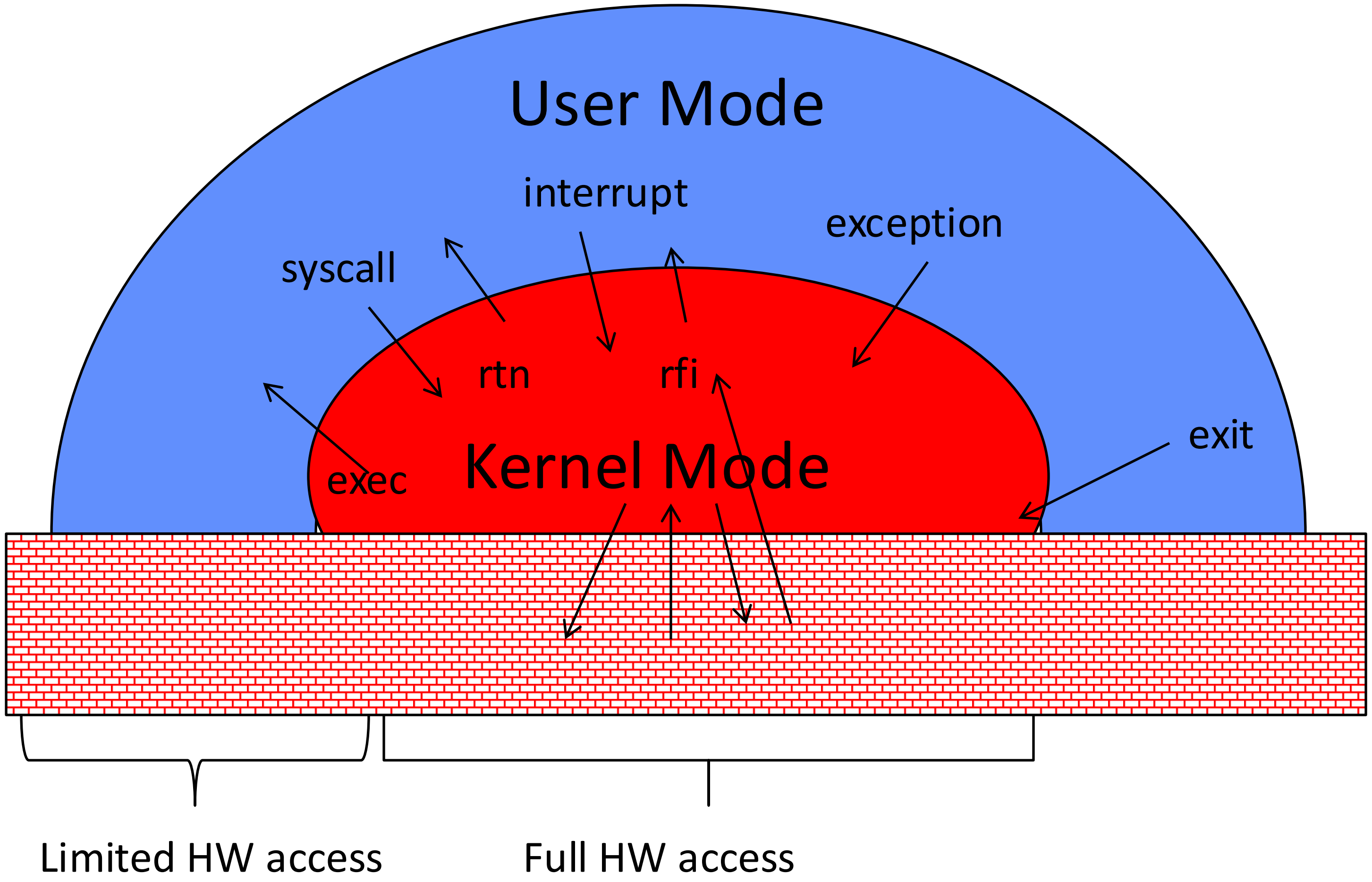
- Hardware provides at least two modes (at least 1 mode bit):
  1. Kernel Mode (or "supervisor" mode)
  2. User Mode
- Certain operations are prohibited when running in user mode
  – Changing the page table pointer, disabling interrupts, interacting directly w/ hardware, writing to kernel memory
- Carefully controlled transitions between user mode and kernel mode
  – System calls, interrupts, exceptions



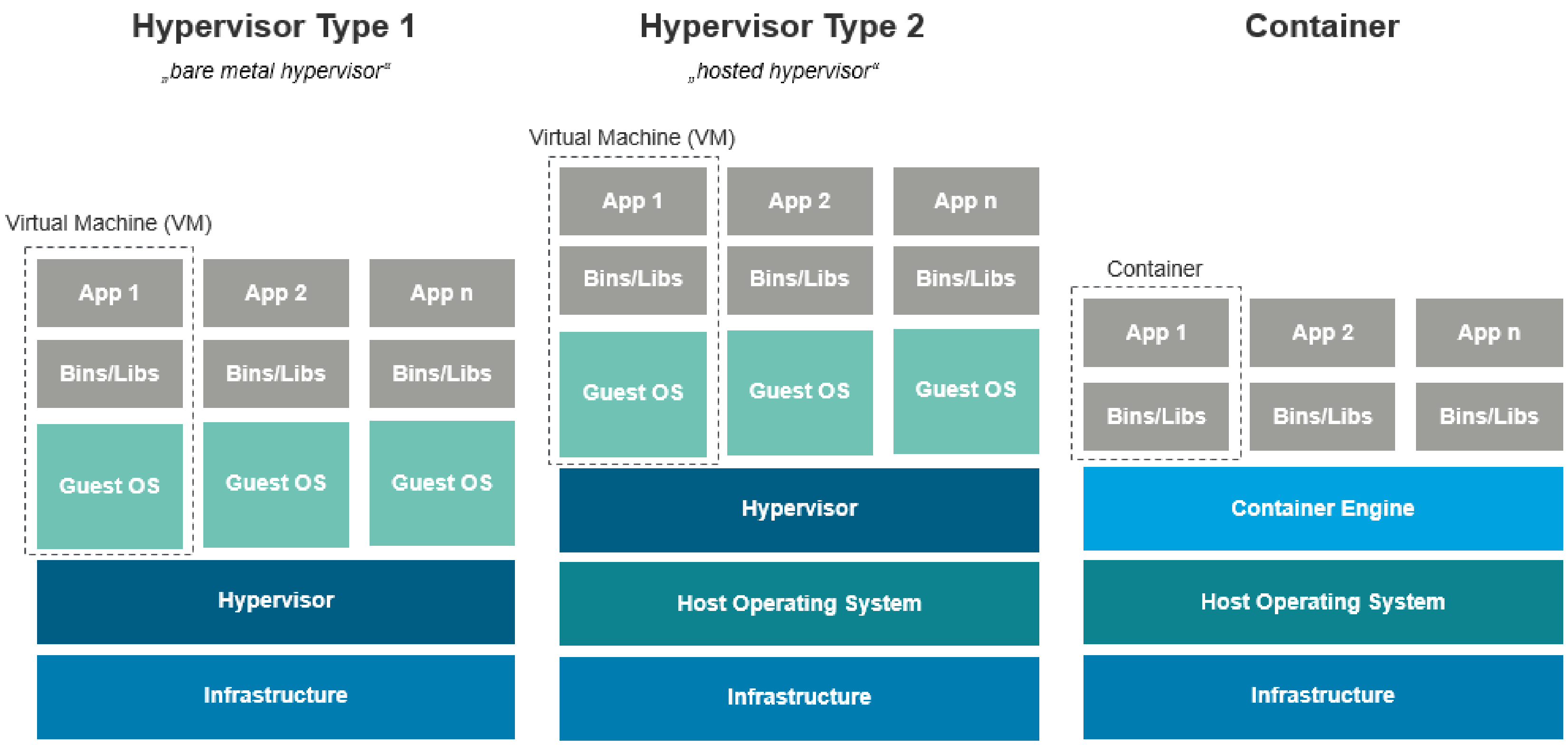
For example: UNIX System Structure



User/Kernel (Privileged) Mode

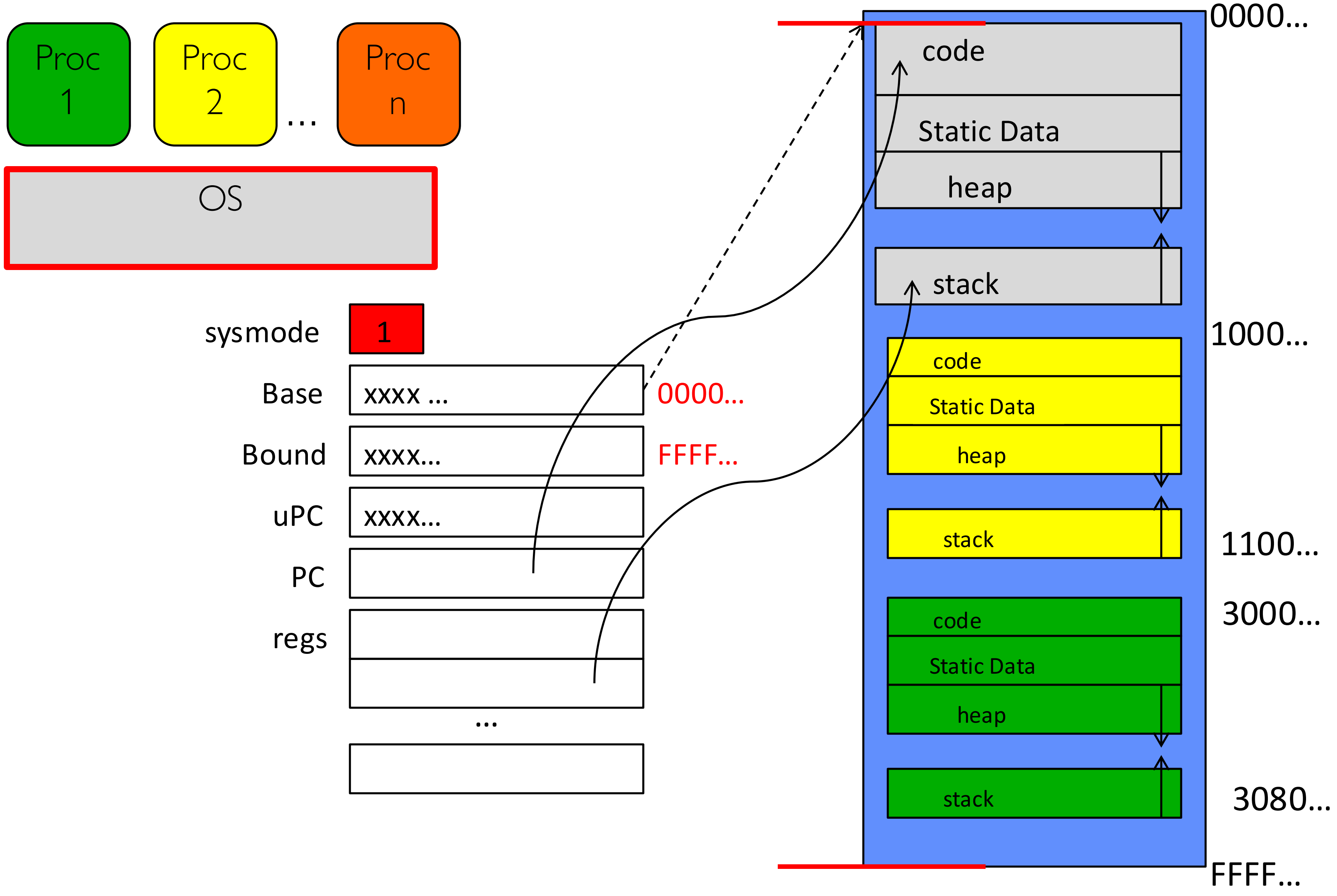


Additional Layers of Protection for Modern Systems

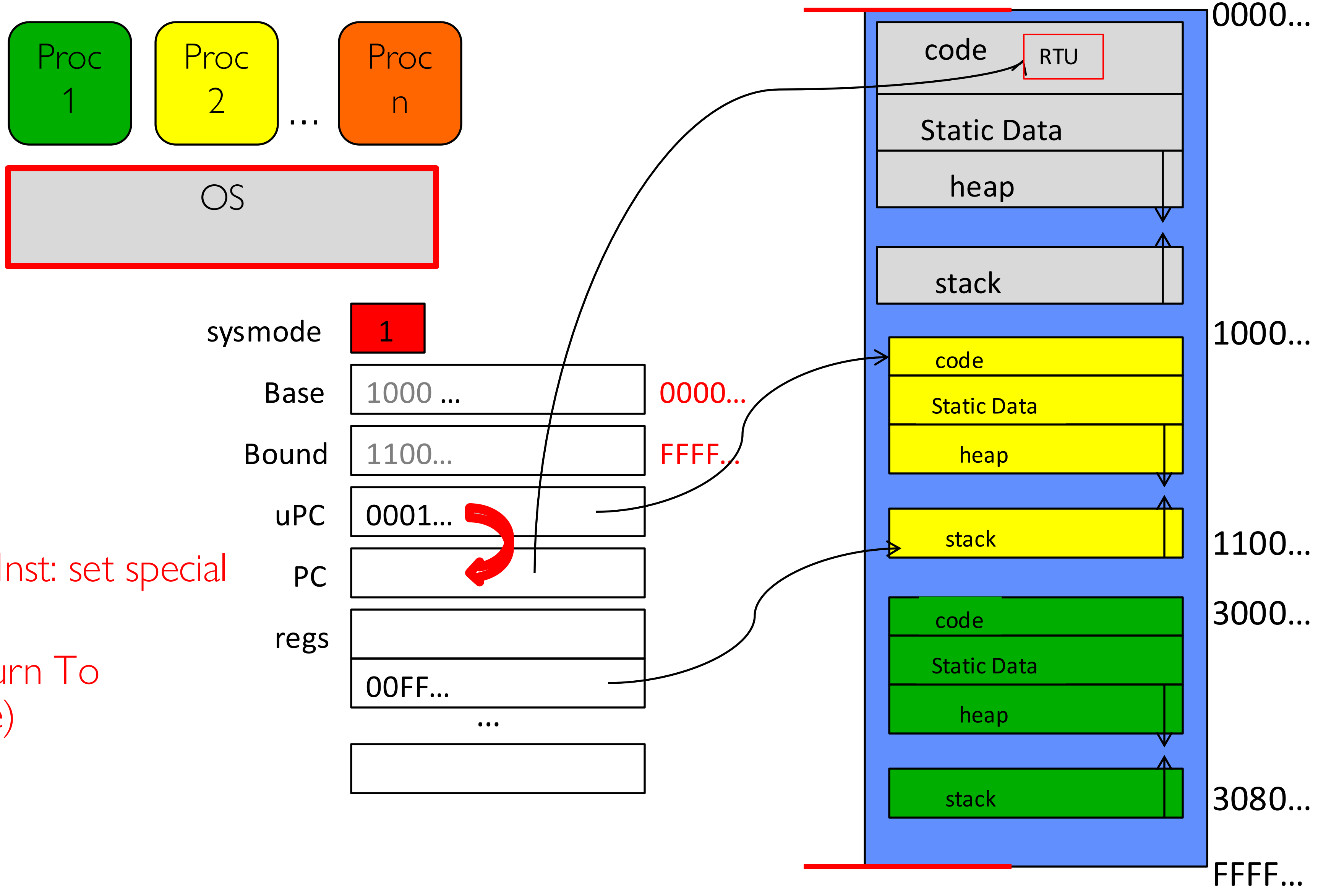


- Additional layers of protection through virtual machines or containers
  – Run a complete operating system in a virtual machine
  – Package all the libraries associated with an app into a container for execution
- More on these ideas later in the class

Tying it together: Simple B&B: OS loads process

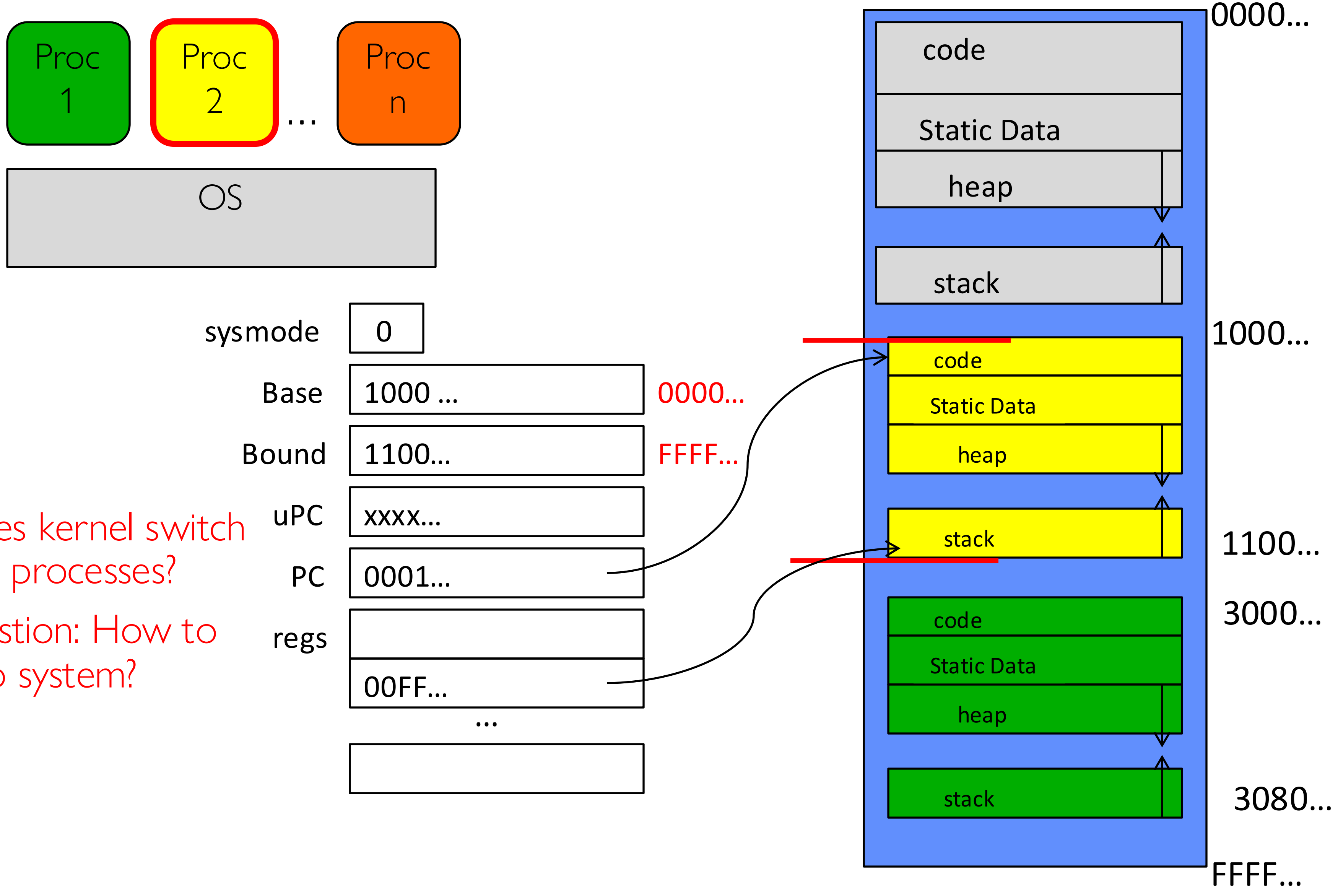


Simple B&B: OS gets ready to execute process



- Privileged Inst: set special registers
- RTU (Return To Usermode)

Simple B&B: User Code Running



- How does kernel switch between processes?
- First question: How to return to system?

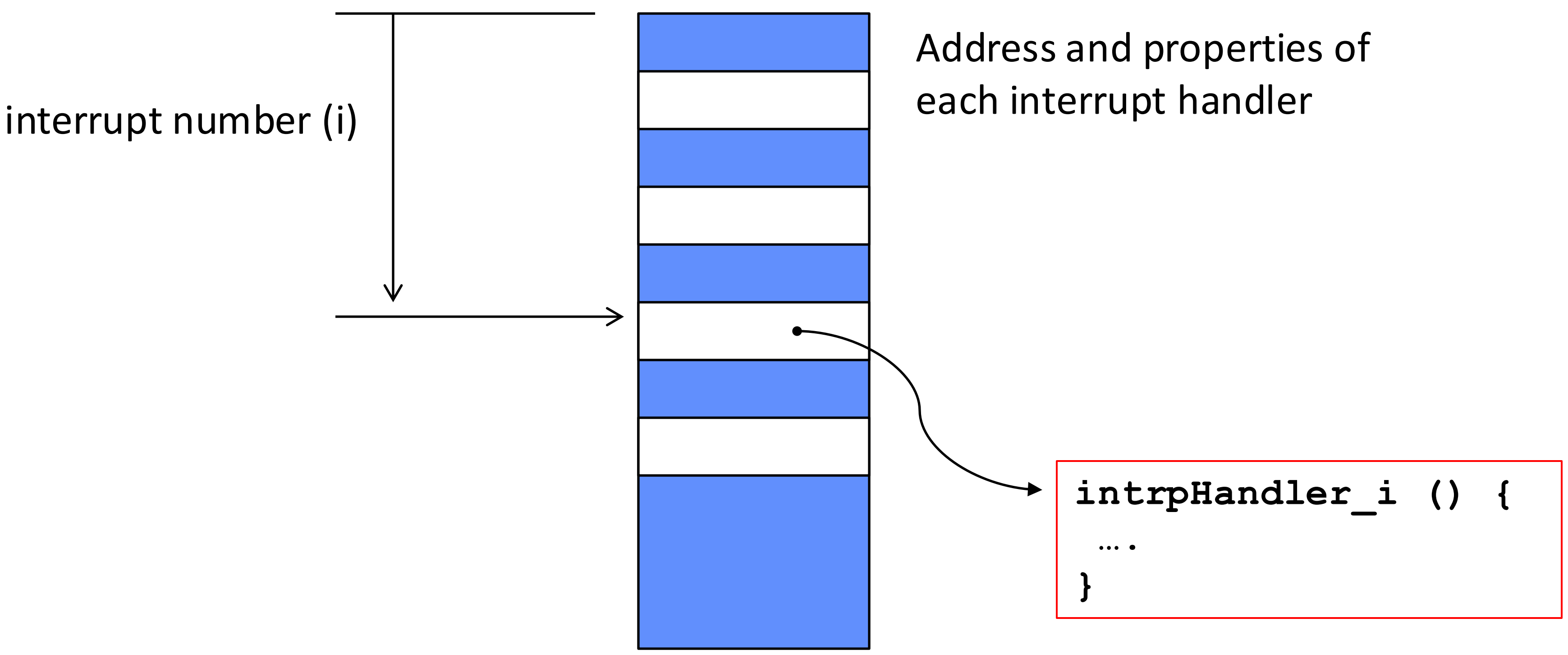
3 types of User ⇒ Kernel Mode Transfer

- Syscall
  - Process requests a system service, e.g., exit
  - Like a function call, but "outside" the process
  - Does not have the address of the system function to call
  - Like a Remote Procedure Call (RPC) – for later
  - Marshall the syscall id and args in registers and exec syscall
- Interrupt
  - External asynchronous event triggers context switch
  - e. g., Timer, I/O device
  - Independent of user process
- Trap or Exception
  - Internal synchronous event in process triggers context switch
  - e.g., Protection violation (segmentation fault), Divide by zero, …
- All 3 are an UNPROGRAMMED* CONTROL TRANSFER
  - Where does it go?

*switching to OS without a direct instruction from the running process

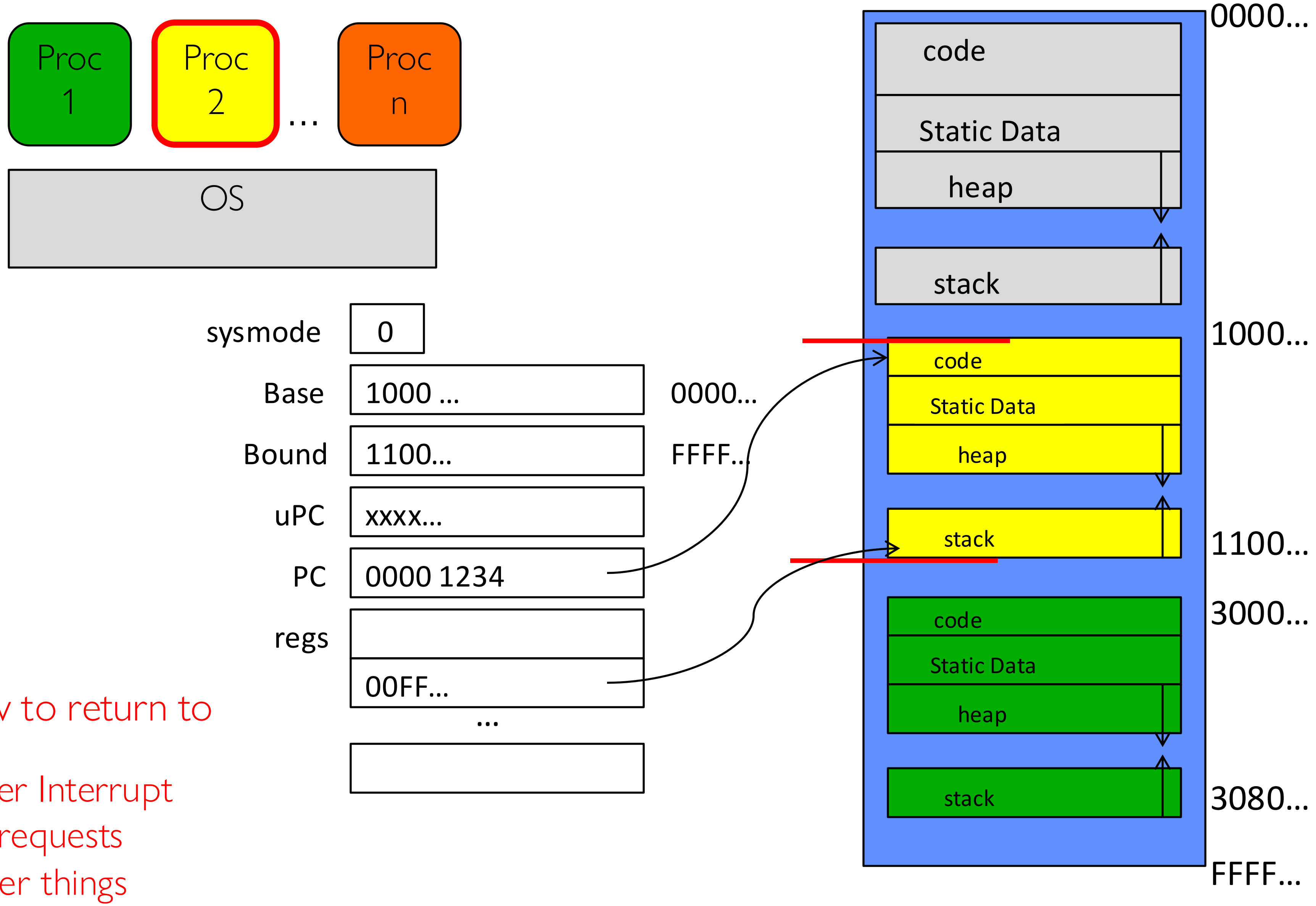
How do we get the system target address of the "unprogrammed control transfer?"

Interrupt Vector



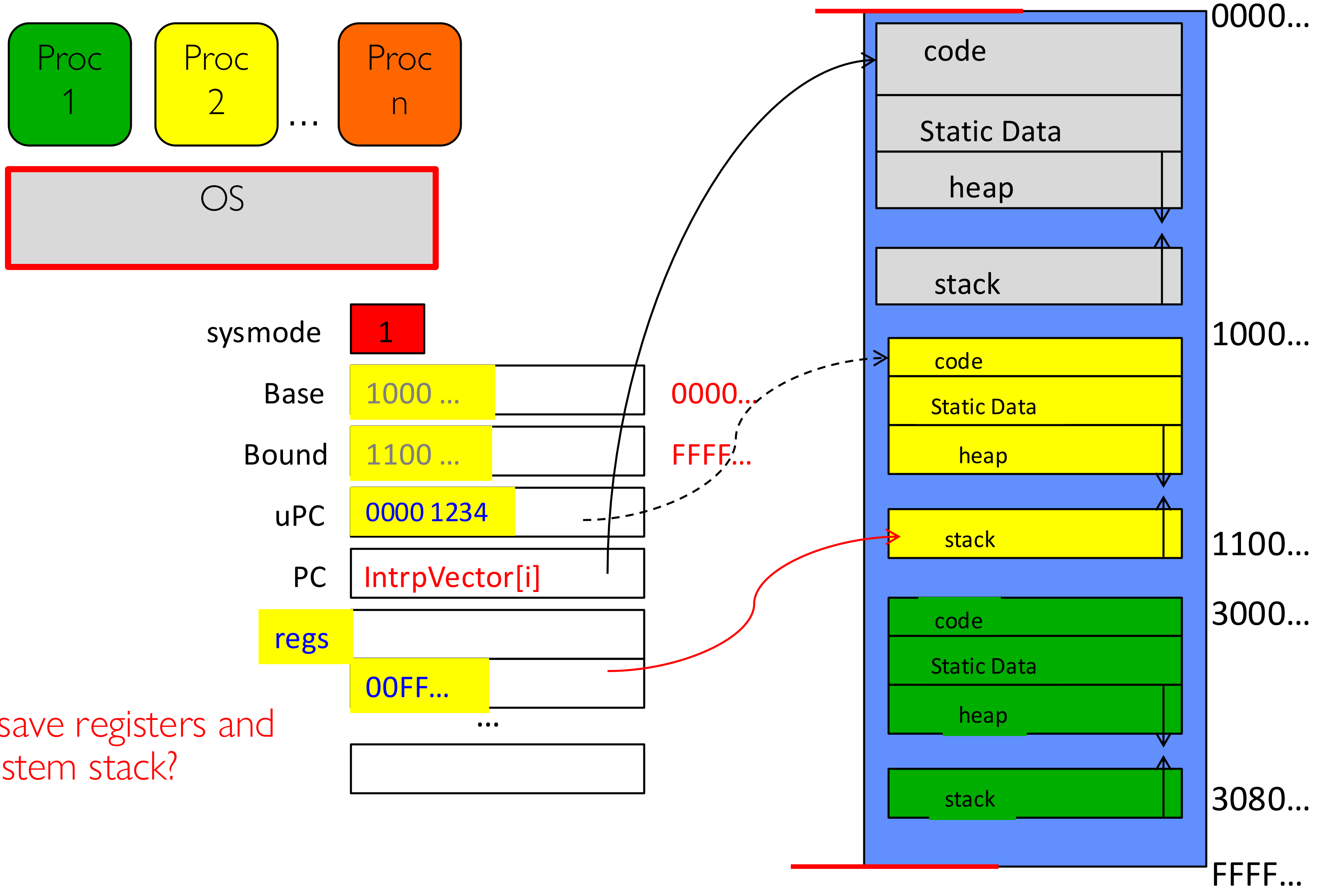
- Where else do you see this dispatch pattern?

Simple B&B: User => Kernel



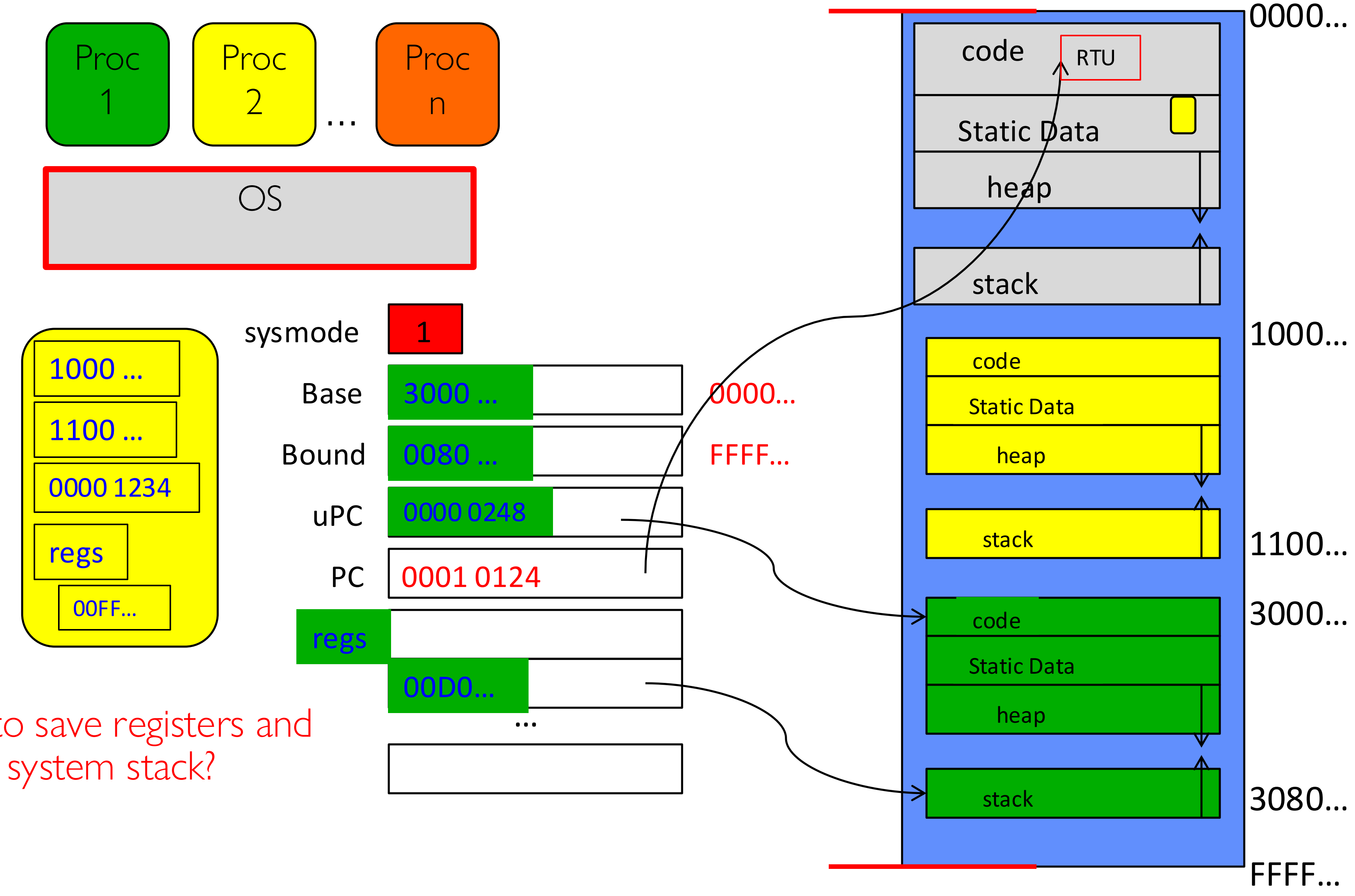
- So: How to return to system?
  - Timer Interrupt
  - I/O requests
  - Other things

Simple B&B: Interrupt



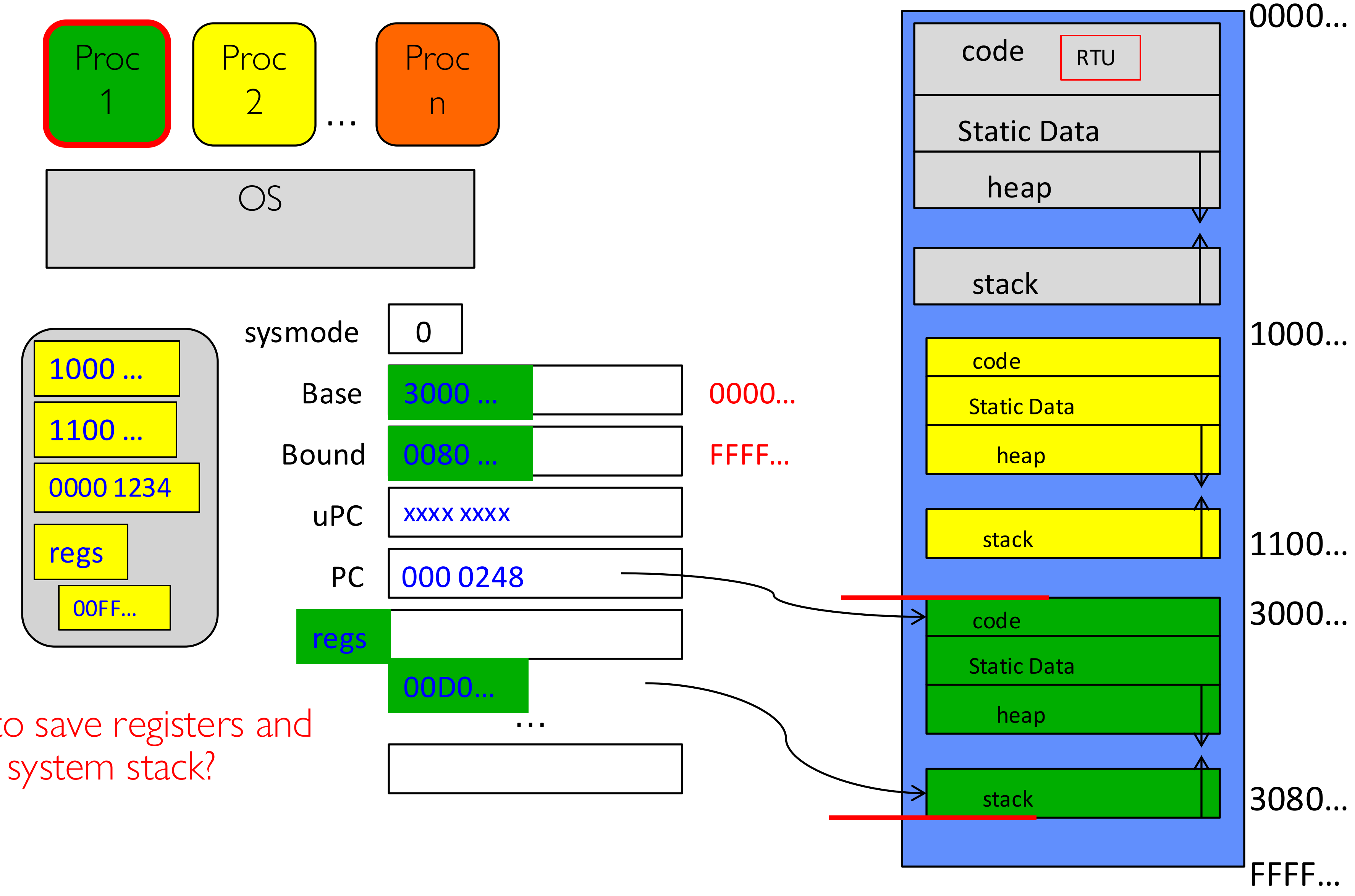
- How to save registers and set up system stack?

Simple B&B: Switch User Process



- How to save registers and set up system stack?

Simple B&B: "resume"



- How to save registers and set up system stack?

Running Many Programs ???

- We have the basic mechanism to
  – switch between user processes and the kernel,
  – the kernel can switch among user processes,
  – Protect OS from user processes and processes from each other

- Questions ???
- How do we decide which user process to run?
- How do we represent user processes in the OS?
- How do we pack up the process and set it aside?
- How do we get a stack and heap for the kernel?
- Aren't we wasting are lot of memory?
- …

Process Control Block

- Kernel represents each process as a process control block (PCB)
  – Status (running, ready, blocked, …)
  – Register state (when not ready)
  – Process ID (PID), User, Executable, Priority, …
  – Execution time, …
  – Memory space, translation, …
- Kernel Scheduler maintains a data structure containing the PCBs
- Scheduling algorithm selects the next one to run

Scheduler

```
if ( readyProcesses(PCBs) ) {
        nextPCB = selectProcess(PCBs);
        run( nextPCB );
} else {
        run_idle_process();
}
```

Conclusion: Four Fundamental OS Concepts

- Thread: Execution Context
  - Fully describes program state
  - Program Counter, Registers, Execution Flags, Stack
- Address space (with or w/o **translation**)
  - Set of memory addresses accessible to program (for read or write)
  - May be distinct from memory space of the physical machine (in which case programs operate in a virtual address space)
- Process: an instance of a running program
  - Protected Address Space + One or more Threads
- Dual mode operation / Protection
  - Only the "system" has the ability to access certain resources
  - Combined with translation, isolates programs from each other and the OS from programs