CS162
Operating Systems and Systems Programming
Lecture 2

Four Fundamental OS Concepts

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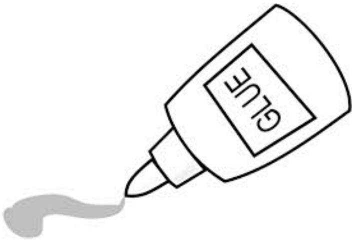
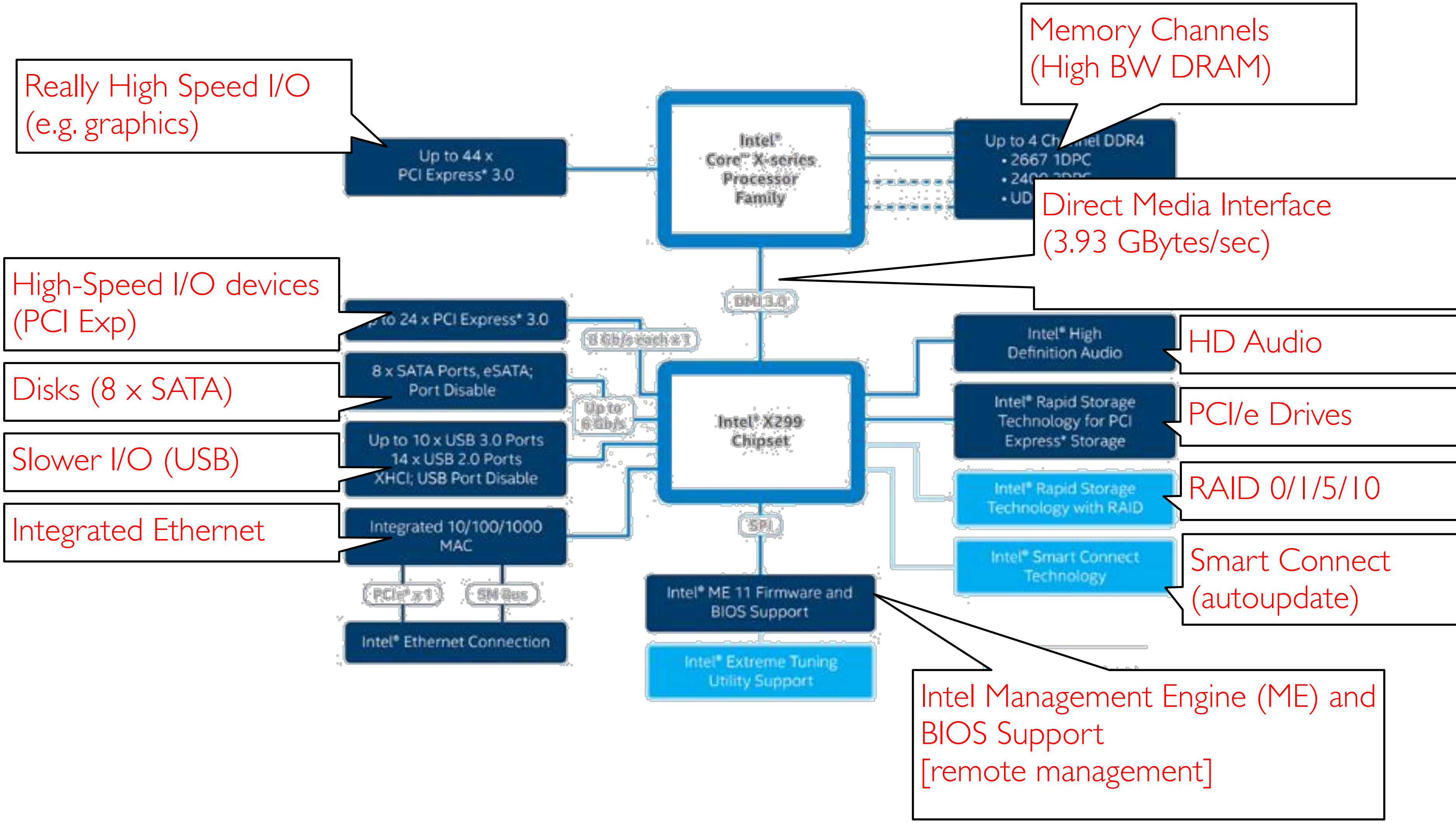
Acknowledgments: Lecture slides are from the Operating Systems course taught by John Kubiatowicz at Berkeley, with few minor updates/changes*. When slides are obtained from other sources, a reference will be noted on the bottom of that slide, in which case a full list of references is provided on the last slide.*

Review: What is an Operating System?



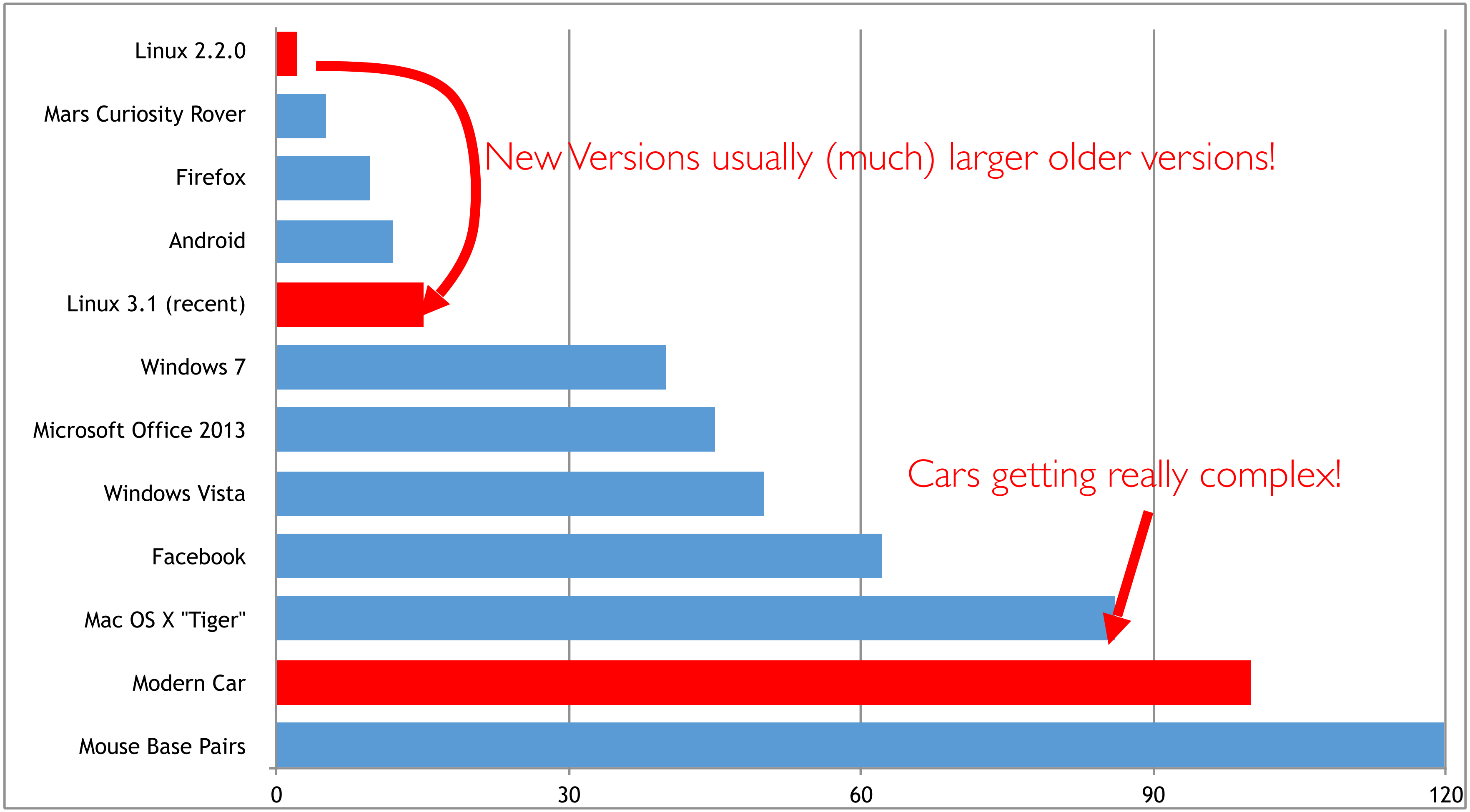
- Referee
  - Manage sharing of resources, Protection, Isolation
    - » Resource allocation, isolation, communication
- Illusionist
  - Provide clean, easy to use abstractions of physical resources
    - » Infinite memory, dedicated machine
    - » Higher level objects: files, users, messages
    - » Masking limitations, virtualization
- Glue
  - Common services
    - » Storage, Window system, Networking
    - » Sharing, Authorization
    - » Look and feel

Recall: HW Functionality ⇒ great complexity!



Intel Skylake-X I/O Configuration

Recall: Increasing Software Complexity



Millions of Lines of Code

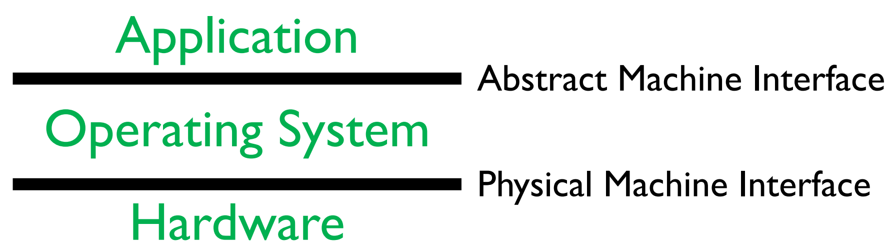
(source https://informationisbeautiful.net/visualizations/million-lines-of-code/)

Recall: How do we tame complexity?

- Every piece of computer hardware different
  - Different CPU
    - » Pentium, PowerPC, ColdFire, ARM, MIPS
  - Different amounts of memory, disk, …
  - Different types of devices
    - » Mice, Keyboards, Sensors, Cameras, Fingerprint readers
  - Different networking environment
    - » Cable, DSL, Wireless, Firewalls,…
- Questions:
  - Does the programmer need to write a single program that performs many independent activities?
  - Does every program have to be altered for every piece of hardware?
  - Does a faulty program crash everything?
  - Does every program have access to all hardware?

OS *Abstracts* underlying hardware

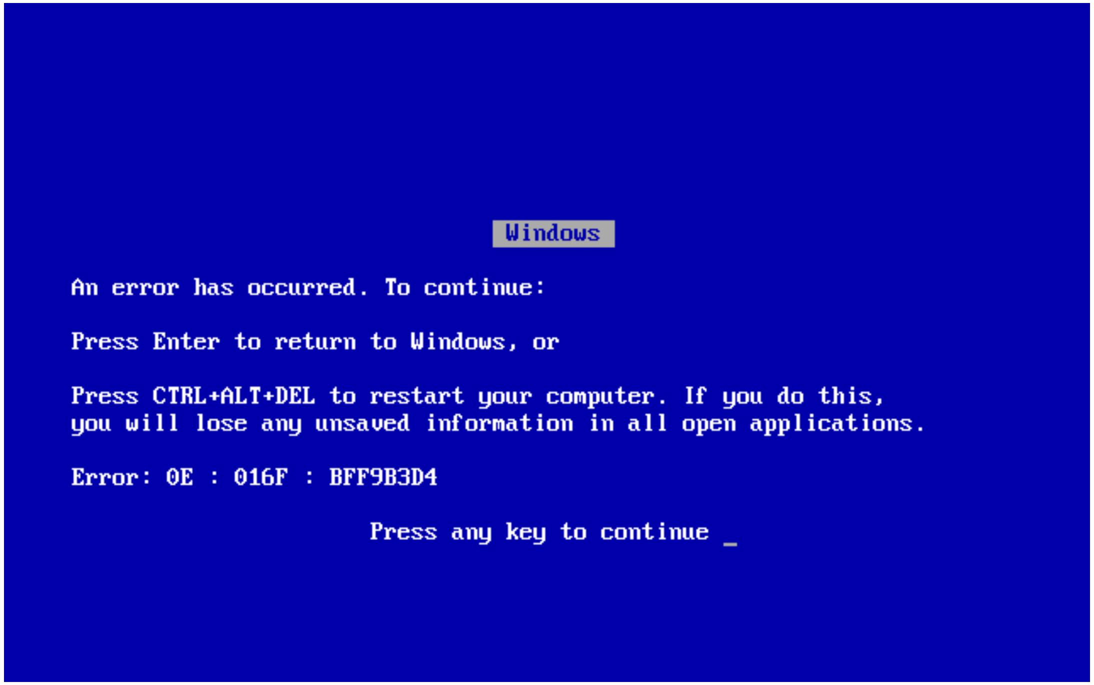
- Processor => Thread
- Memory => Address Space
- Disks, SSDs, … => Files
- Networks => Sockets
- Machines => Processes



- OS Goals:
  - 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)

OS Goal: Protecting Processes & The Kernel

- Run multiple applications and:
  - Keep them from interfering with or crashing the operating system
  - Keep them from interfering with or crashing each other



Virtual Machines

- Software emulation of an abstract machine
  – Give programs illusion they own the machine
  – Make it look like hardware has features you want
- Two types of "Virtual Machine"s
  – Process VM: supports the execution of a single program; this functionality typically provided by OS
  – System VM: supports the execution of an entire OS and its applications (e.g., VMWare Fusion, Virtual box, Parallels Desktop, Xen)

Java

Process VMs

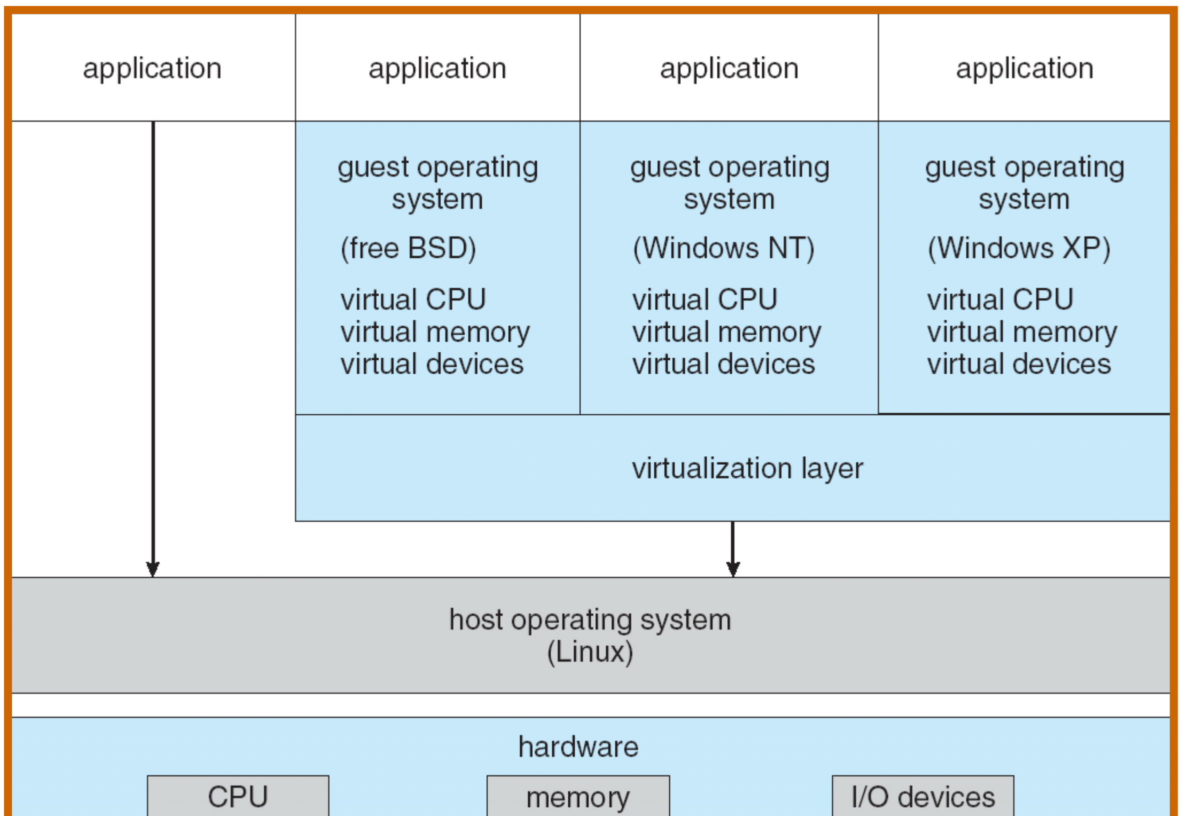
- Programming simplicity
  - Each process thinks it has all memory/CPU time
  - Each process thinks it owns all devices
  - Different devices appear to have same high level interface
  - Device interfaces more powerful than raw hardware
    - » Bitmapped display ⇒ windowing system
    - » Ethernet card ⇒ reliable, ordered, networking (TCP/IP)
- Fault Isolation
  - Processes unable to directly impact other processes
  - Bugs cannot crash whole machine
- Protection and Portability
  - Java interface safe and stable across many platforms

Virtual Machines

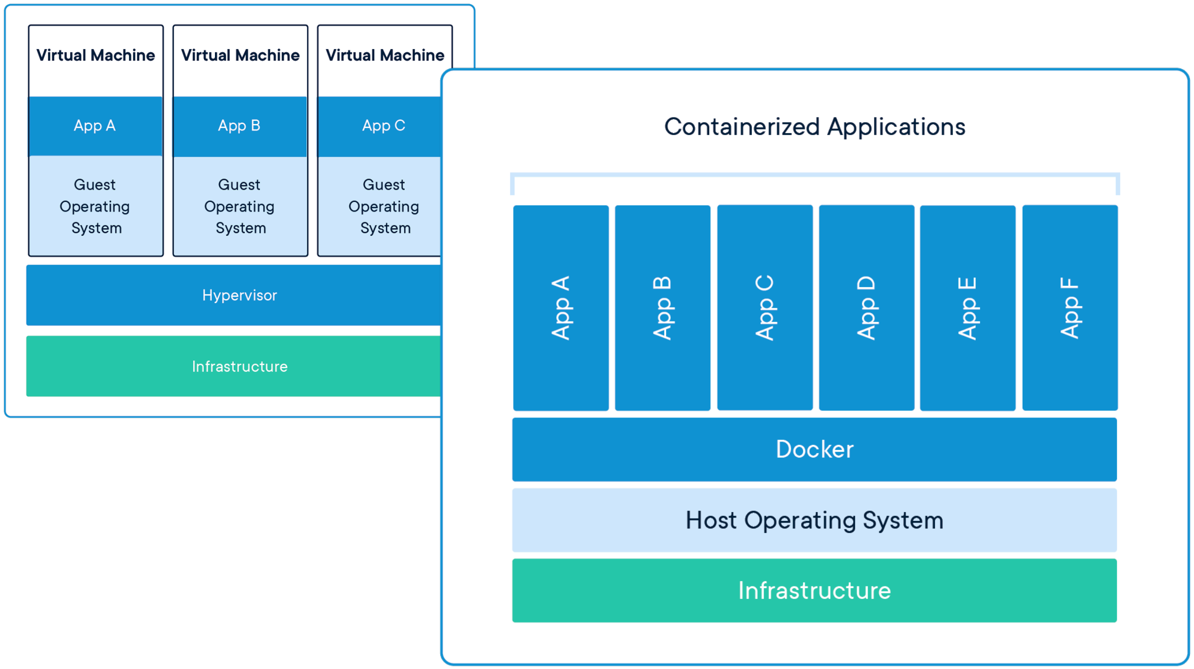
- Virtualize every detail of a hardware configuration so perfectly that you can run an operating system (and many applications) on top of it.
  - VMWare Fusion, Virtual box, Parallels Desktop, Xen, Vagrant
- Provides isolation
- Complete insulation from change
- The norm in the Cloud (server consolidation)
- Long history (60's in IBM OS development)
- All our work will take place INSIDE a VM
  - Vagrant (new image just for you)

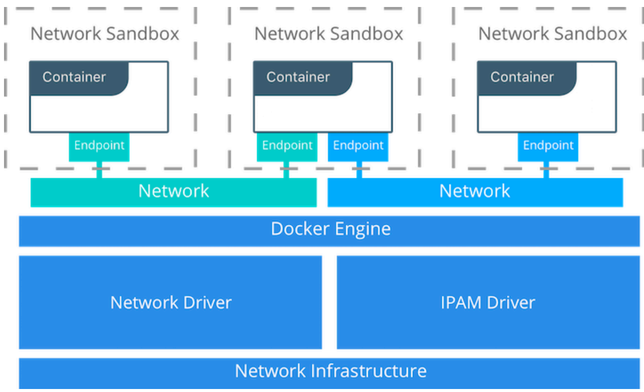
System Virtual Machines: Layers of OSs

- Useful for OS development
  - When OS crashes, restricted to one VM
  - Can aid testing/running programs on other Oss
- Use for deployment
  - Running different OSes at the same time



Containers *virtualize the OS*

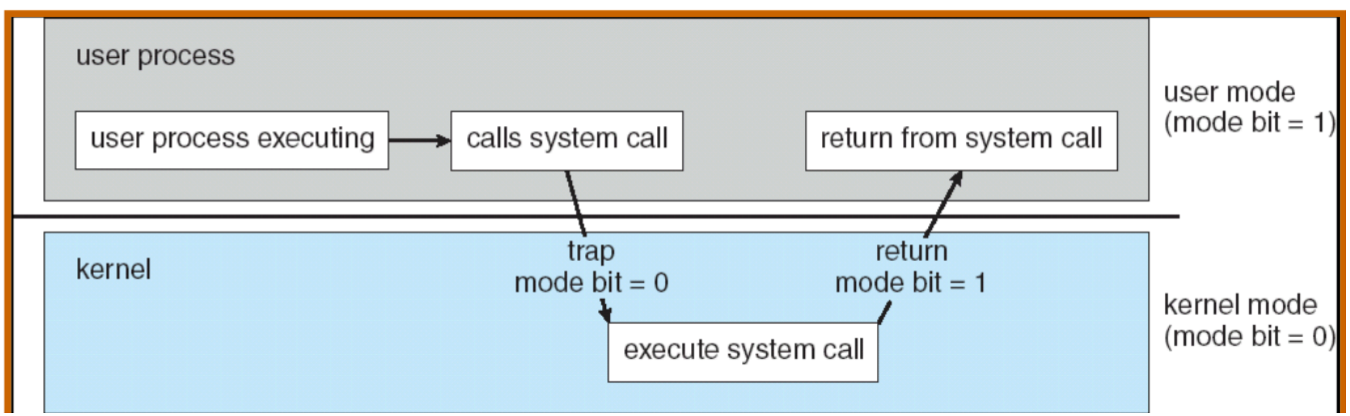




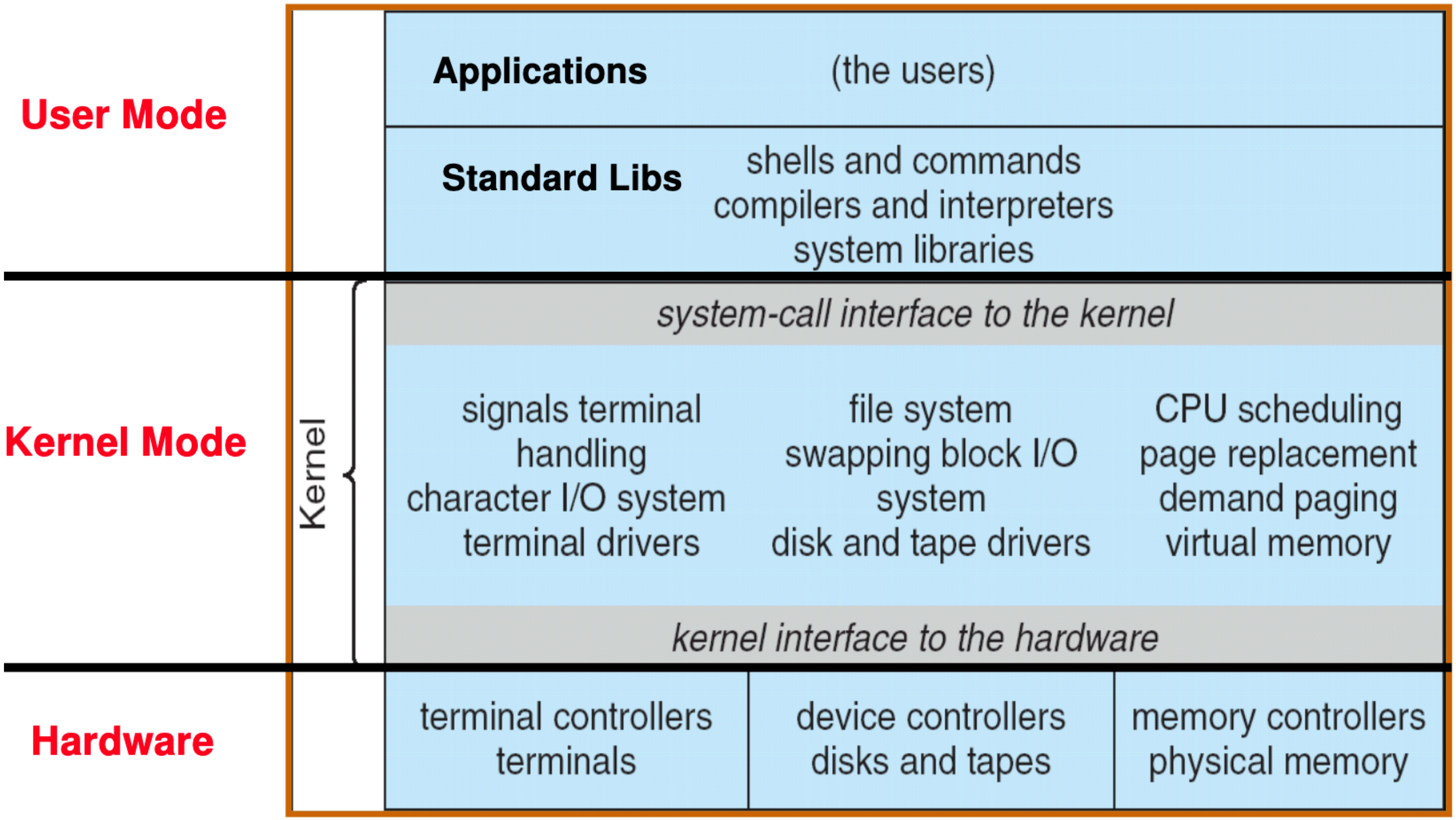
- Roots in OS developments to provide protected systems abstraction, not just application abstraction
  - User-level file system (route syscalls to user process)
  - Cgroups – predictable, bounded resources (CPU, Mem, BW)

Basic tool: Dual Mode Operation

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



UNIX OS Structure



What is an Operating System,… Really?

- Most Likely:
  - Memory Management
  - I/O Management
  - CPU Scheduling
  - Communications? (Does Email belong in OS?)
  - Multitasking/multiprogramming?
- What about?
  - File System?
  - Multimedia Support?
  - User Interface?
  - Internet Browser? ☺
- Is this only interesting to Academics??

Operating System Definition (Cont.)

- No universally accepted definition
- "Everything a vendor ships when you order an operating system" is good approximation
  - But varies wildly
- "The one program running at all times on the computer" is the kernel
  - Everything else is either a system program (ships with the operating system) or an application program

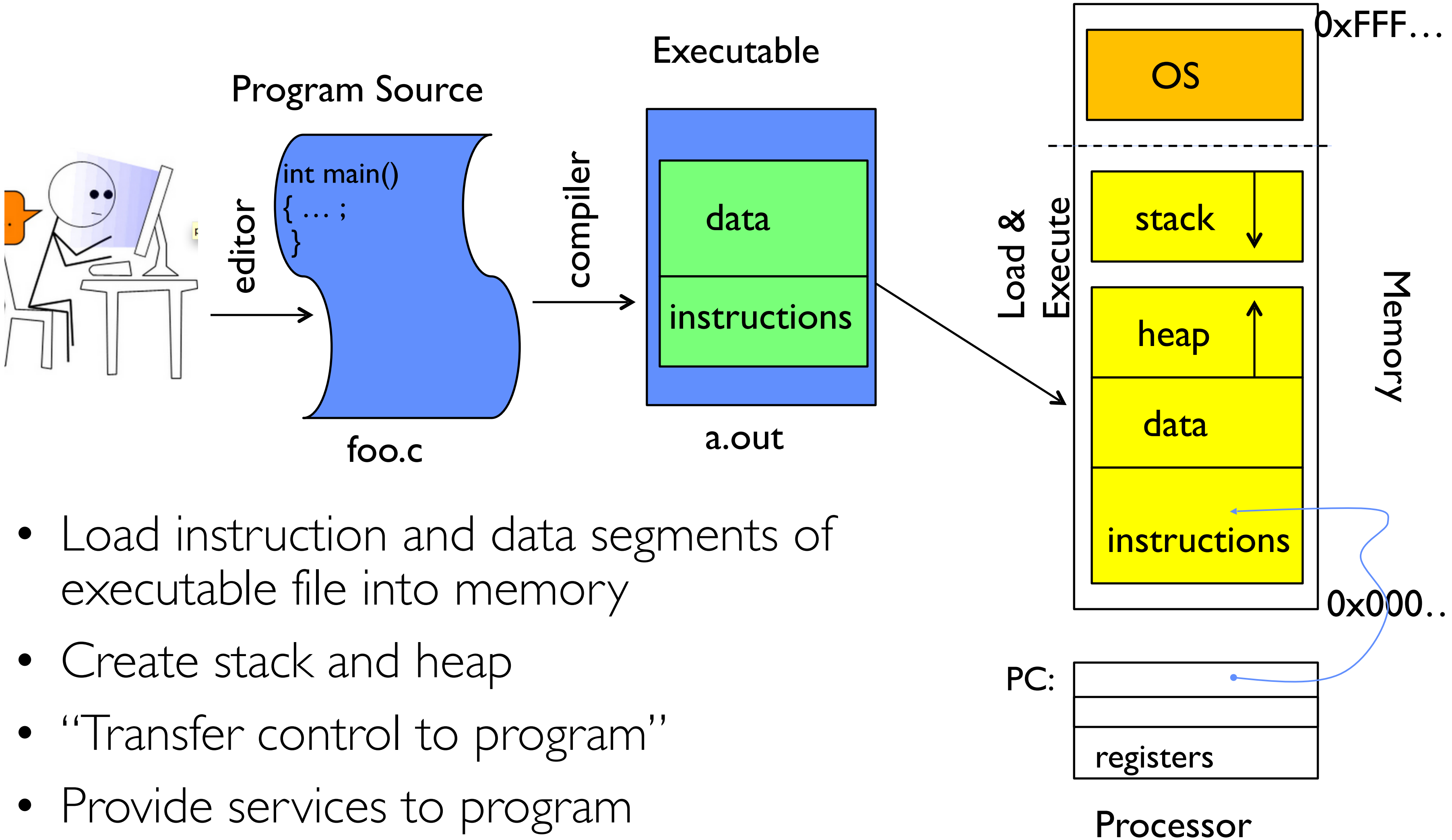
"In conclusion…"

- Operating systems provide a virtual machine abstraction to handle diverse hardware
  - Operating systems simplify application development by providing standard services
- Operating systems coordinate resources and protect users from each other
  - Operating systems can provide an array of fault containment, fault tolerance, and fault recovery
- CE424 combines things from many other areas of computer science:
  - Languages, data structures, hardware, and algorithms

Today: Four Fundamental OS Concepts

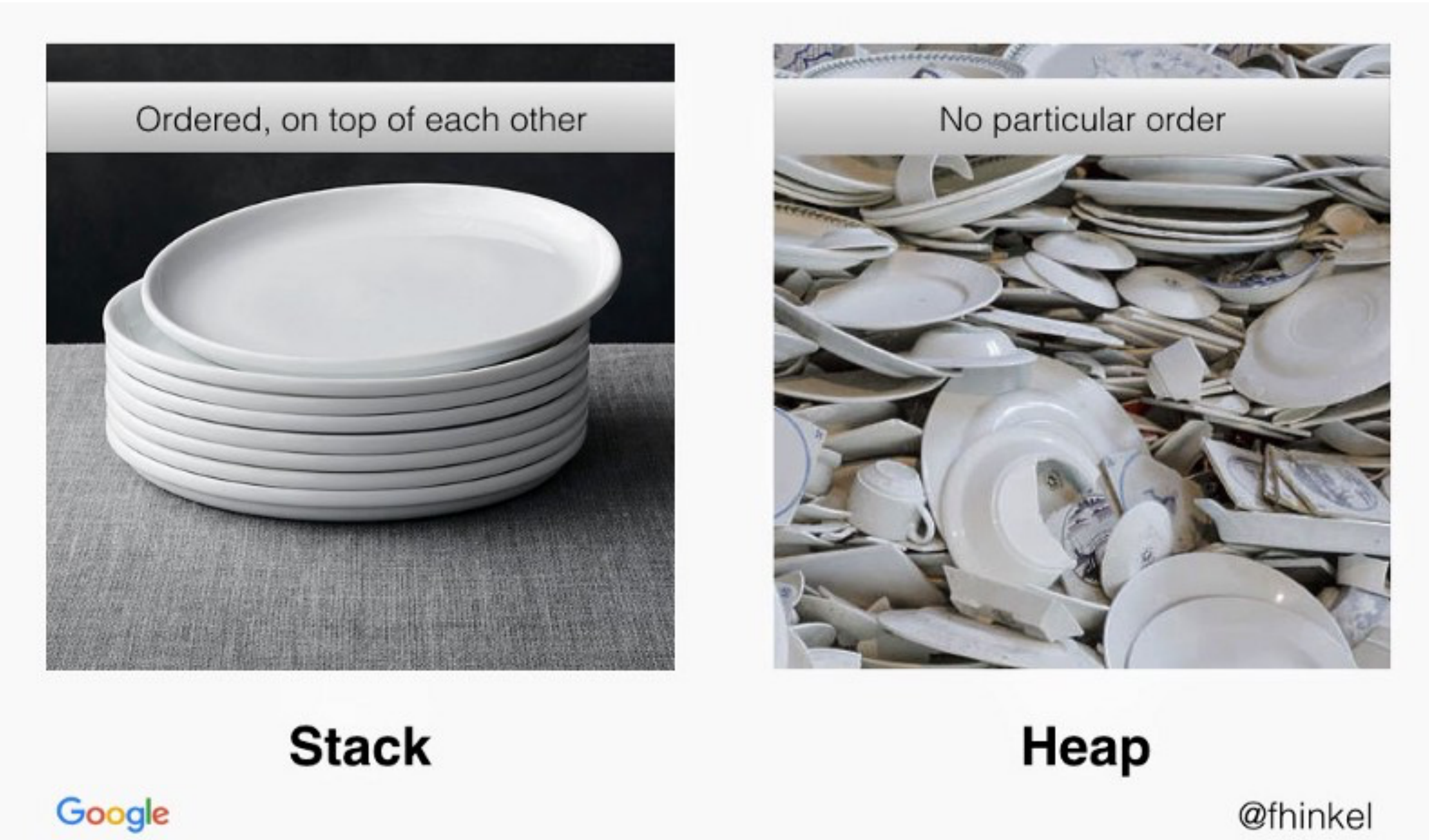
- Thread: Execution Context
  - Fully describes program state
  - Program Counter, Registers, Execution Flags, Stack
- Address space (with or w/o translation)
  - Set of memory addresses accessible to program (for read or write)
  - May be distinct from memory space of the physical machine (in which 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



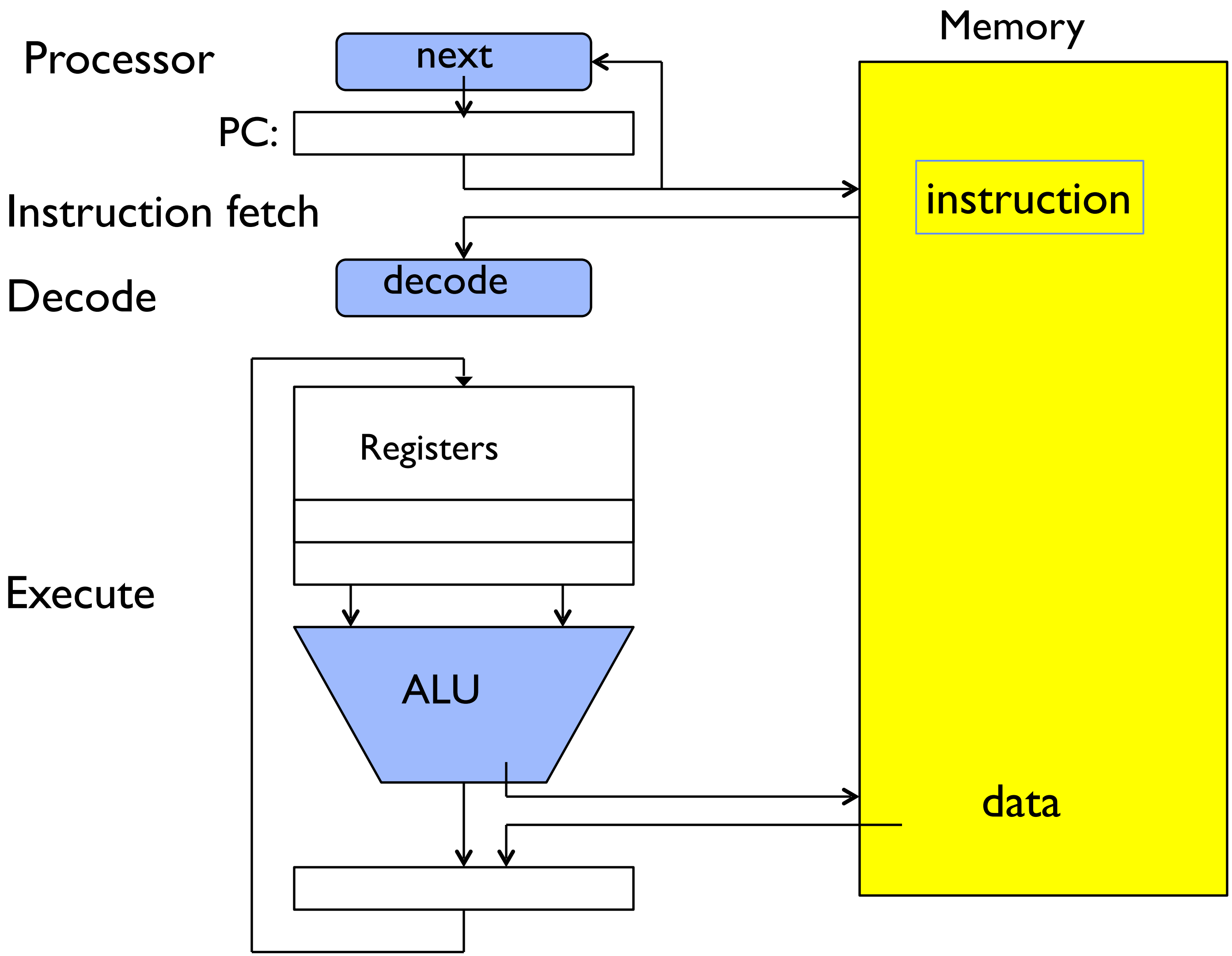
- Load instruction and data segments of executable file into memory
- Create stack and heap
- "Transfer control to program"
- Provide services to program
- While protecting OS and program

Stack vs. Heap



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

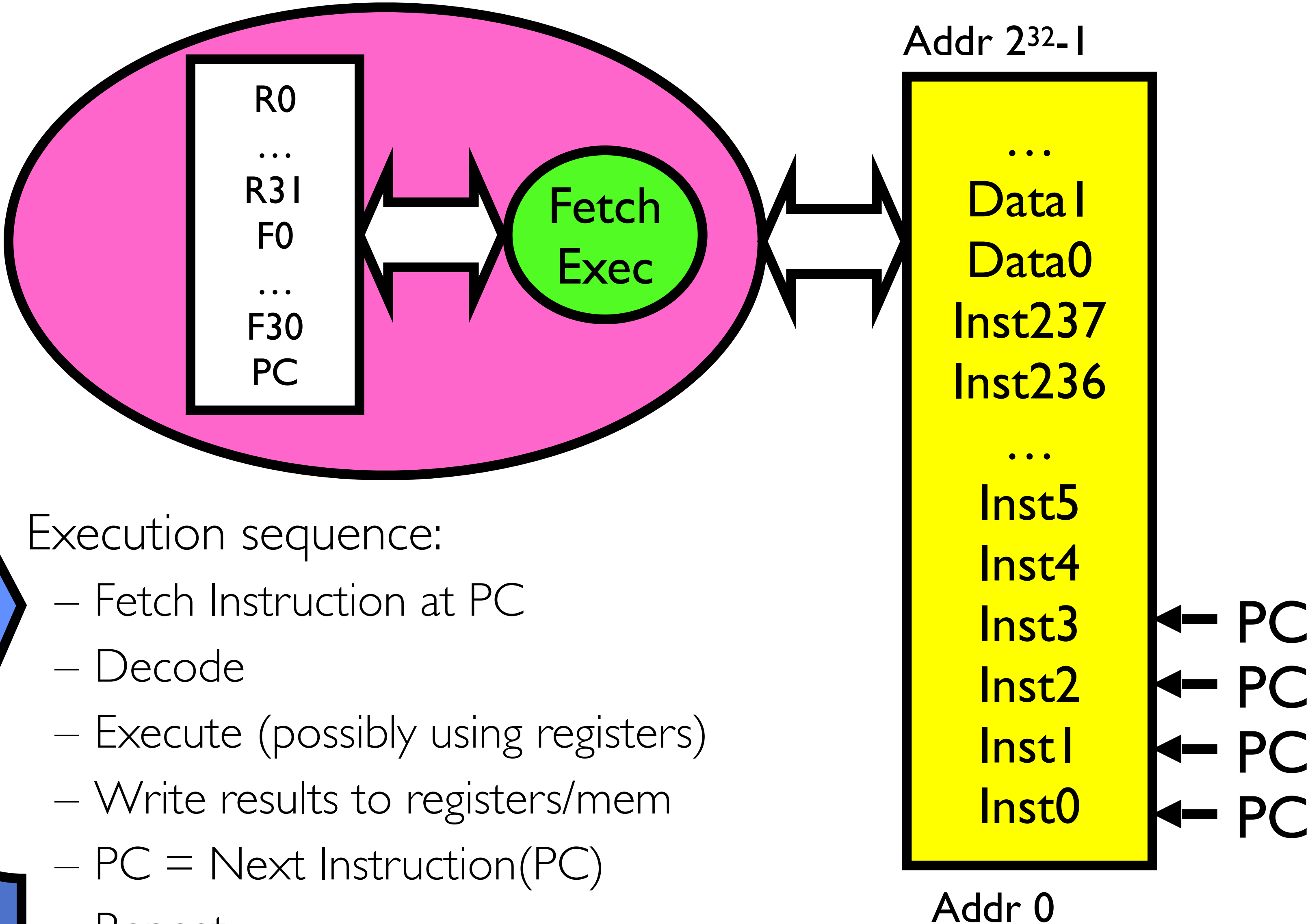
The instruction cycle



First OS Concept: Thread of Control

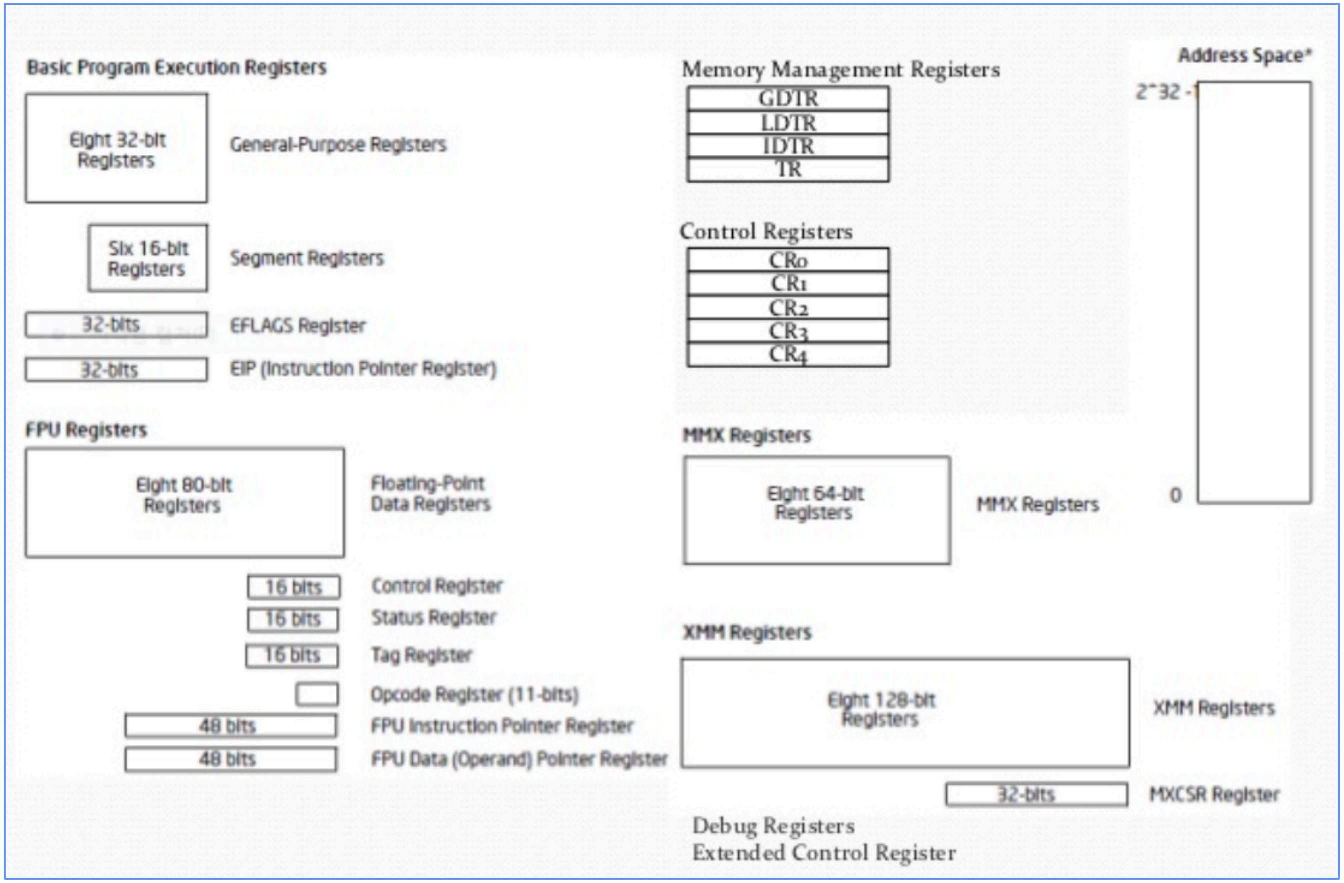
- Thread: Single unique execution context
  - Program Counter, Registers, Execution Flags, Stack, Memory State
- A thread is *executing* on a processor (core) when it is *resident* in the processor registers
- Resident means: Registers hold the root state (context) of the thread:
  - Including program 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?



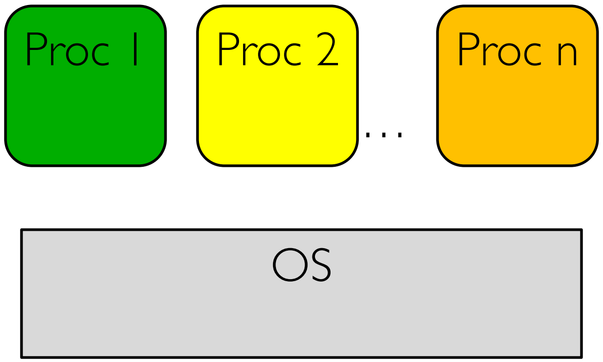
- Execution sequence:
  - Fetch Instruction at PC
  - Decode
  - Execute (possibly using registers)
  - Write results to registers/mem
  - PC = Next Instruction(PC)
  - Repeat

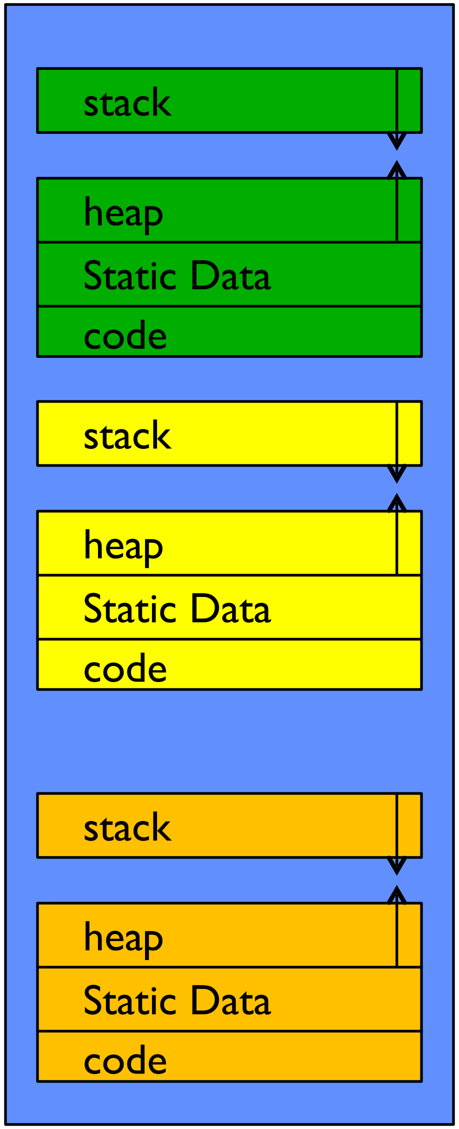
x86 Registers



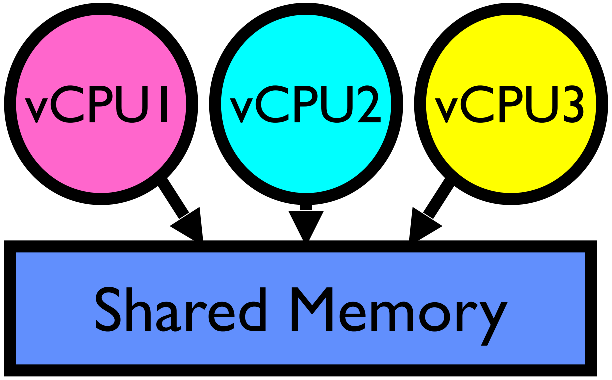
Complex mem-mem arch (x86) with specialized registers and "segments"

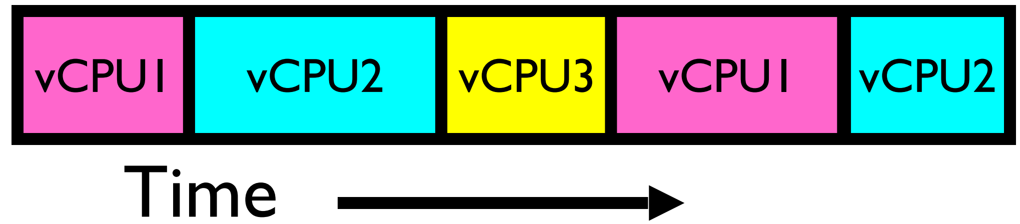
Multiprogramming - Multiple Threads of Control





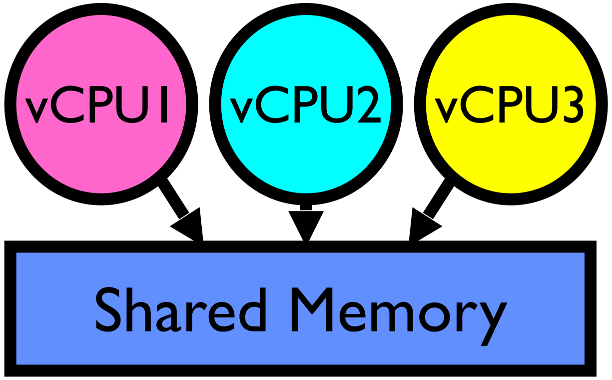
Illusion of Multiple Processors

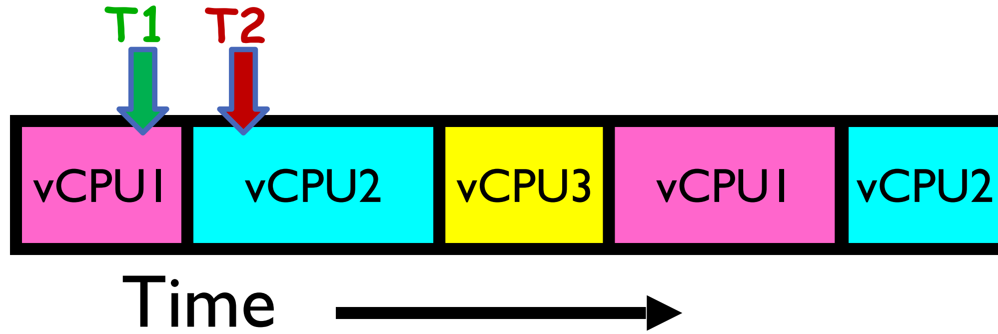




- Assume a single processor (core). How do we provide the illusion of multiple processors?
  – Multiplex in time!
- Threads are *virtual cores*
- Contents of virtual core (thread):
  – Program counter, stack pointer
  – Registers
- Where is "it" (the thread)?
  – On the real (physical) core, or
  – Saved 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

OS object representing a thread?

- Traditional term: Thread Control Block (TCB)
- Holds contents of registers when thread is not running
- What other information?

- PINTOS? – read thread.h and thread.c

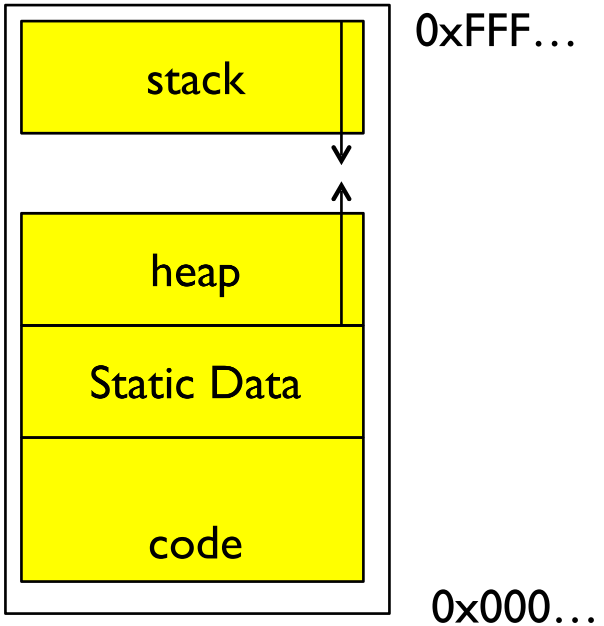
Administrivia: Getting started

- Start homework 0 immediately ⇒ Due next Monday (12/3)!
  - Vagrant and VirtualBox – VM environment for the course
    - » Consistent, managed environment on your machine
  - Get familiar with all the tools, submit via git
- TA Class
  - Do we need one or discord will do?
- Any questions on class rules and regulations?
- Schedule
  - Any issues?

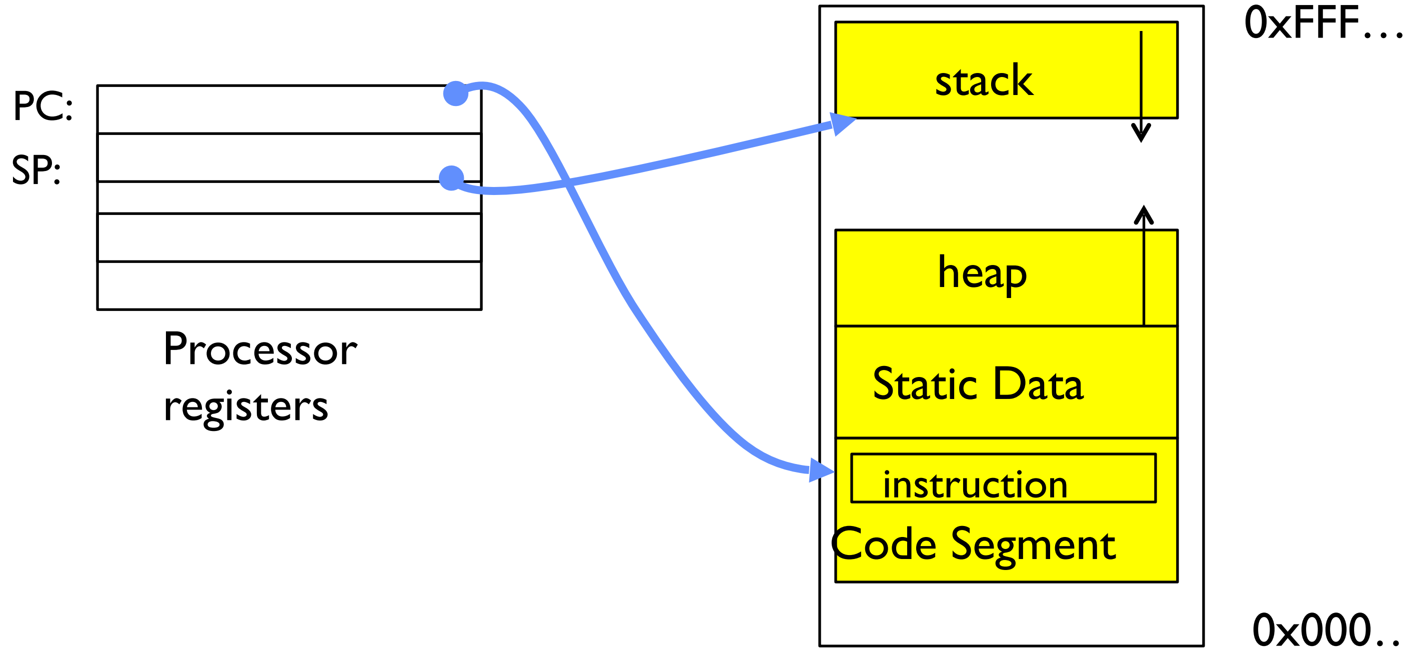
Second OS Concept: Address Space

- Address space ⇒ the set of accessible addresses + state associated with them:
  - For a 32-bit processor there are 2^{32} = 4 billion 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

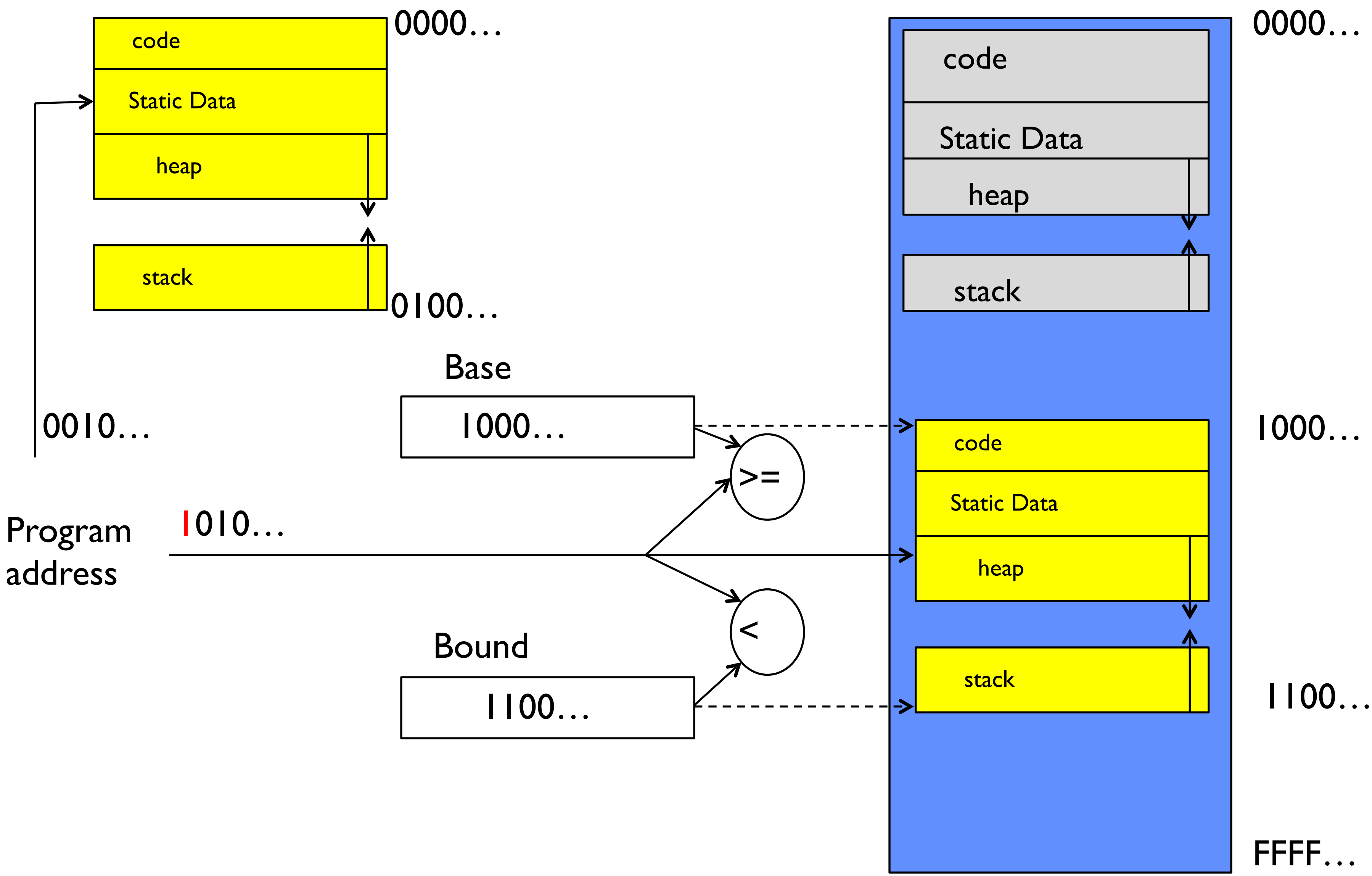
- All vCPU's share non-CPU resources
  - Memory, I/O Devices
- Each thread can read/write memory
  - Perhaps data of others
  - can overwrite OS ?
- Unusable?
- This approach is used in
  - Very early days of computing
  - Embedded applications
  - MacOS 1-9/Windows 3.1 (switch only with voluntary yield)
  - Windows 95-ME (switch with yield or timer)
- However it is risky…

Simple Multiplexing has no Protection

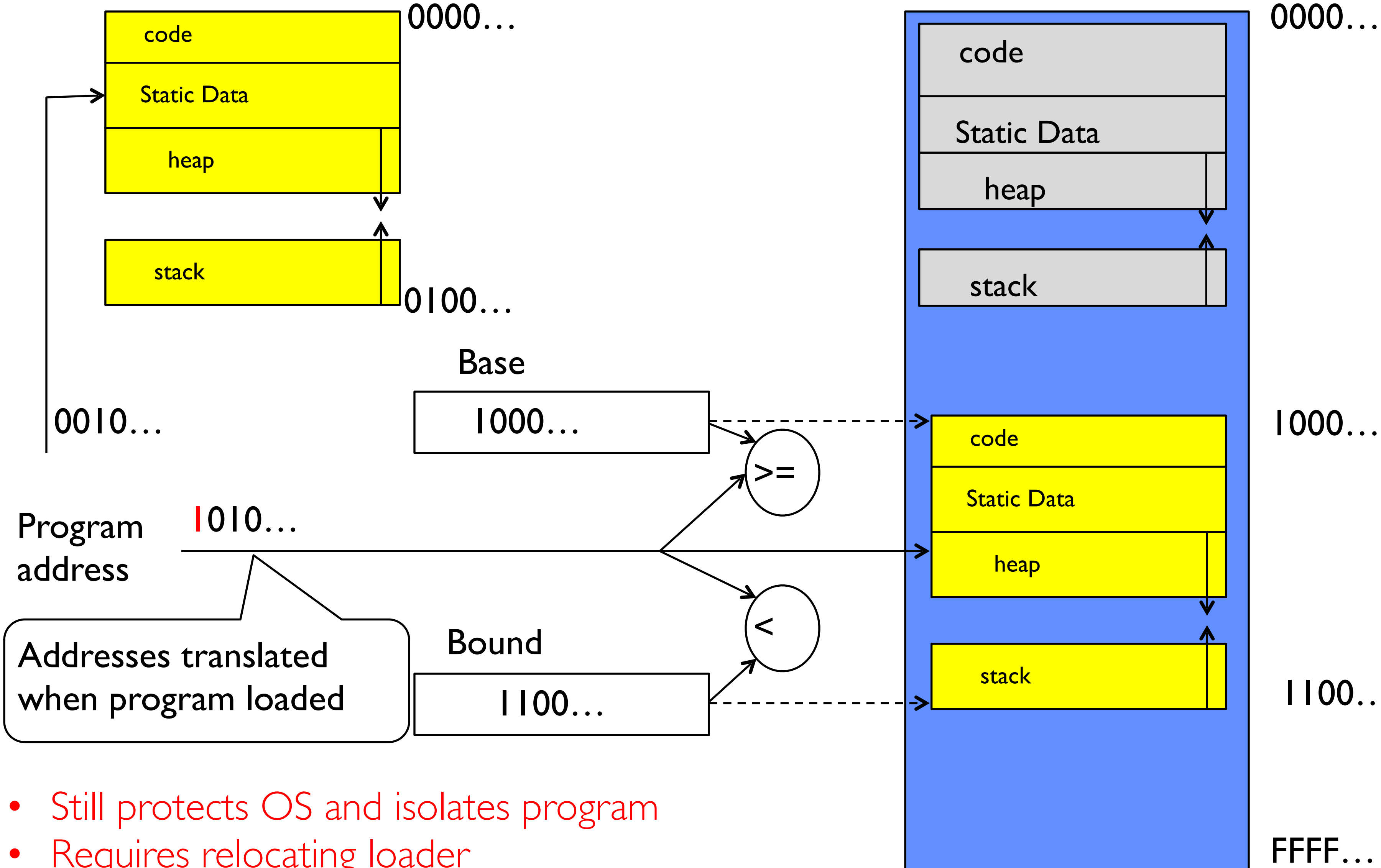
- Operating System must protect itself from user programs
  - Reliability: compromising the operating system generally causes it to crash
  - Security: limit the scope of what threads can do
  - Privacy: limit each thread to the data it is permitted to access
  - Fairness: each thread should be limited 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???

Simple Protection: Base and Bound (B&B)

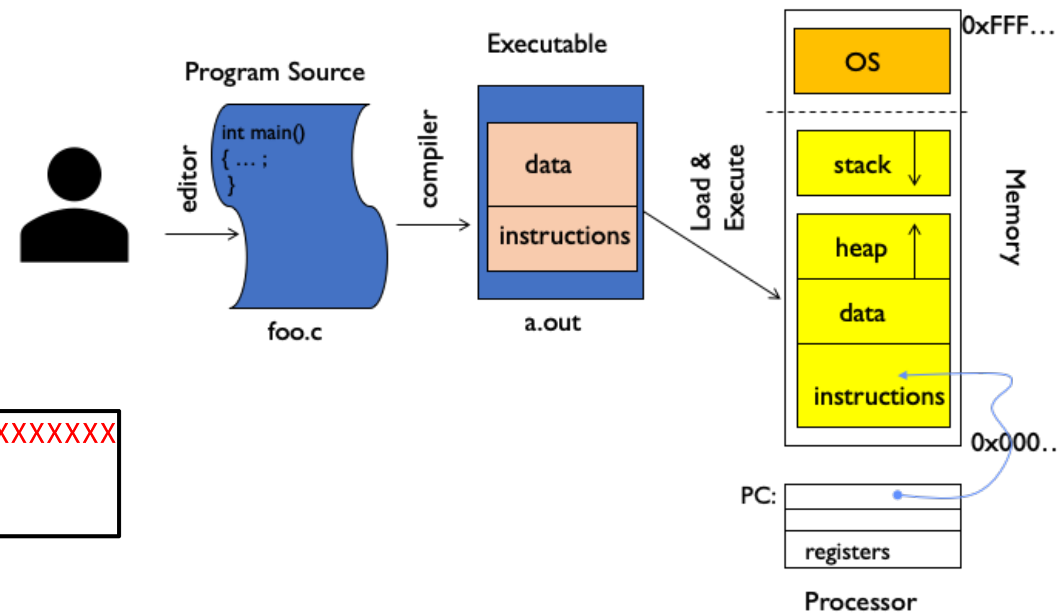


Simple Protection: Base and Bound (B&B)



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

Review: Relocation



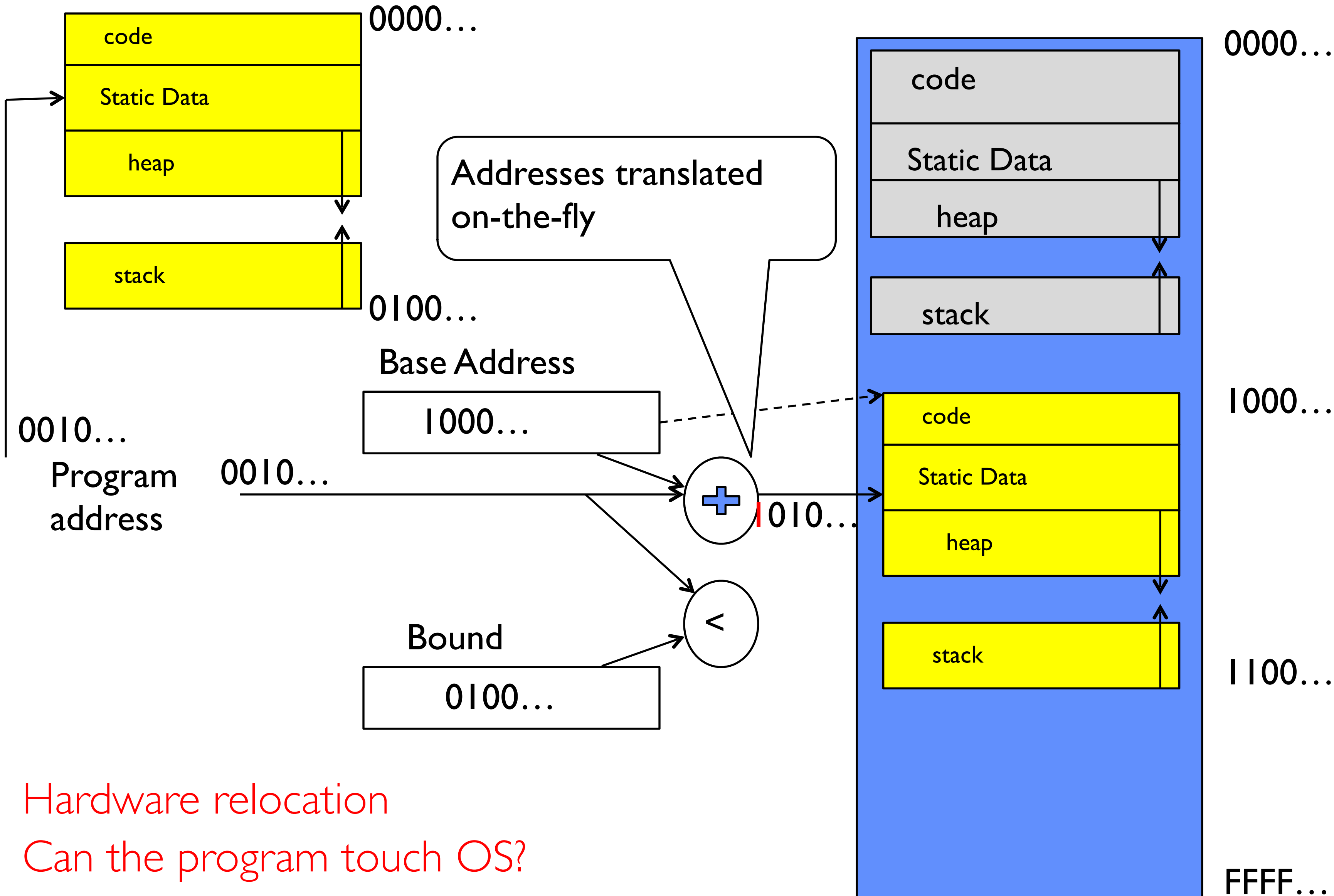

```
jal printf
```

```
000011 XX XXXXXXX XXXXXXX XXXXXXX
```

opcode for jal — **address of `printf` (shifted right by 2)**

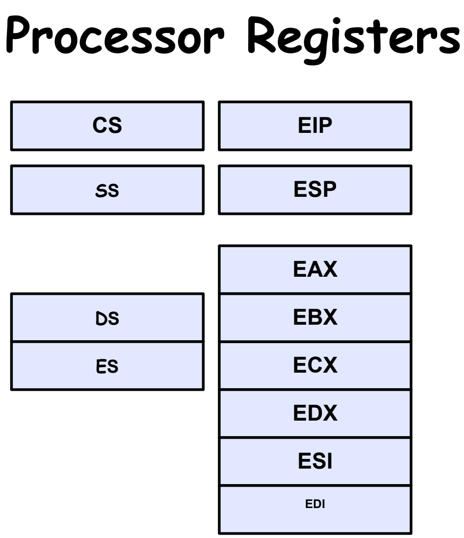
- Compiled .obj file linked together in an .exe
- All address in the .exe are as if it were loaded at memory address 00000000
- File contains a list of all the addresses that need to be adjusted when it is "relocated" to somewhere else.

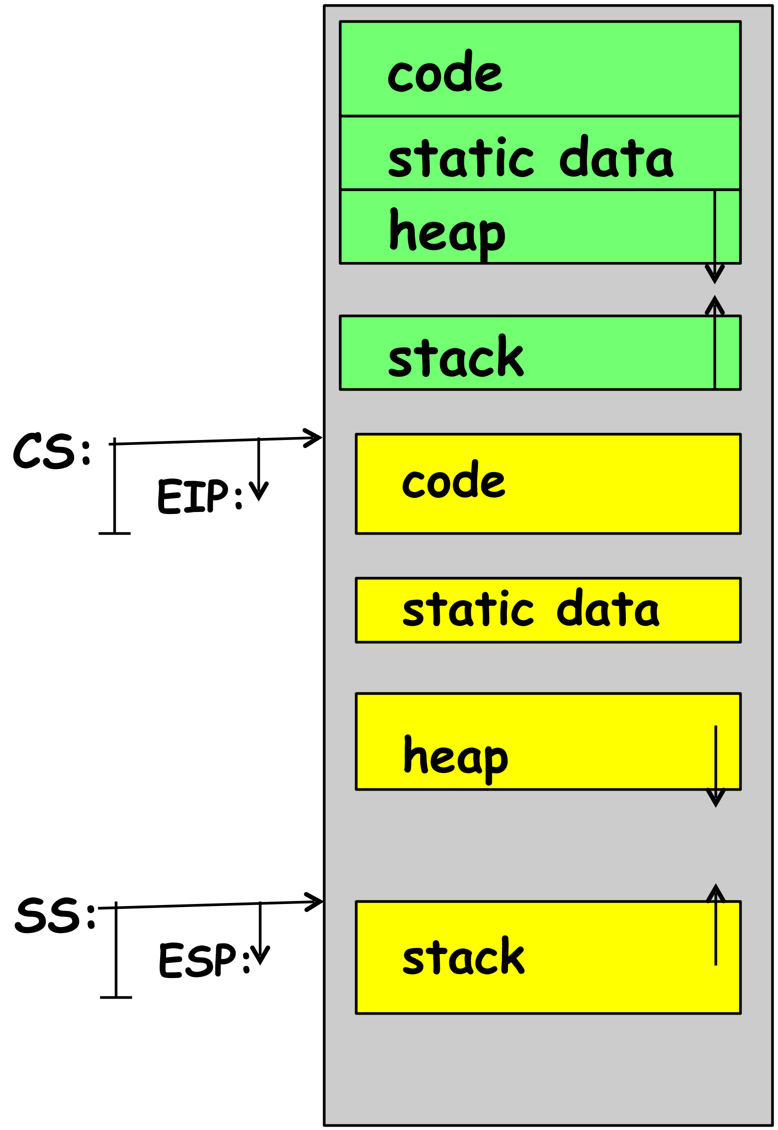
Simple address translation with Base and Bound



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

x86 – segments and stacks

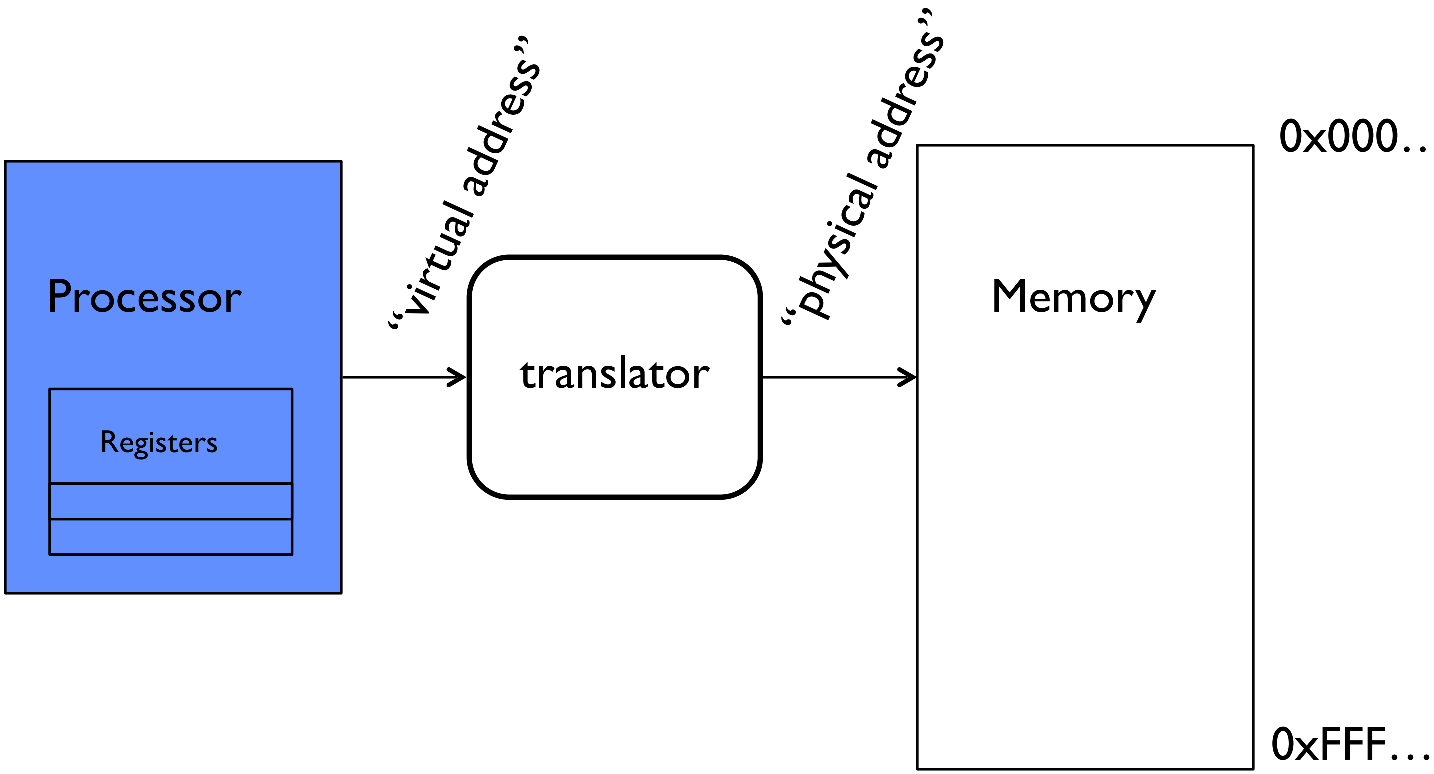




Start address, length and access rights associated with each segment register

Another idea: Address Space Translation

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

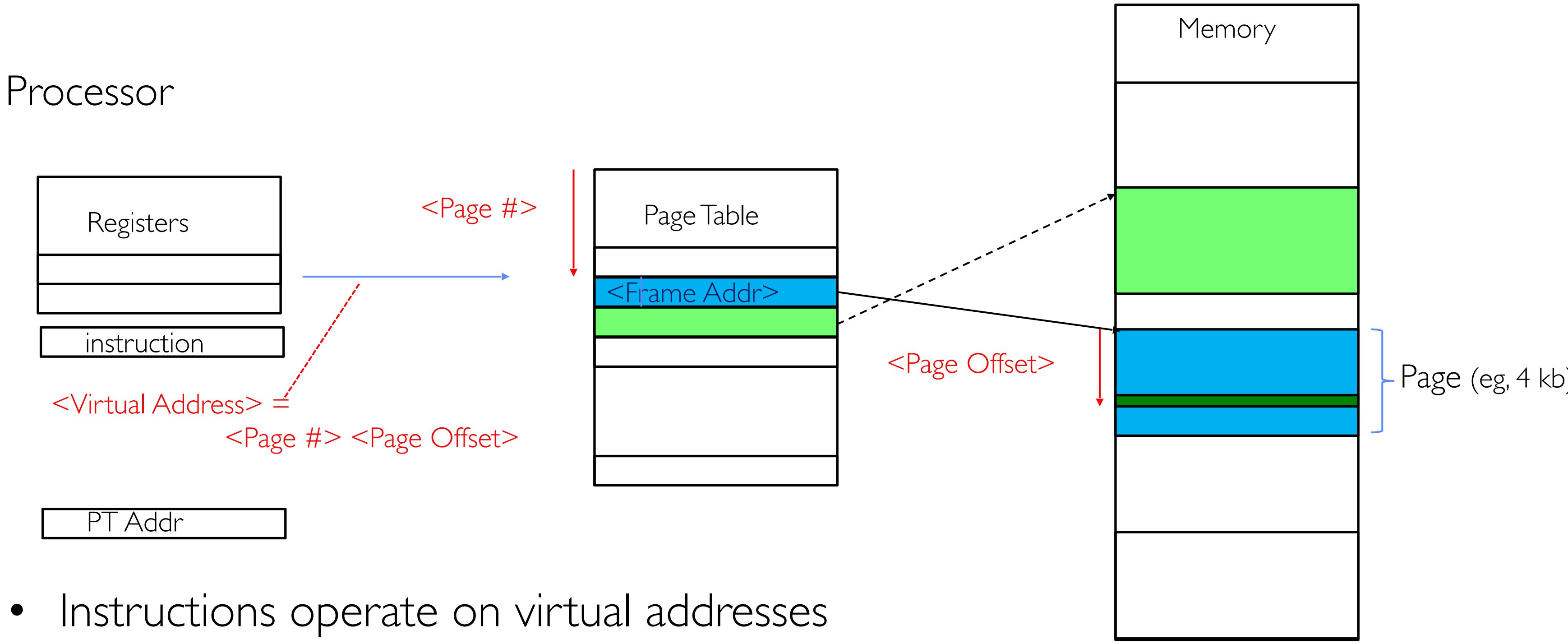


Paged Virtual Address Space

- What if we break the entire virtual address space into equal size chunks (i.e., pages) have a base for each?
- Treat memory as page size frames and put any page into any frame …

- Another review…

Paged Virtual Address

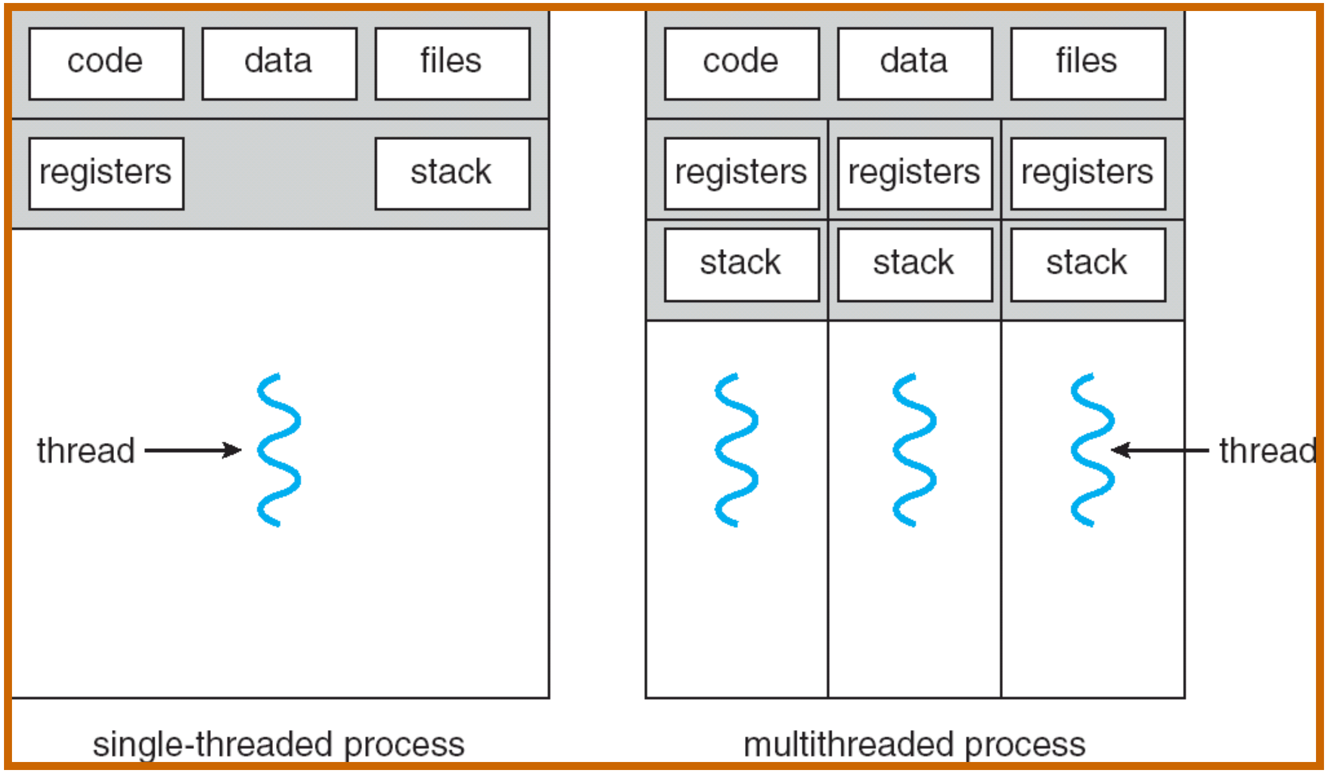


- Instructions operate on virtual addresses
  - Instruction address, load/store data address
- Translated to a physical address (or Page Fault) through a Page Table by the hardware
- Any Page of address space can be in any (page sized) frame in memory
  - Or not-present (access generates a page fault)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

Third OS Concept: Process

- **Process:** 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
  - Threads more efficient than processes for parallelism (later)
- 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" part
  - Keeps buggy program from trashing the system
- Why have multiple threads per address space?

Kernel code/data in process Virtual Address Space?

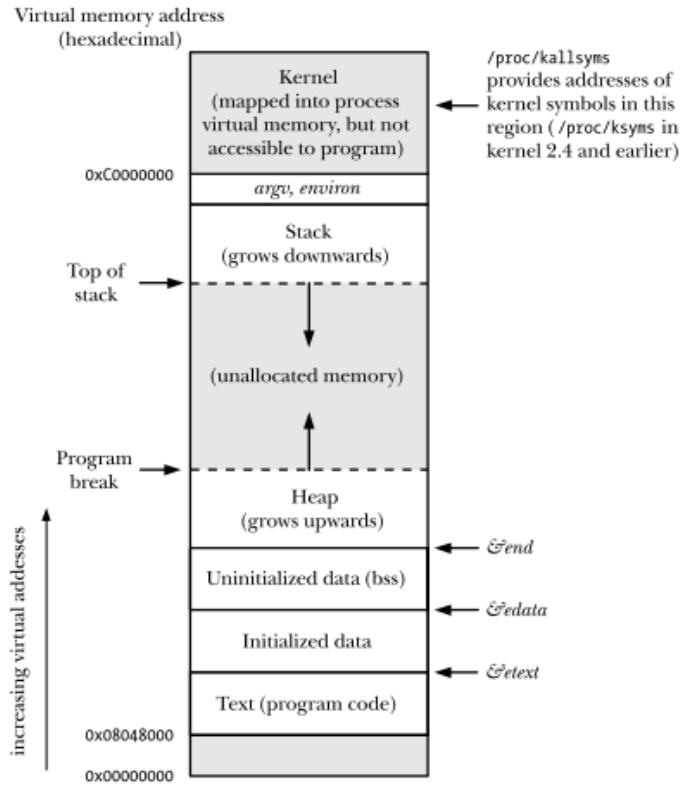


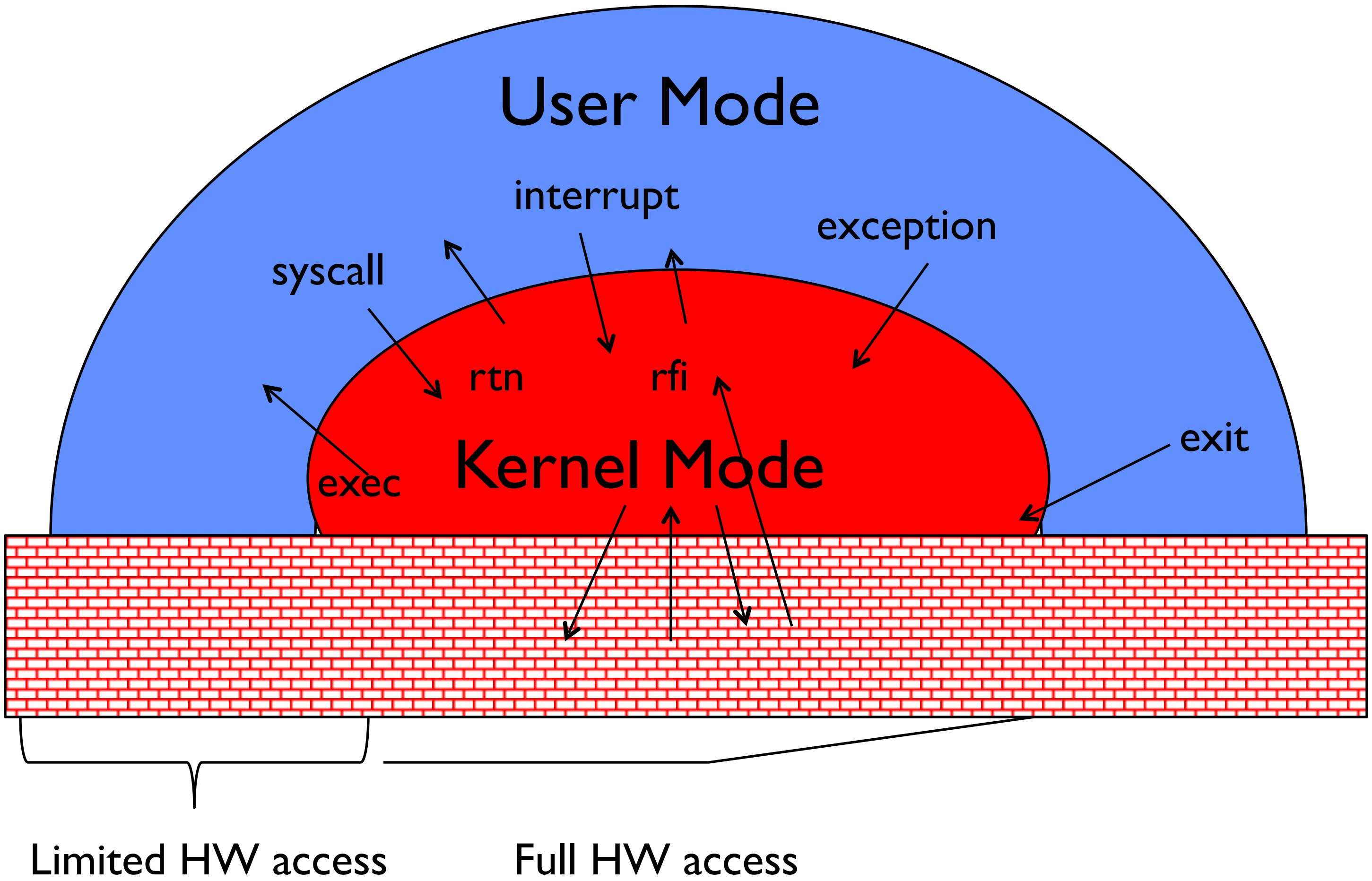
Figure 6-1: Typical memory layout of a process on Linux/x86-32

- Unix: Kernel space is mapped in high - but inaccessible to user processes

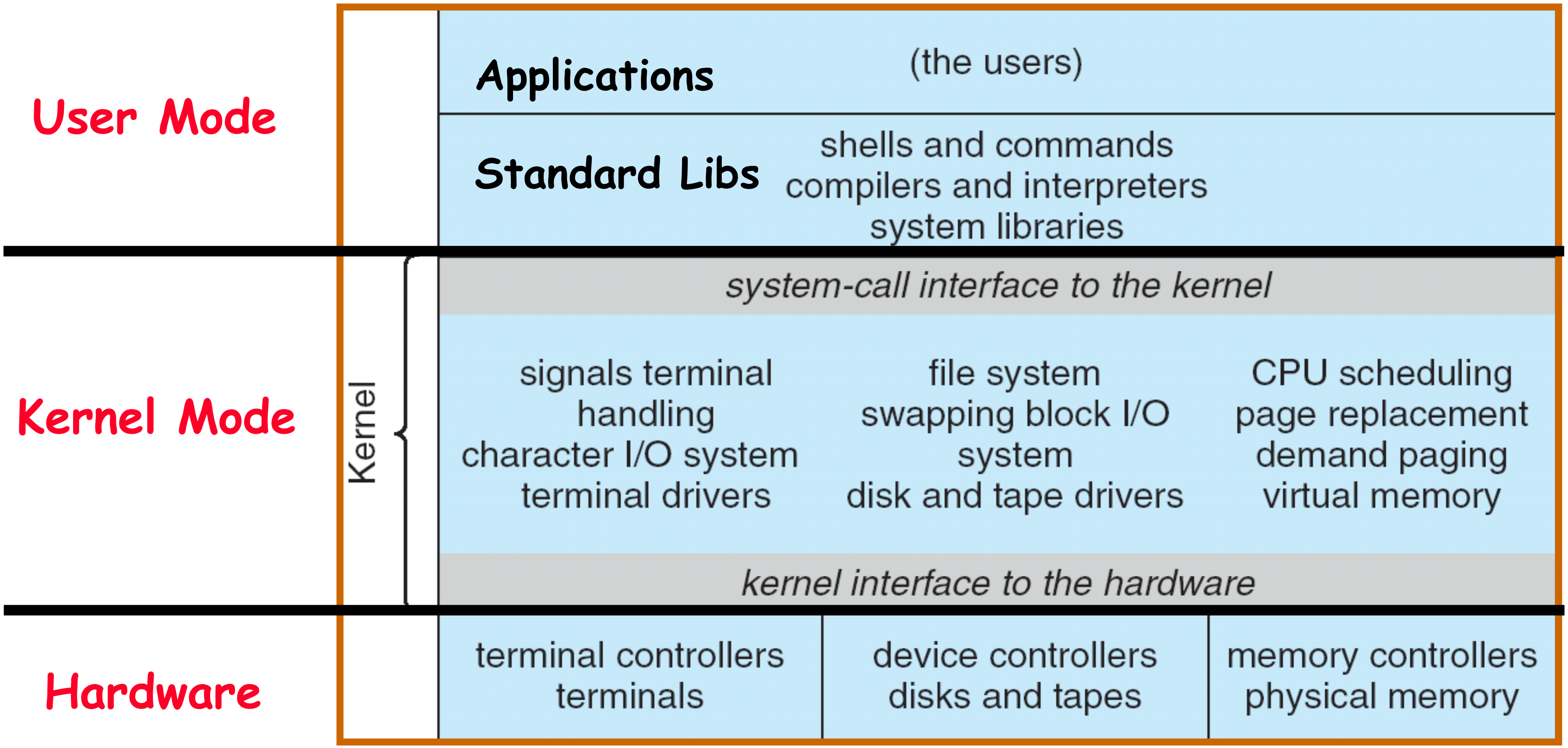
Fourth OS Concept: Dual Mode Operation

- Hardware provides at least two modes:
  - "Kernel" mode (or "supervisor" or "protected")
  - "User" mode: Normal programs executed
- What is needed in the hardware to support "dual mode" operation?
  - A bit of state (user/system mode bit)
  - Certain operations / actions only permitted in system/kernel mode
    - » In user mode they fail or trap
  - User → Kernel transition *sets* system mode AND saves the user PC
    - » Operating system code carefully puts aside user state then performs the necessary operations
  - Kernel → User transition *clears* system mode AND restores appropriate user PC
    - » return-from-interrupt

User/Kernel (Privileged) Mode

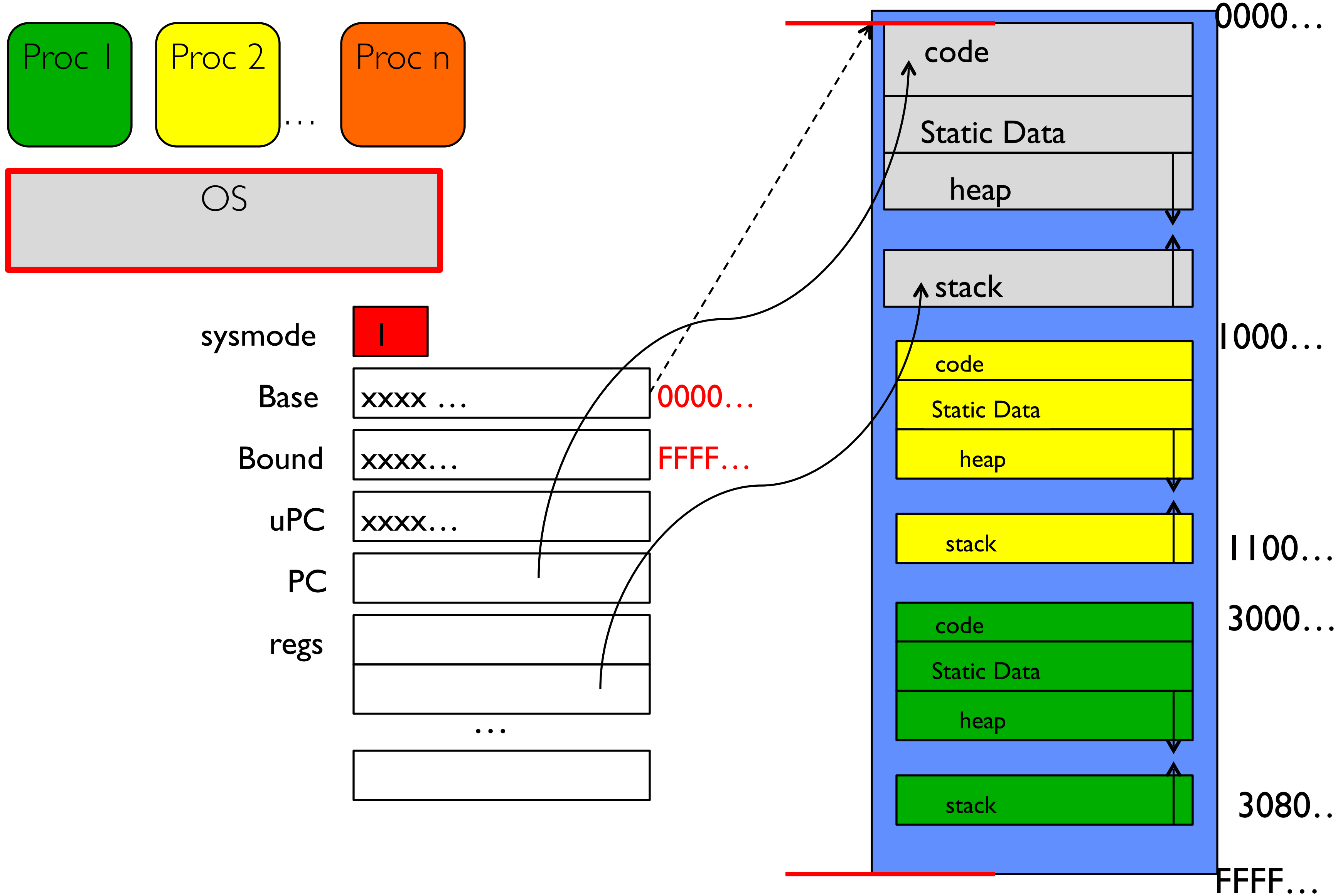


For example: UNIX System Structure

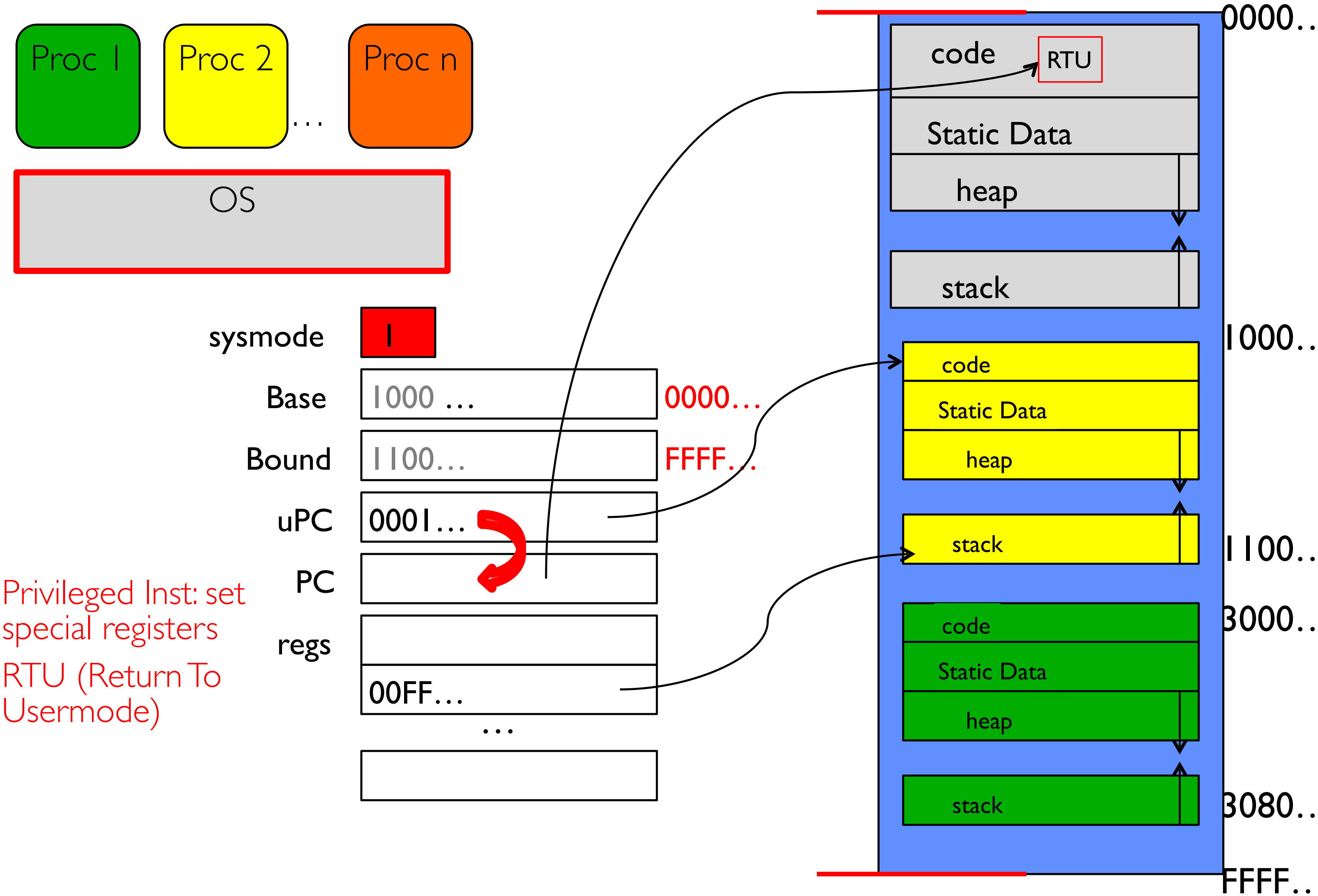


Break!

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

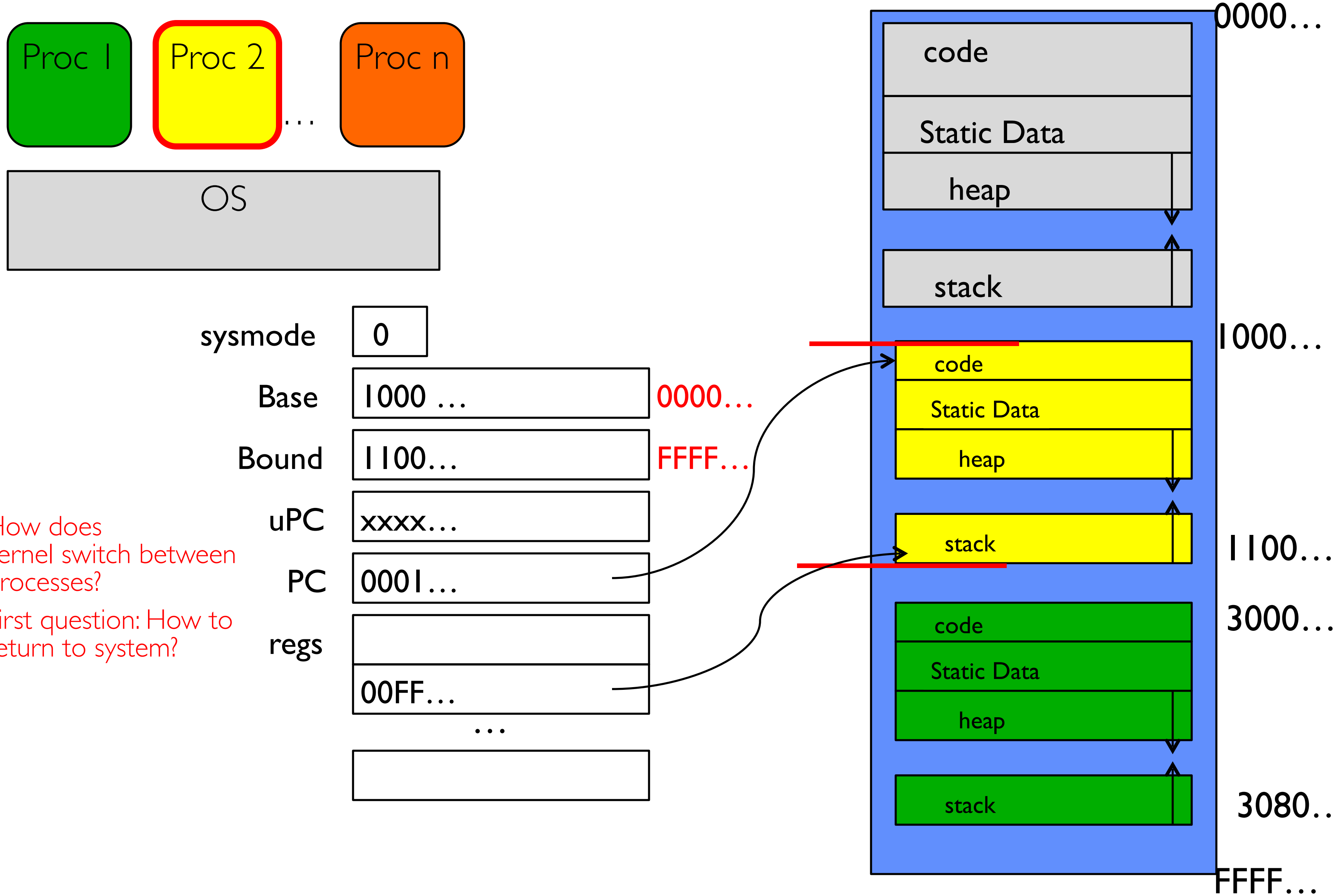


Simple B&B: OS gets ready to execute process



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

Simple B&B: User Code Running



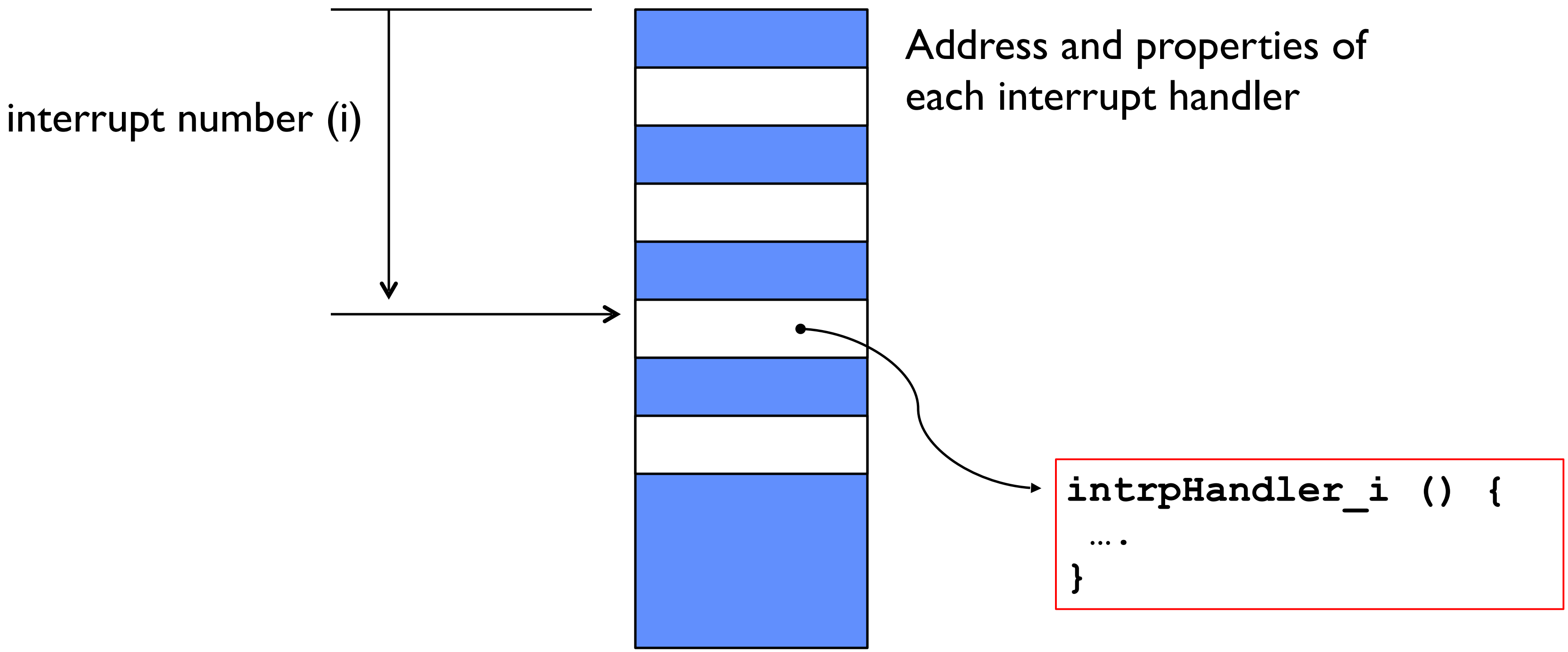
- How does kernel switch between processes?
- First question: How to return to system?

3 types of Mode Transfer

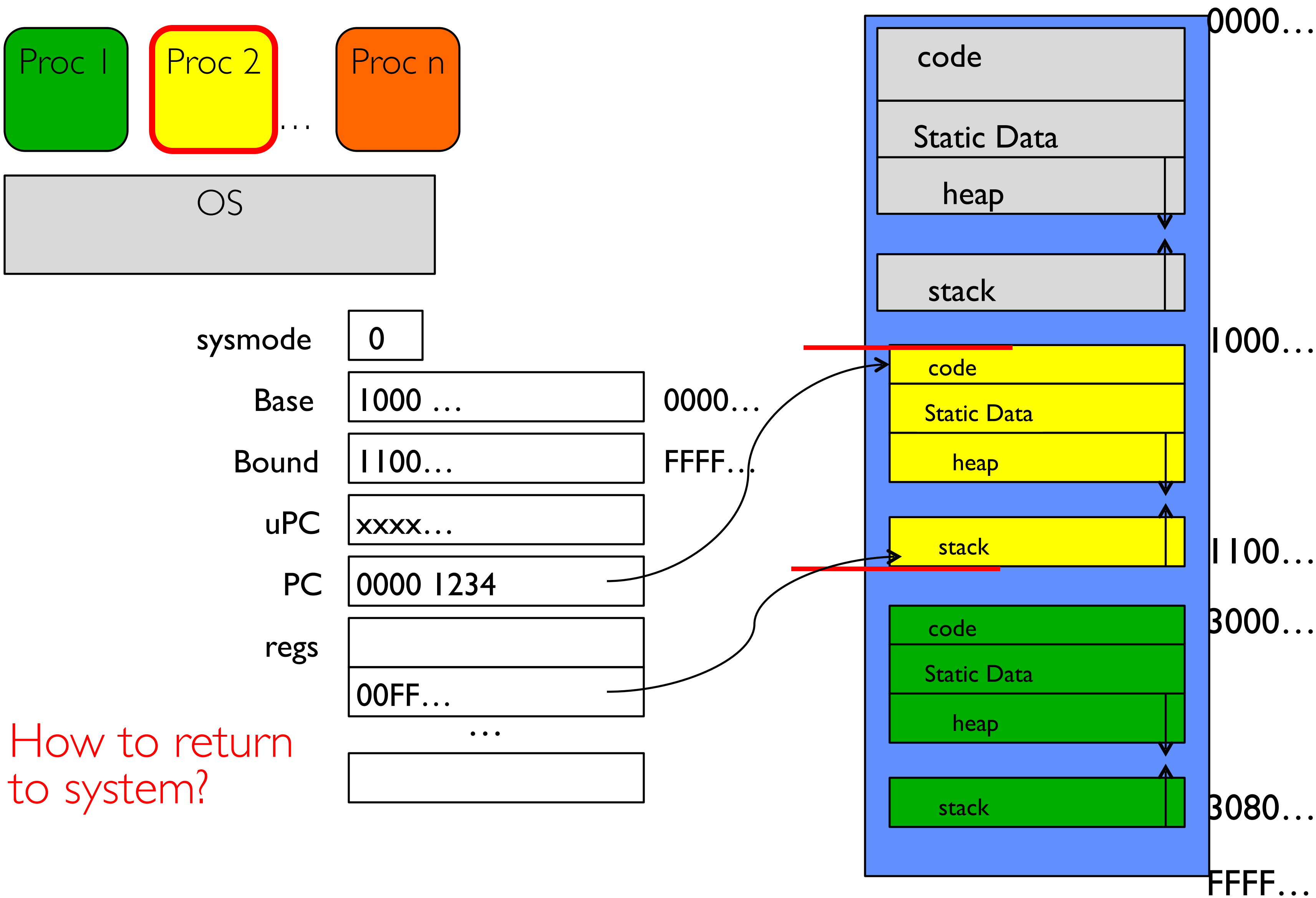
- Syscall
  - Process requests a system service, e.g., exit
  - Like a function call, but "outside" the process
  - Does not have the address of the system function to call
  - Like a Remote Procedure Call (RPC) – for later
  - Marshall the syscall id and args in registers and exec syscall
- Interrupt
  - 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?

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

Interrupt Vector

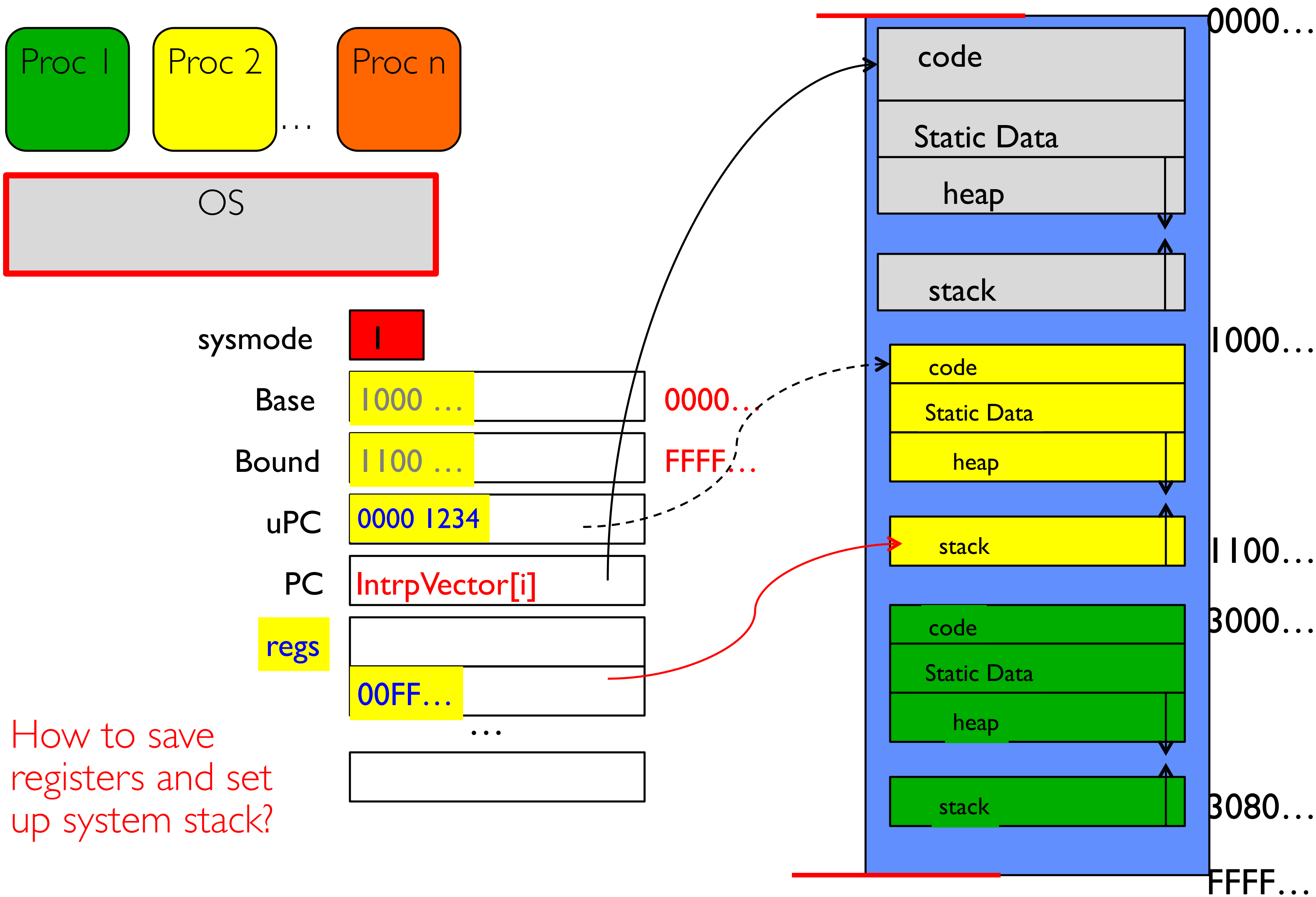


Simple B&B: User => Kernel



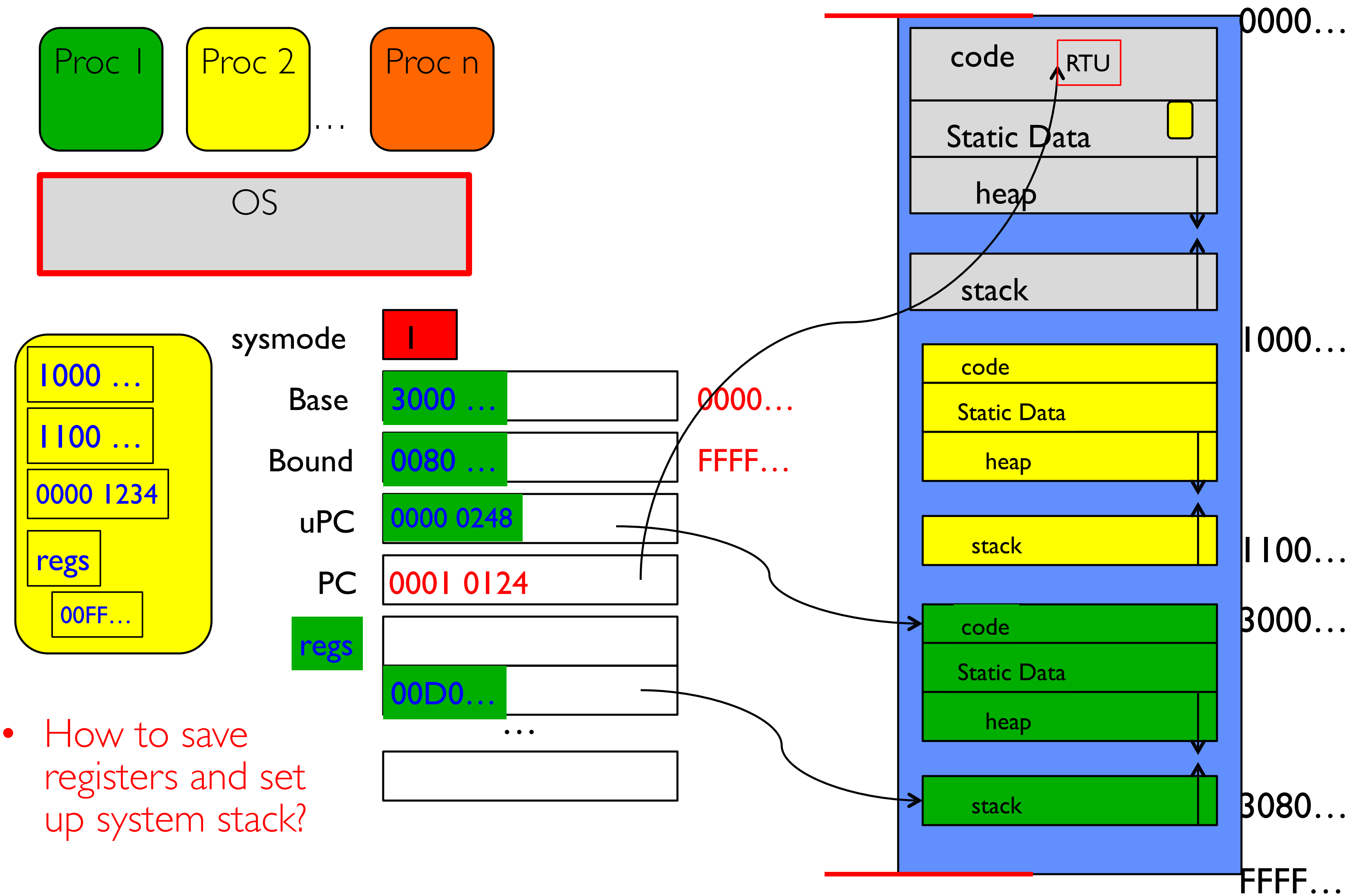
- How to return to system?

Simple B&B: Interrupt



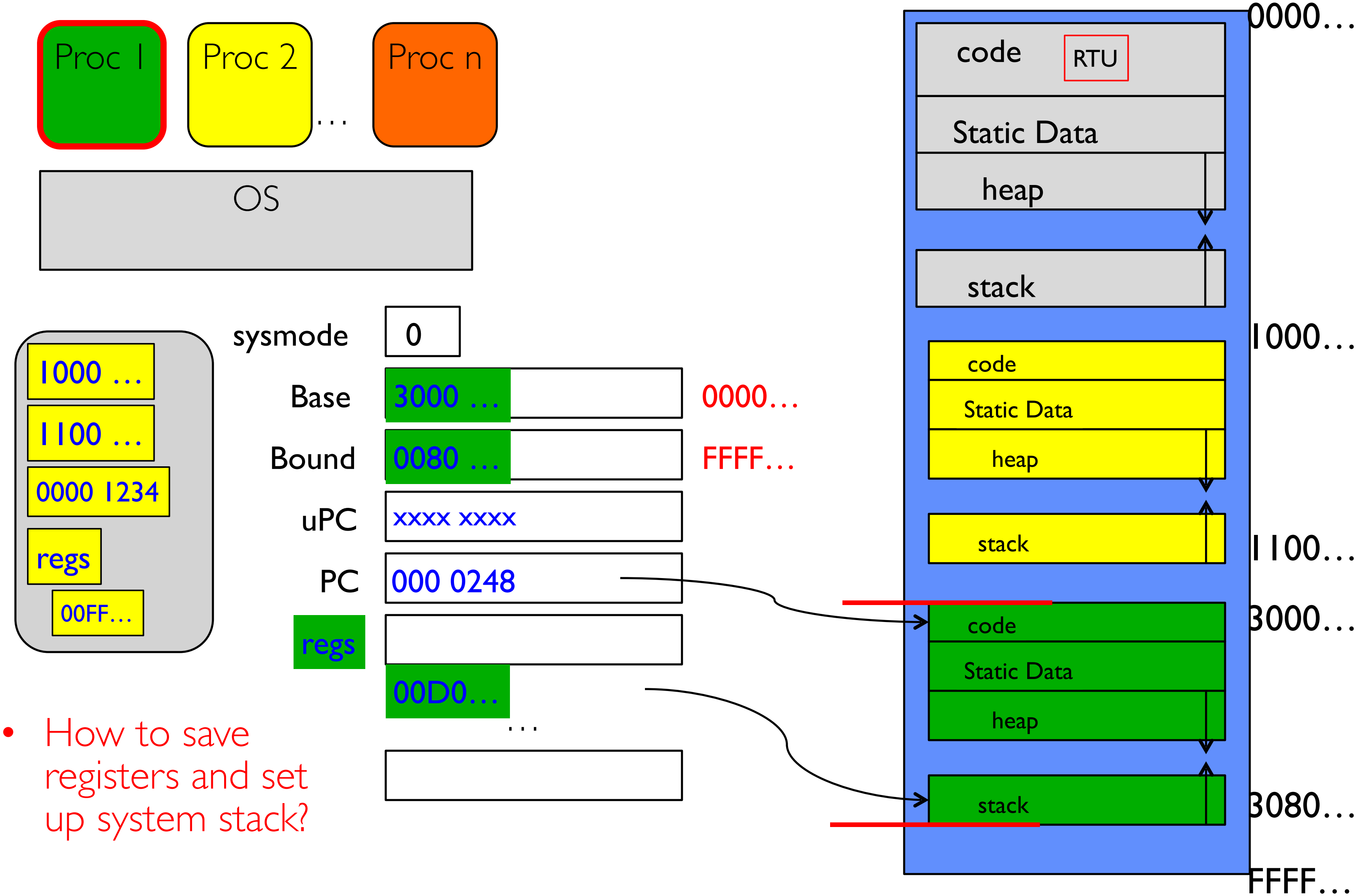
- How to save registers and set up system stack?

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 a 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