CSC 112: Computer Operating Systems
Lecture 2

Four Fundamental OS Concepts

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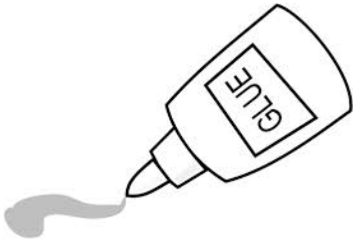
Hofstra University

Acknowledgement: Lecture slides based on UC Berkeley CS 162: Operating Systems and System Programming

Recall: What is an Operating System?

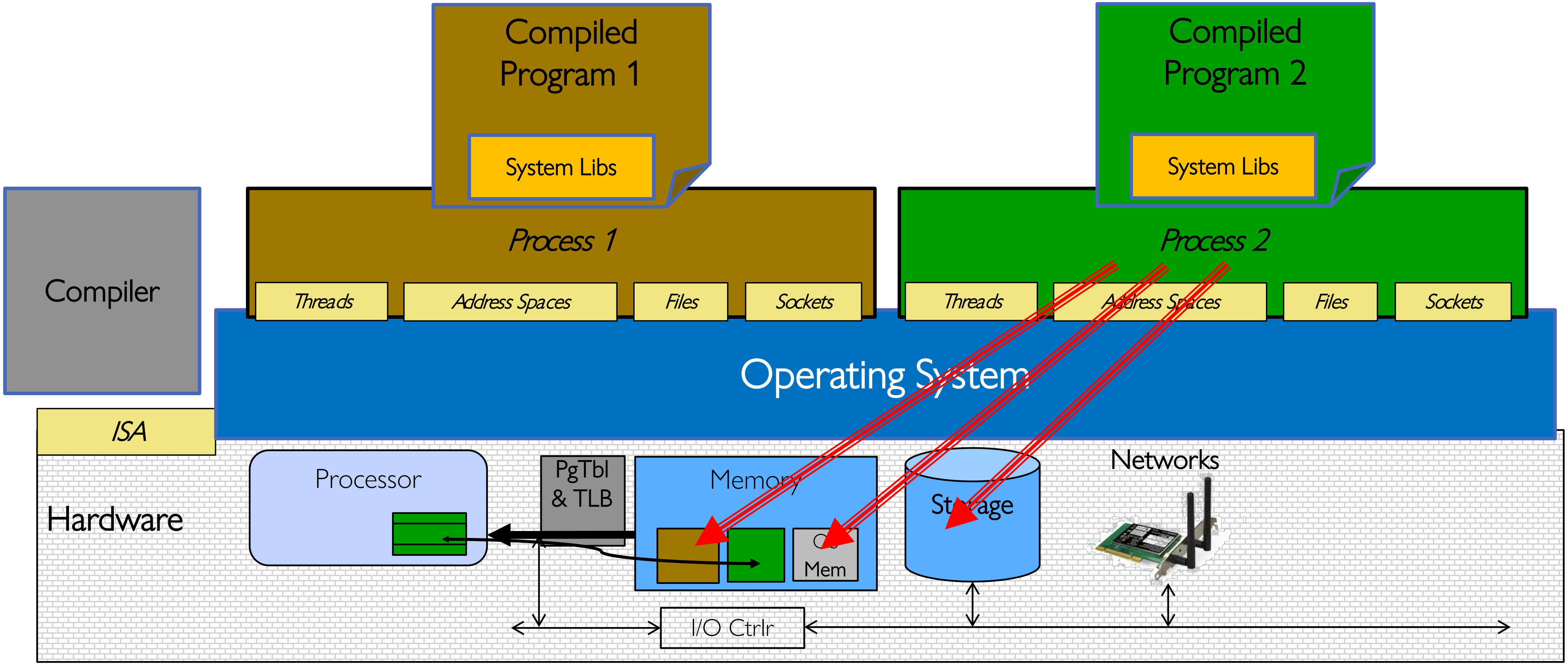
- Referee
  - Manage protection, isolation, and sharing of resources
    - » Resource allocation and communication

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

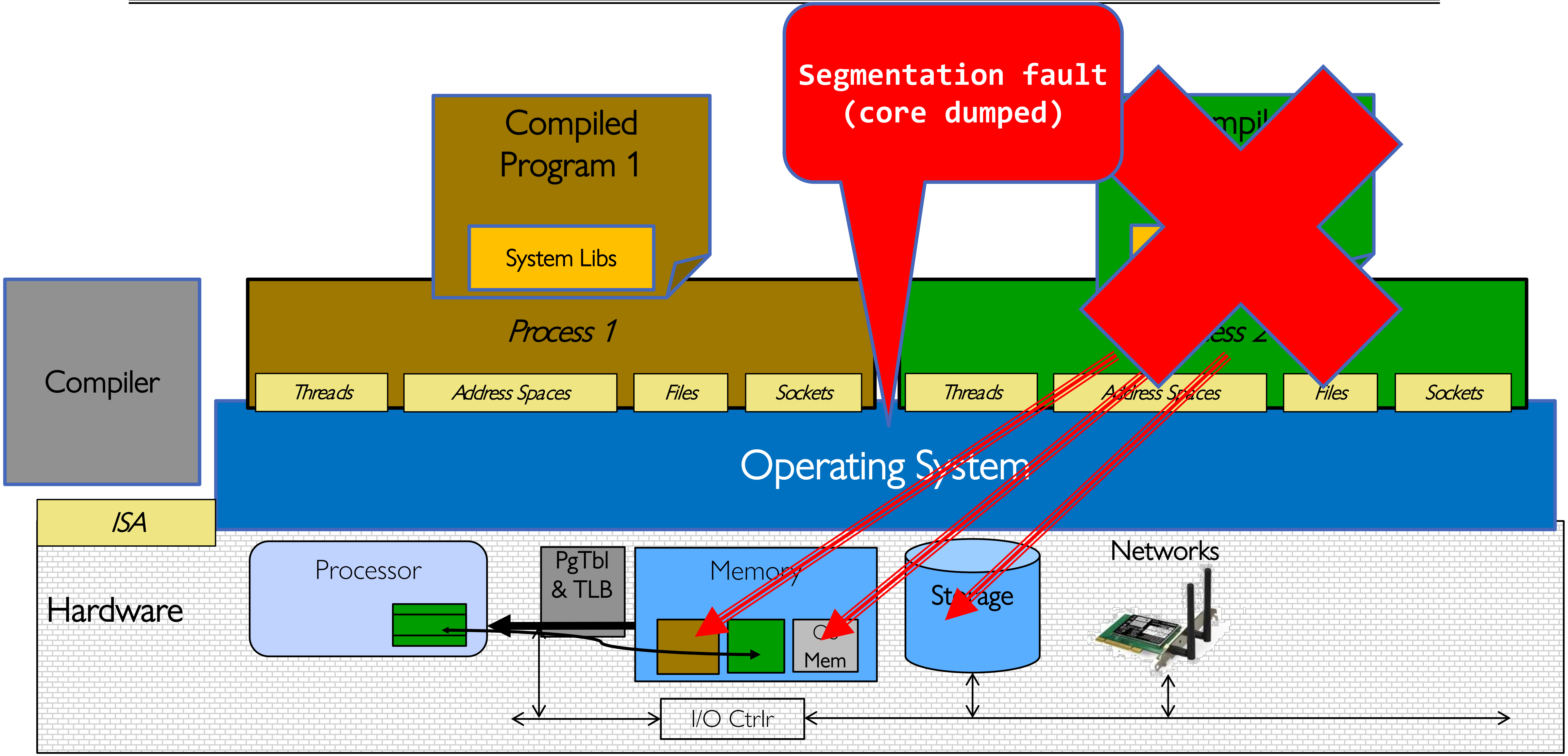


- Glue
  - Common services
    - » Storage, Window system, Networking
    - » Sharing, Authorization
    - » Look and feel

Recall: OS Protection



Recall: OS Protection



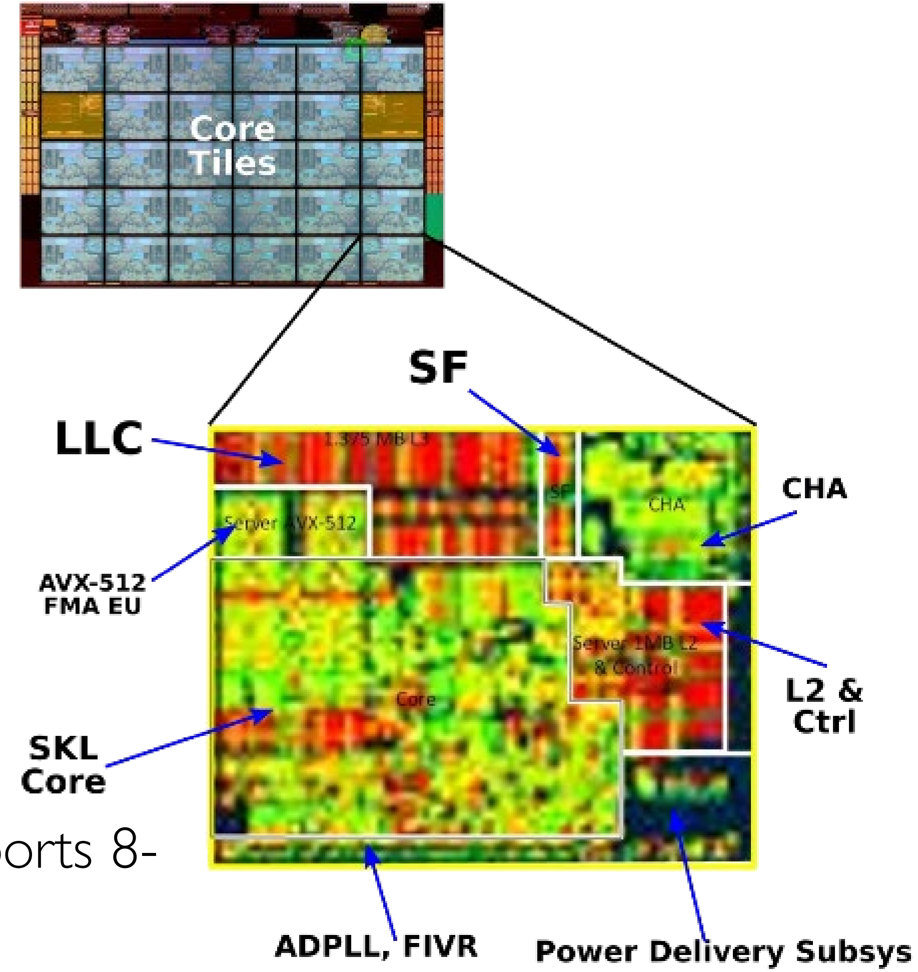
Challenge: Complexity

- Applications consisting of…
  - … a variety of software modules that …
  - … run on a variety of devices (machines) that
    - » … implement different hardware architectures
    - » … run competing applications
    - » … fail in unexpected ways
    - » … can be under a variety of attacks

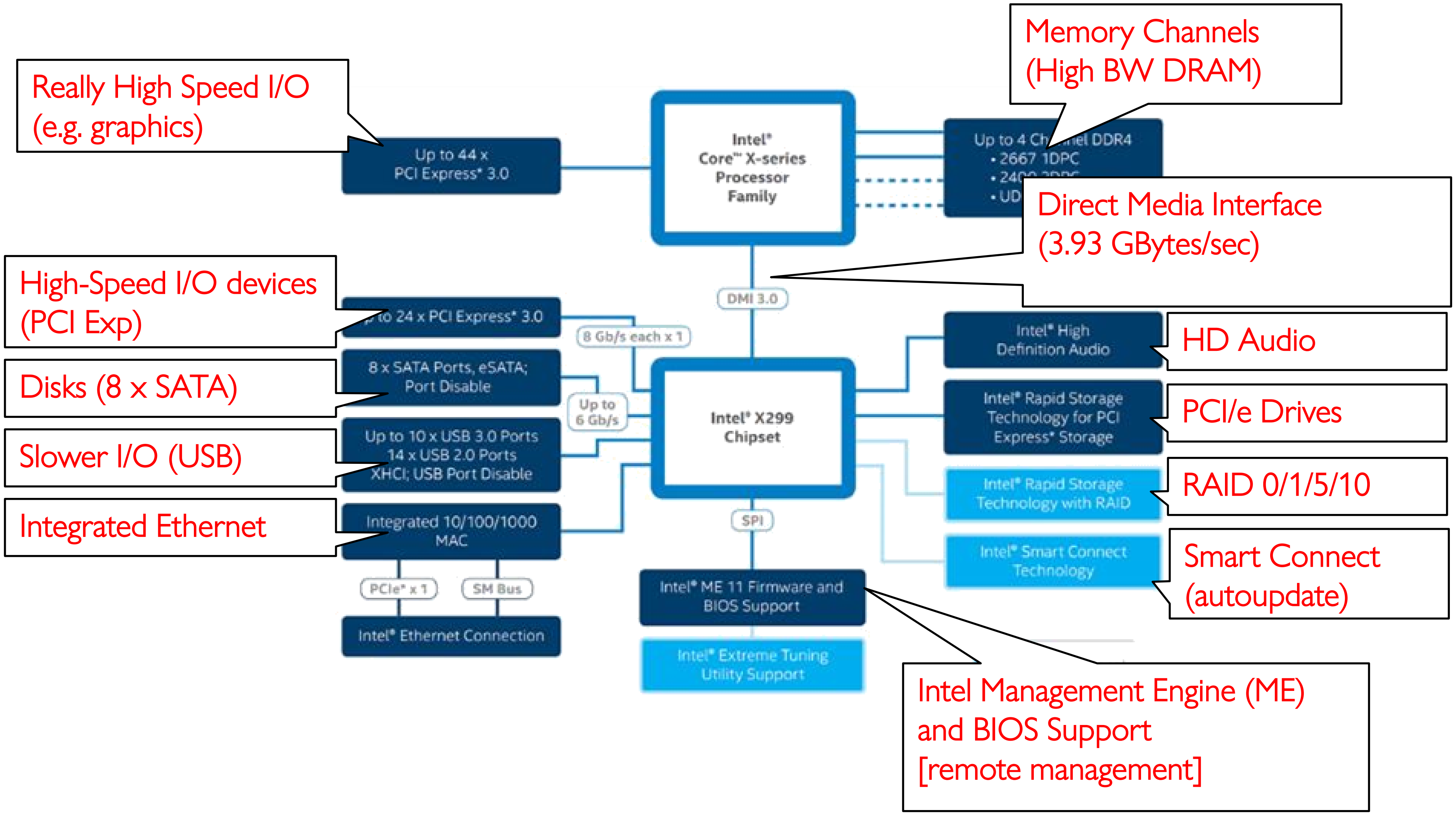
- Not feasible to test software for all possible environments and combinations of components and devices
  - The question is not whether there are bugs but how serious are the bugs!

The World Is Parallel: Intel SkyLake (2017)

- Up to 28 Cores, 56 Threads
  - 694 mm^2 die size (estimated)
- Many different instructions
  - Security, Graphics
- Caches on chip:
  - L2: 28 MiB
  - Shared L3: 38.5 MiB (non-inclusive)
  - Directory-based cache coherence
- Network:
  - On-chip Mesh Interconnect
  - Fast off-chip network directlry supports 8-chips connected
- DRAM/chips
  - Up to 1.5 TiB
  - DDR4 memory

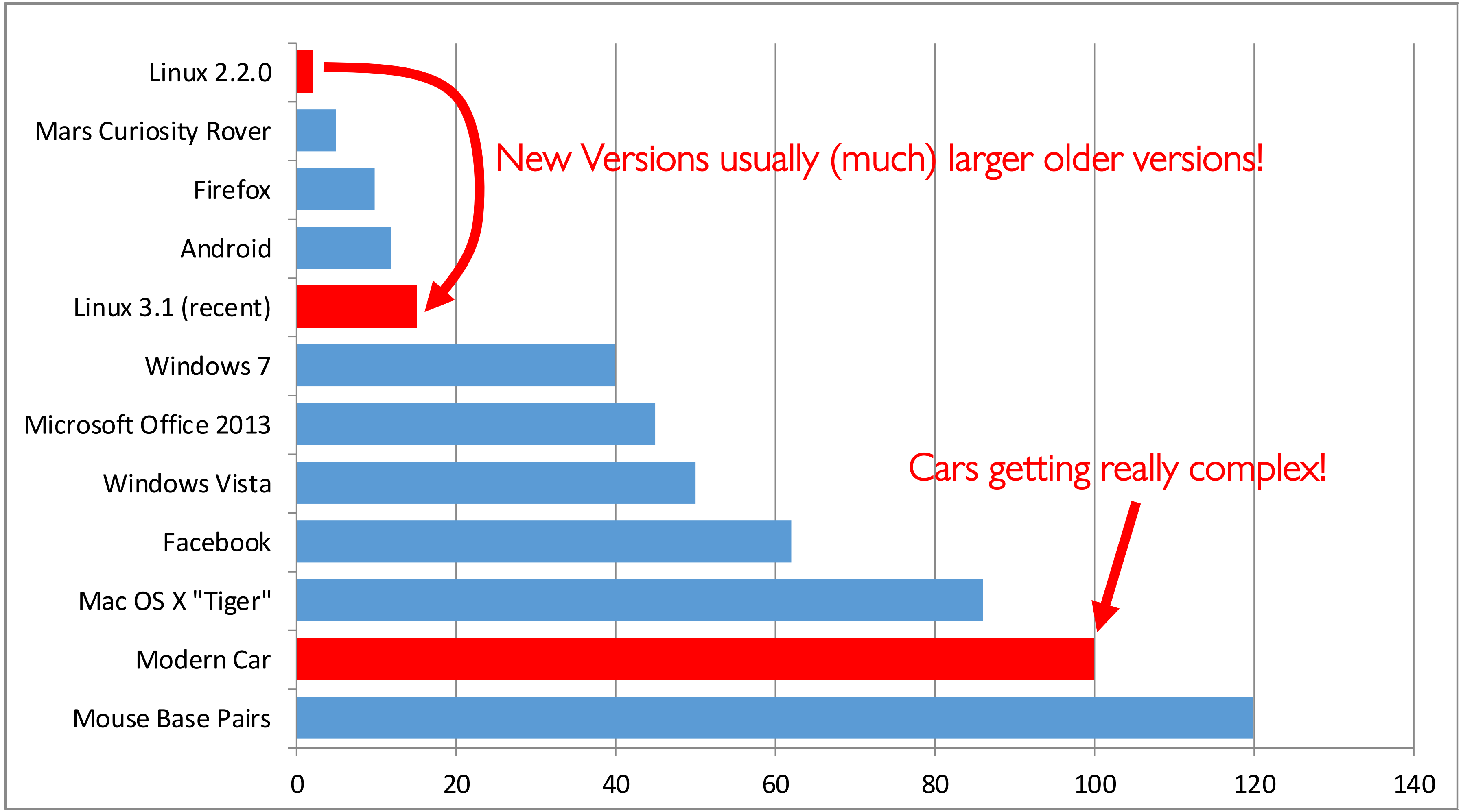


HW Functionality comes with great complexity!



Intel Skylake-X I/O Configuration

Recall: Increasing Software Complexity

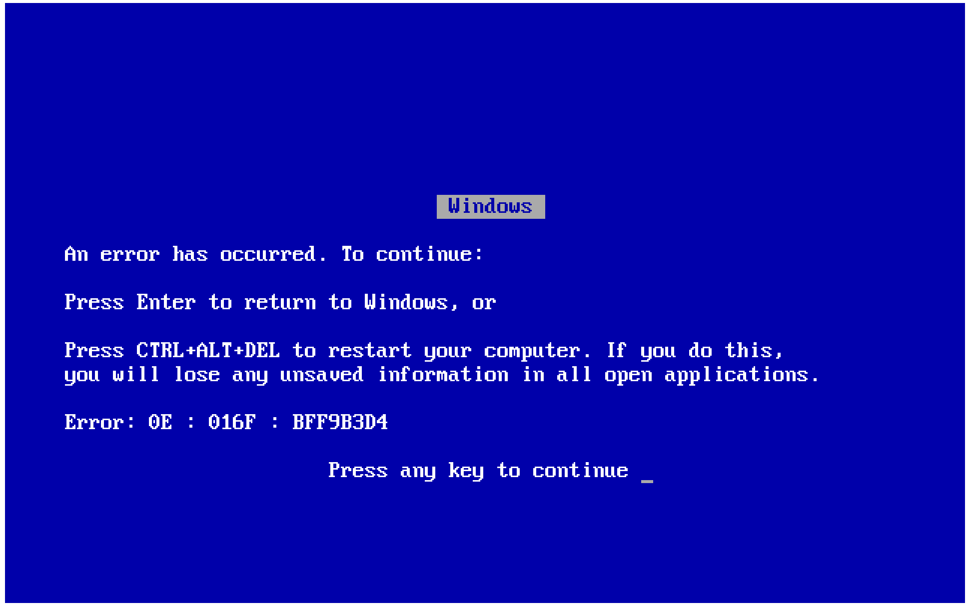


Millions of Lines of Code

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

Complexity leaks into OS if not properly designed:

- Third-party device drivers are one of the most unreliable aspects of OS
  - Poorly written by non-stake-holders
  - Ironically, the attempt to provide clean abstractions can lead to crashes!
- Holes in security model or bugs in OS lead to instability and privacy breaches
  - Great Example: Meltdown (2017)
    - » Extract data from protected kernel space!
- Version skew on Libraries can lead to problems with application execution
- Data breaches, DDOS attacks, timing channels….
  - Heartbleed (SSL)



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

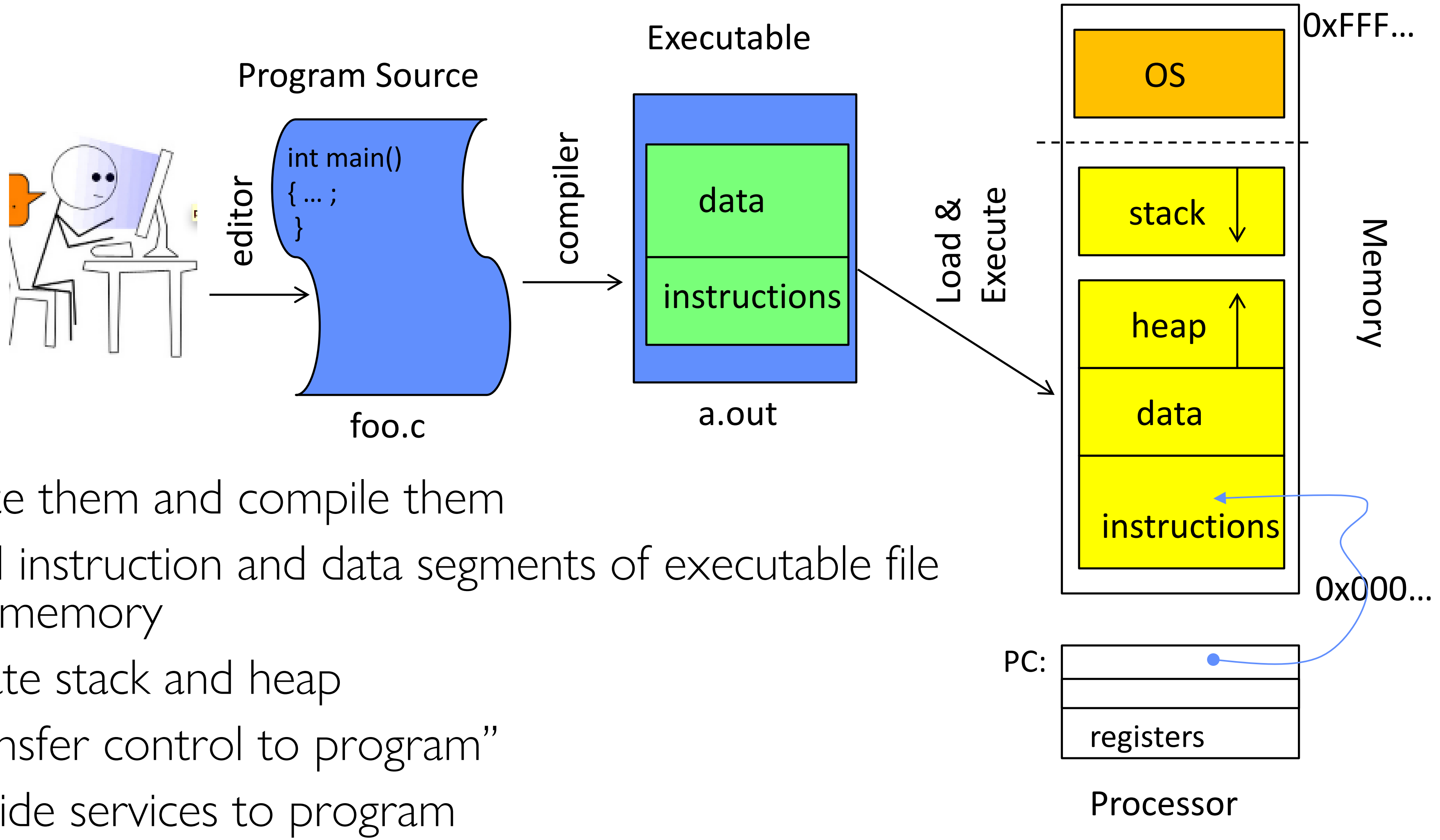
Hardware

- 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

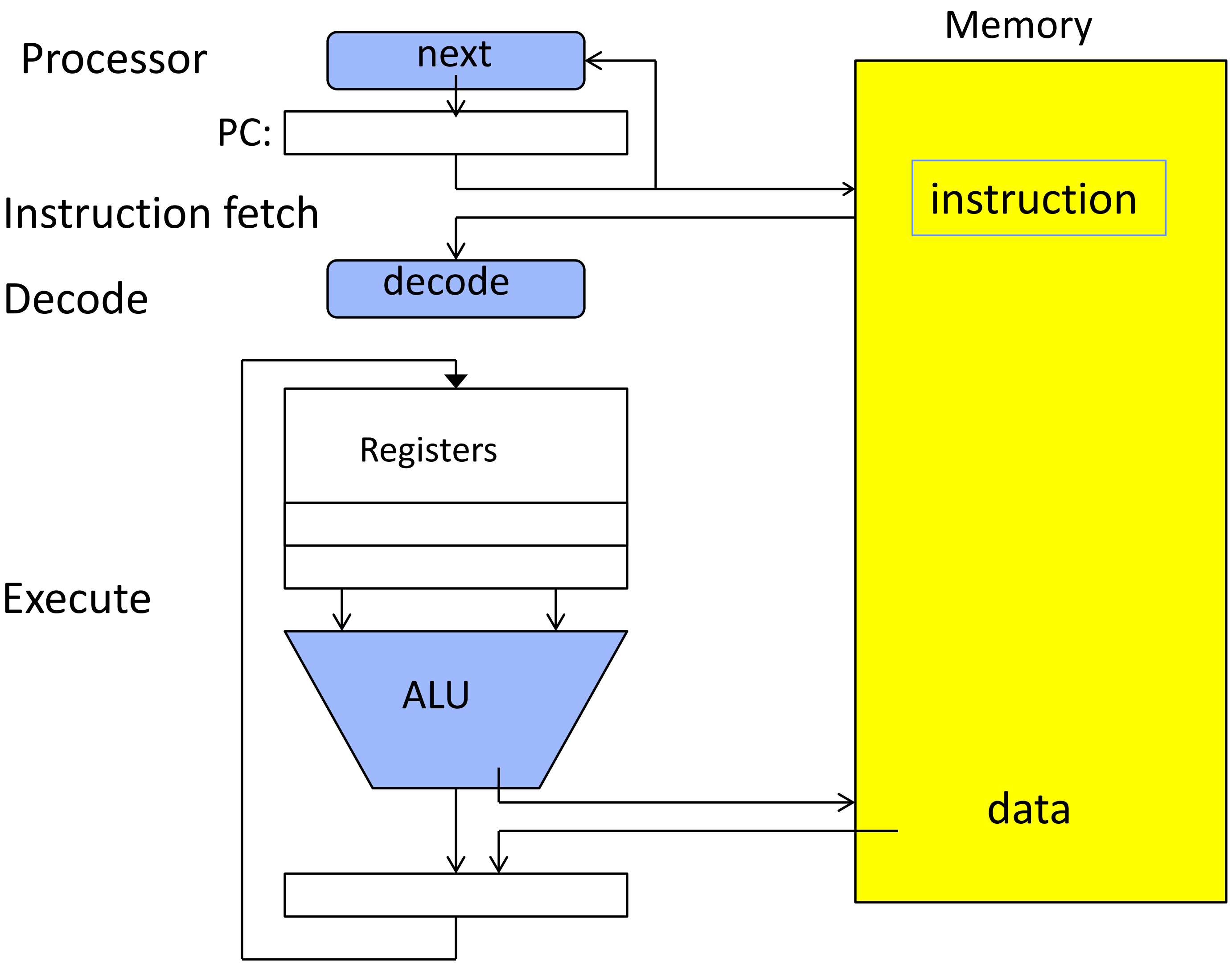
OS Bottom Line: Run Programs



- 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

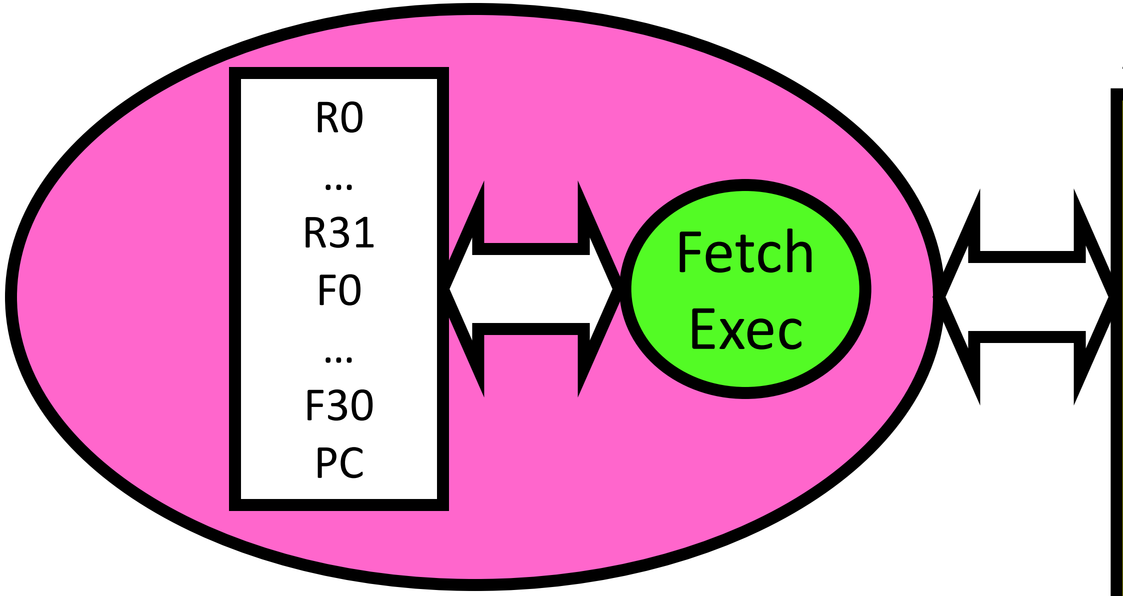
The instruction cycle

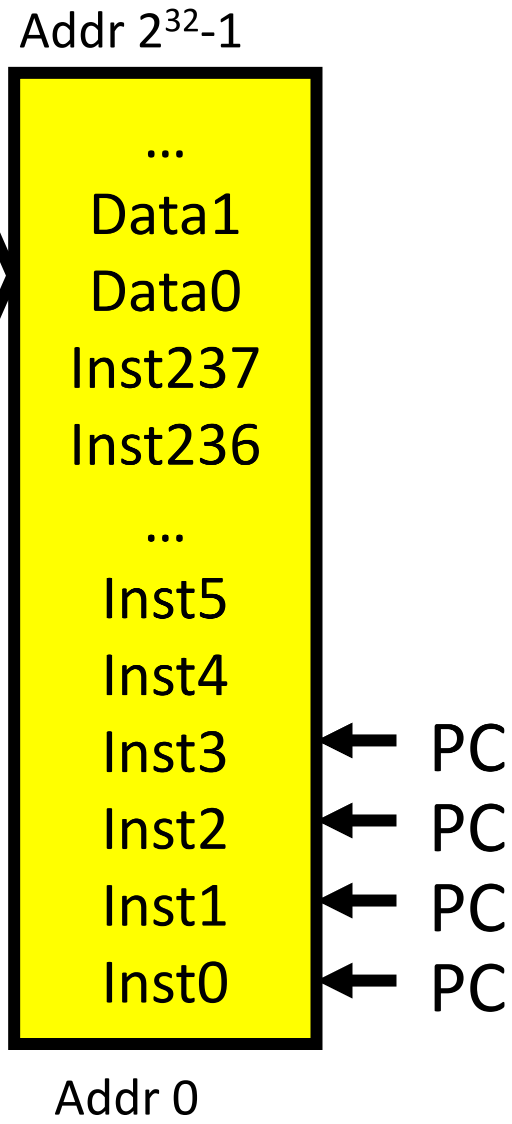


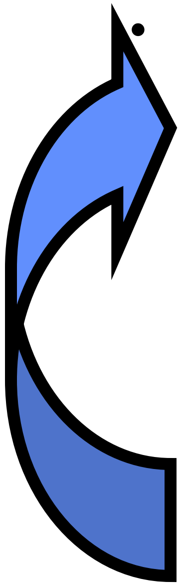
First OS Concept: Thread of Control

- **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?





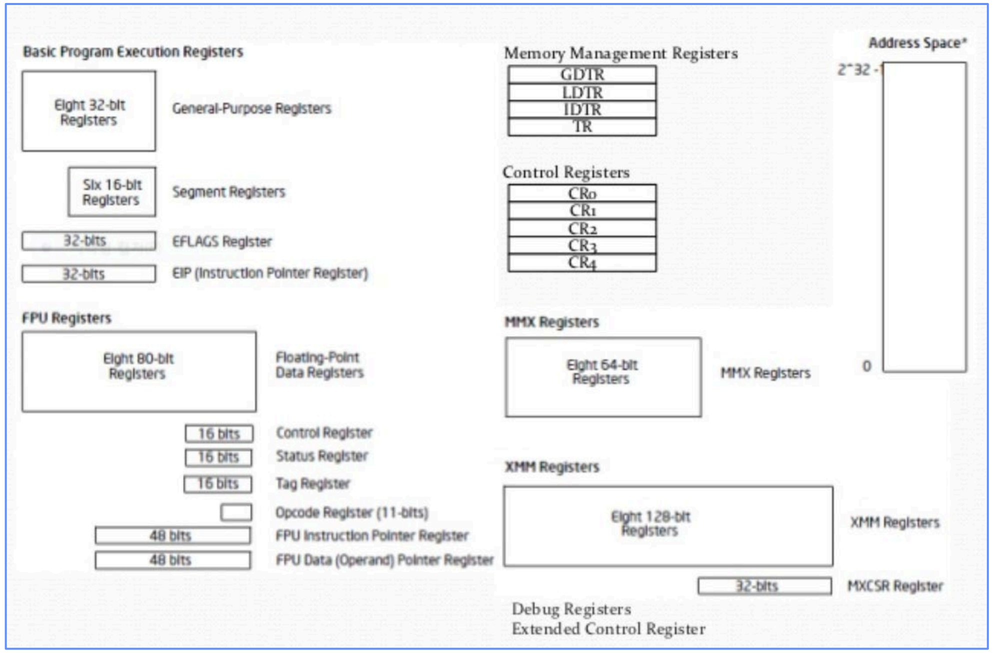


- Execution sequence:
  - Fetch Instruction at PC
  - Decode
  - Execute (possibly using registers)
  - Write results to registers/mem
  - PC = Next Instruction(PC)
  - Repeat

Registers: RISC-V ⇒ x86

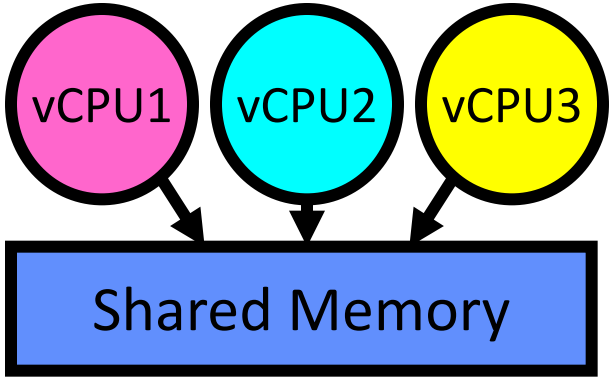
Register	ABI Name	Description	Saver
x0	zero	Hard-wired zero	—
x1	ra	Return address	Caller
x2	sp	Stack pointer	Callee
x3	gp	Global pointer	—
x4	tp	Thread pointer	—
x5	t0	Temporary/alternate link register	Caller
x6–7	t1–2	Temporaries	Caller
x8	s0/fp	Saved register/frame pointer	Callee
x9	s1	Saved register	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



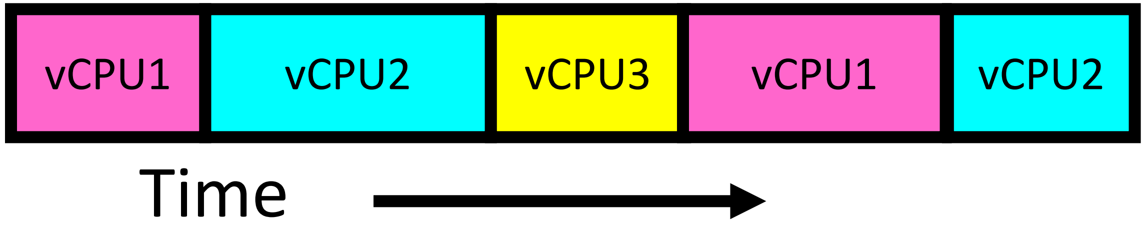
Complex mem-mem arch (x86) with specialized registers and "segments"

Illusion of Multiple Processors



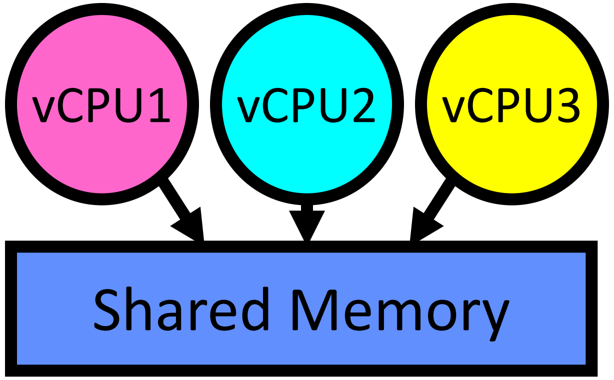
Programmer’s View

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



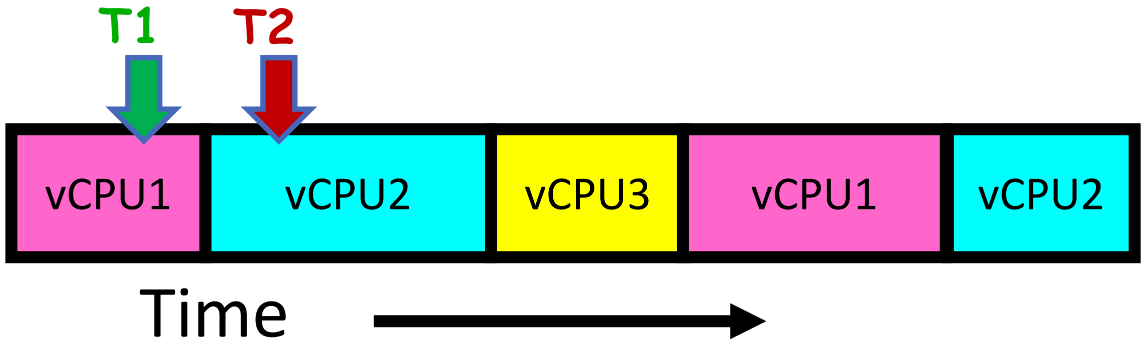
- Contents of virtual core (thread):
  - Program counter, stack pointer
  - Registers
- Where is “it” (the thread)?
  - On the real (physical) core, or
  - Saved in chunk of memory – called the *Thread Control Block (TCB)*

Illusion of Multiple Processors (Continued)



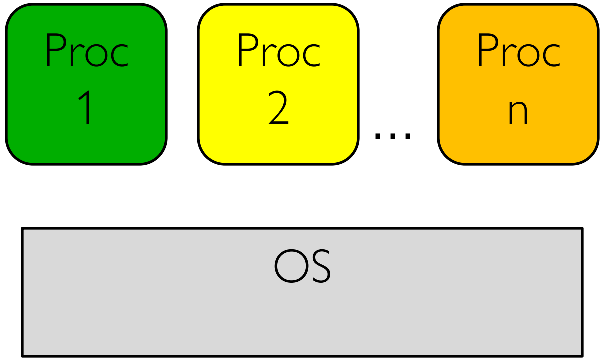
Programmer's View

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

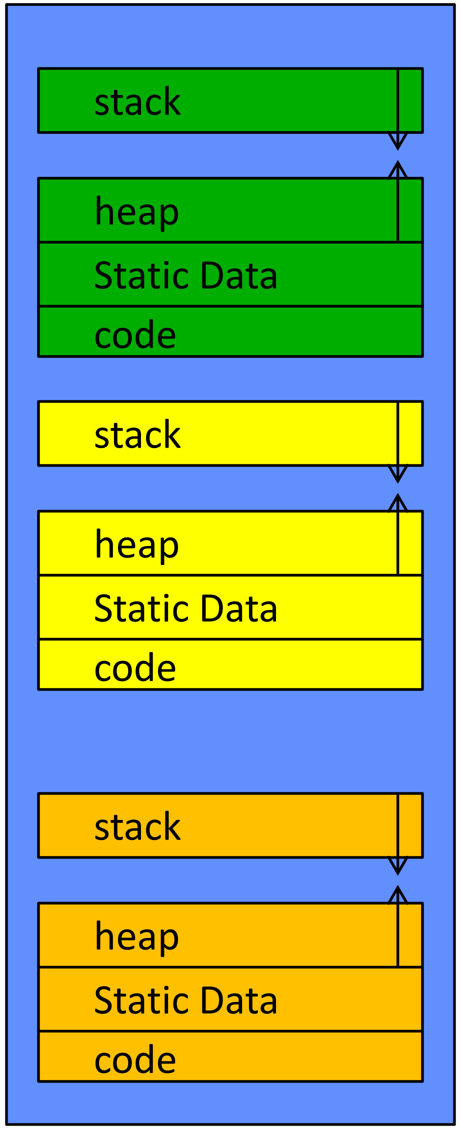


- What happened?
  - OS Ran [how?]
  - Saved PC, SP, … in vCPU1's thread control block (memory)
  - Loaded PC, SP, … from vCPU2's TCB, jumped to PC
- What triggered this switch?
  - Timer, voluntary yield, I/O, other things we will discuss

Multiprogramming - Multiple Threads of Control



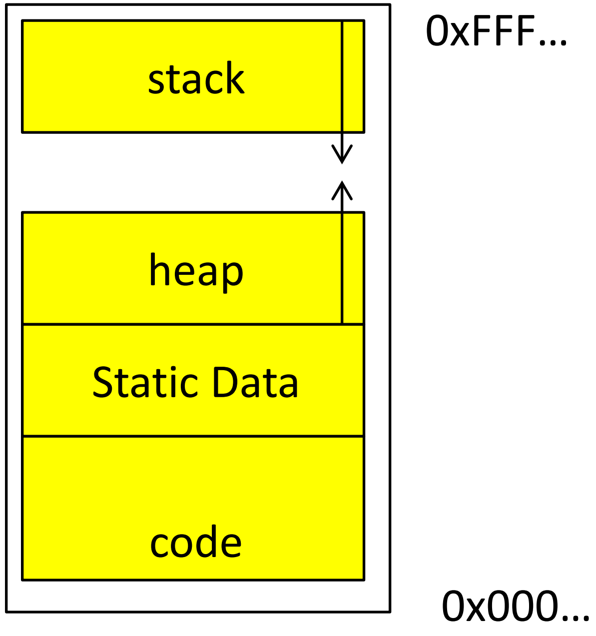
- Thread Control Block (TCB)
  - Holds contents of registers when thread not running
  - What other information?
- Where are TCBs stored?
  - For now, in the kernel



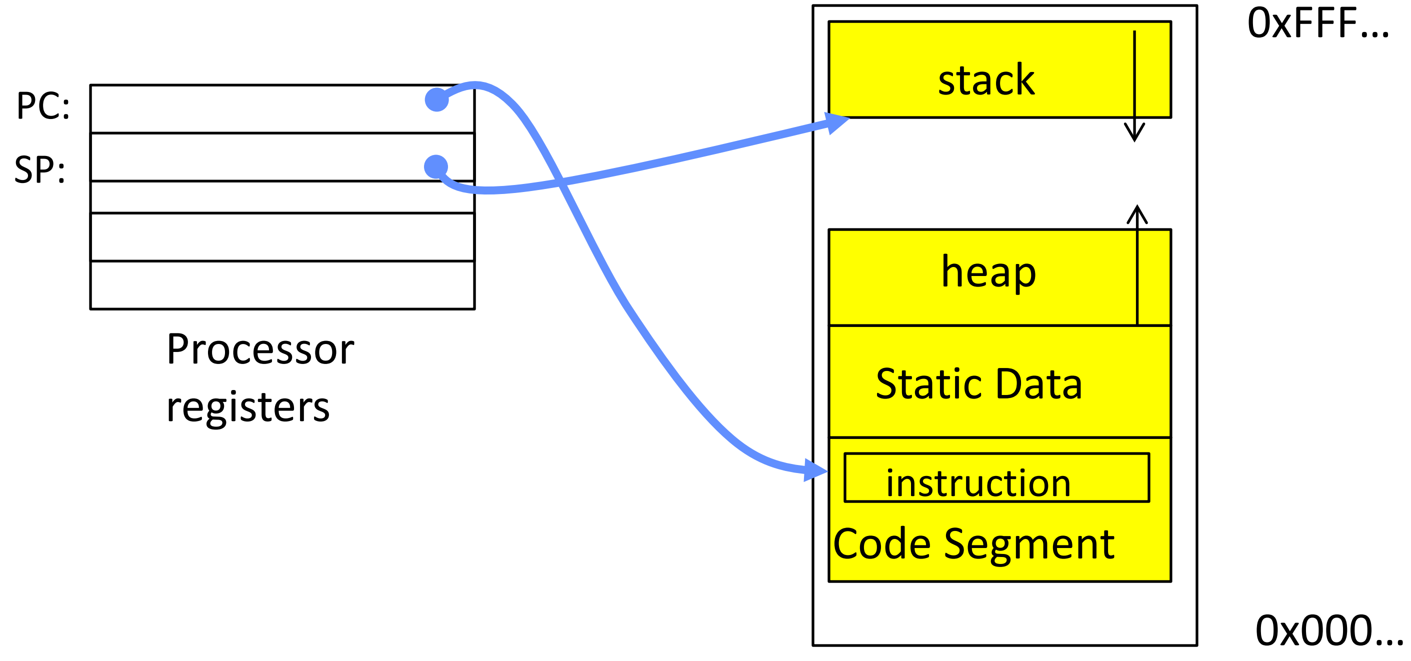
Second OS Concept: Address Space

- 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
  – ….



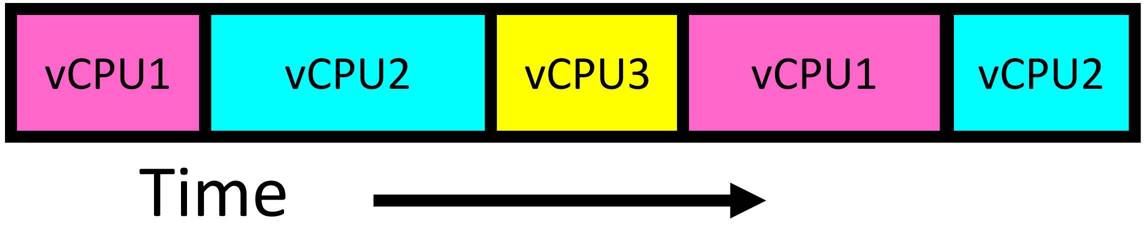
Address Space: In a Picture



- 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)
  - Windows 95-ME (switch with yield or timer)
- However it is risky…

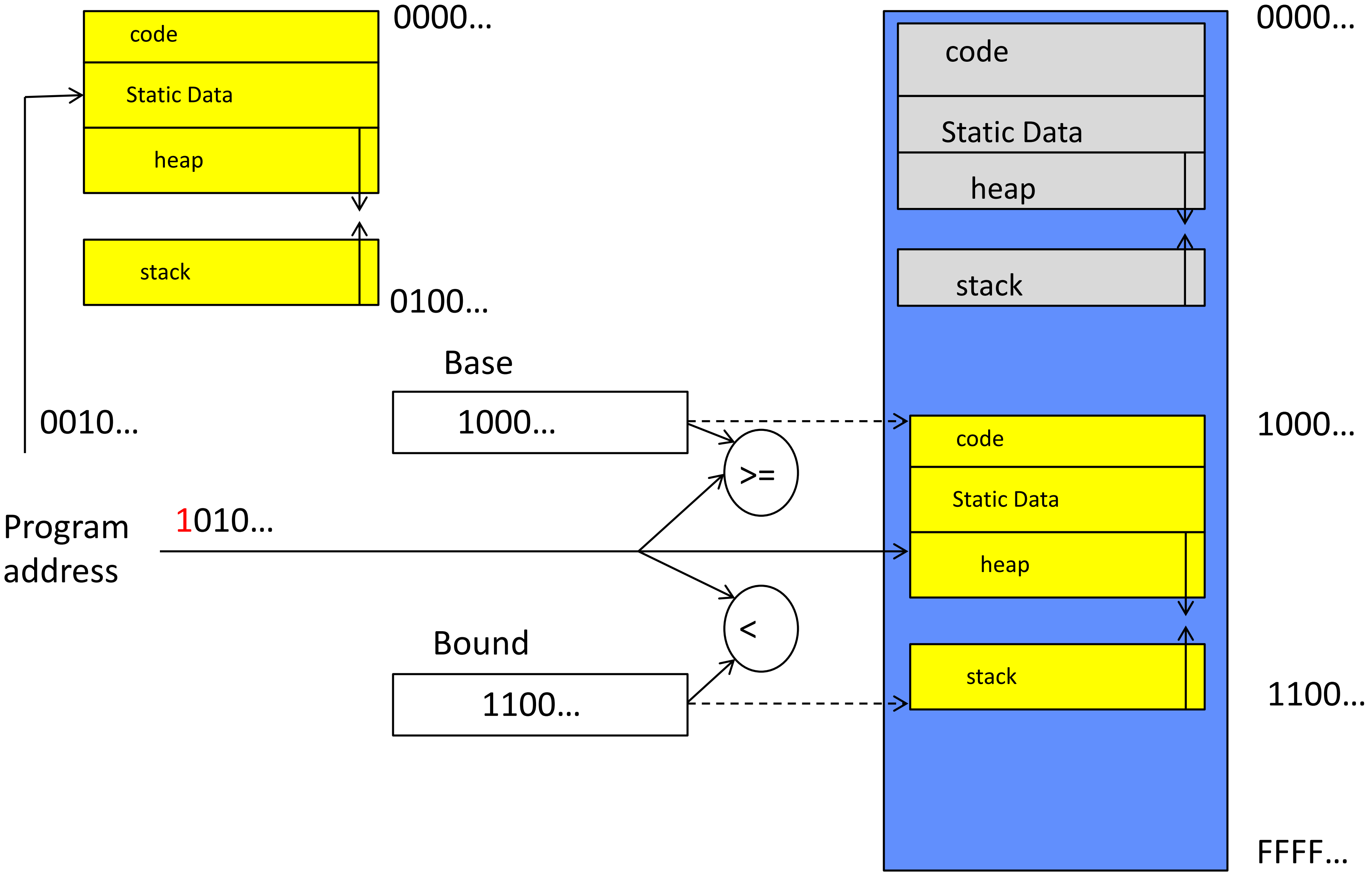


Simple Multiplexing has no Protection!

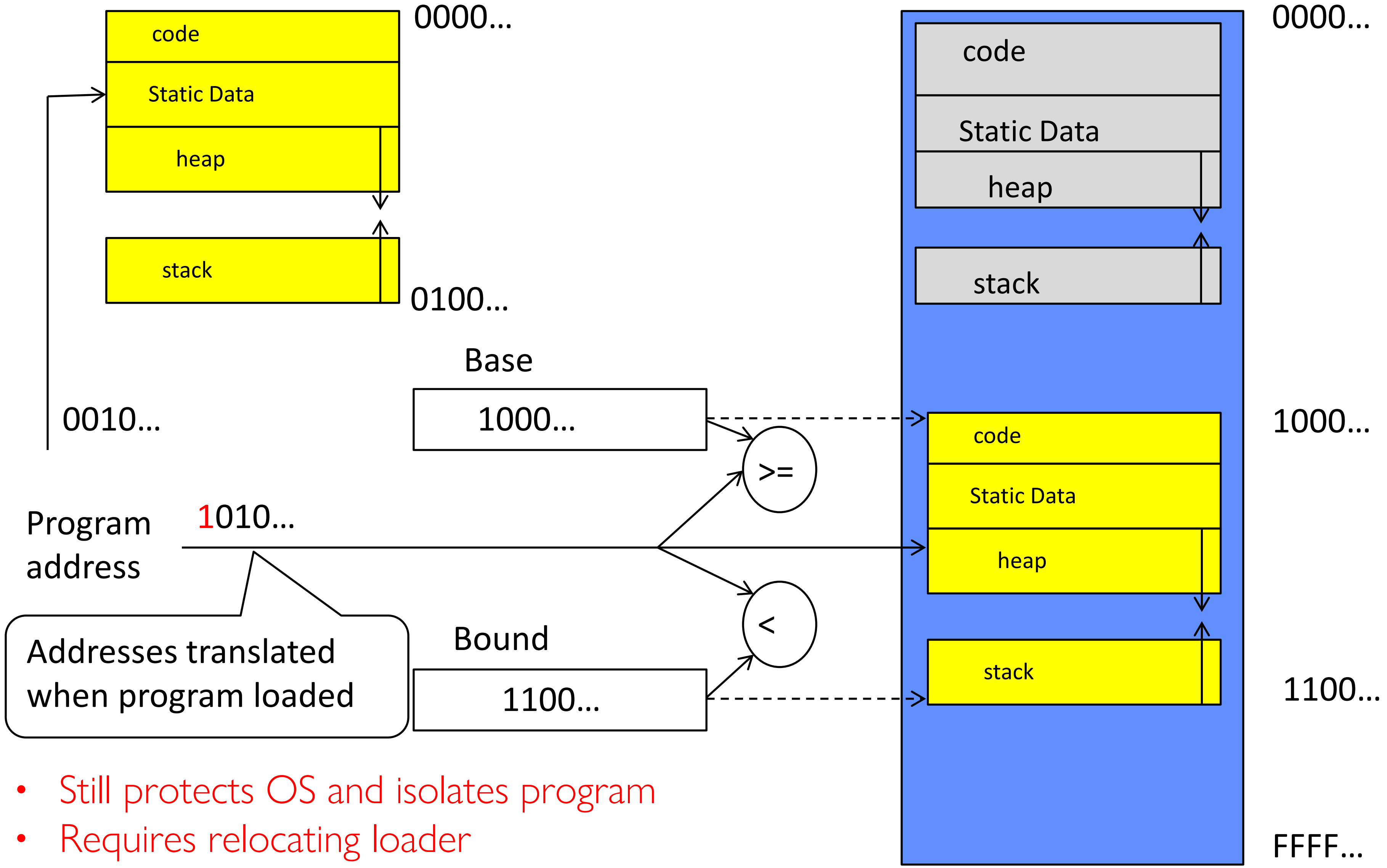
- Operating System must protect itself from user programs
  - Reliability: compromising the operating system generally causes it to crash
  - Security: limit the scope of what threads can do
  - Privacy: limit each thread to the data it is permitted to access
  - Fairness: each thread should be limited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

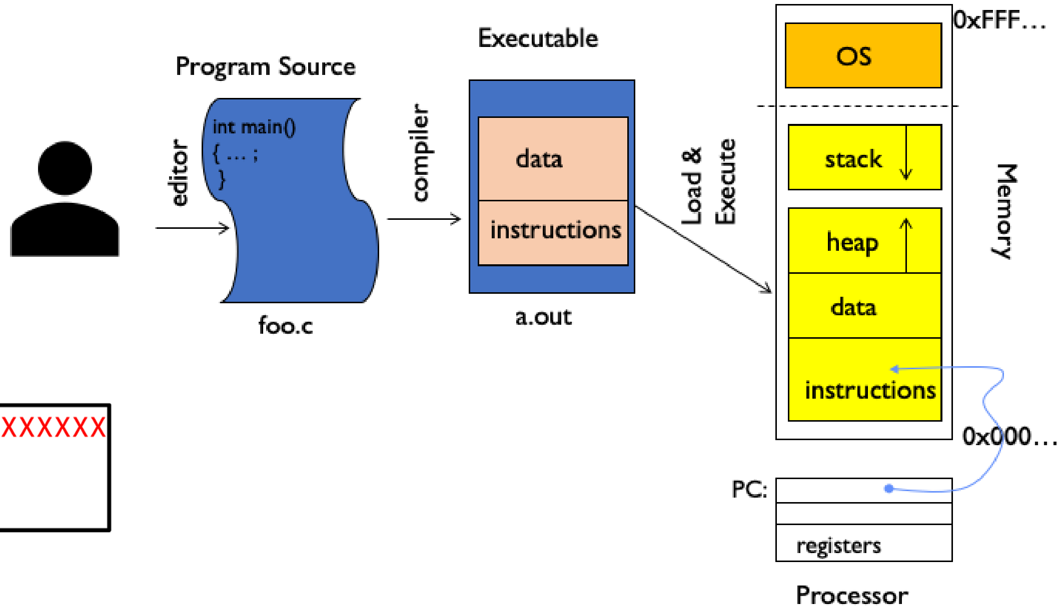


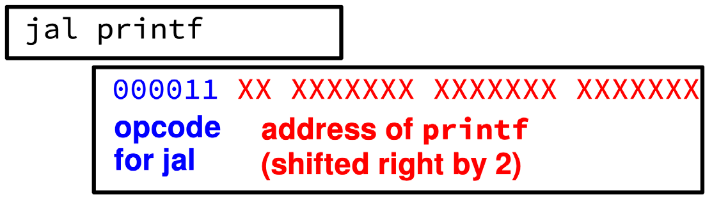
Simple Protection: Base and Bound (B&B)



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

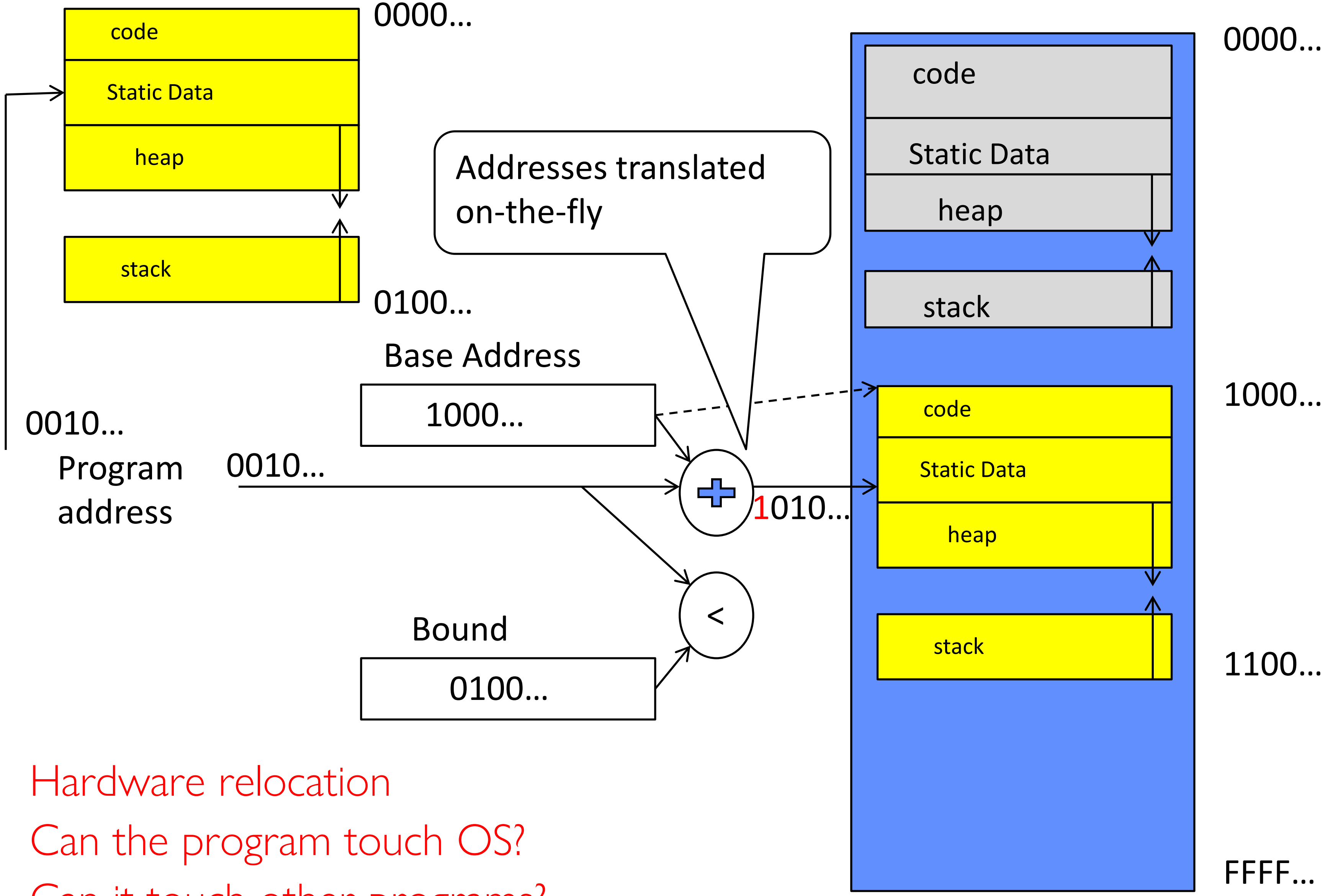
61C Review: Relocation





- 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.

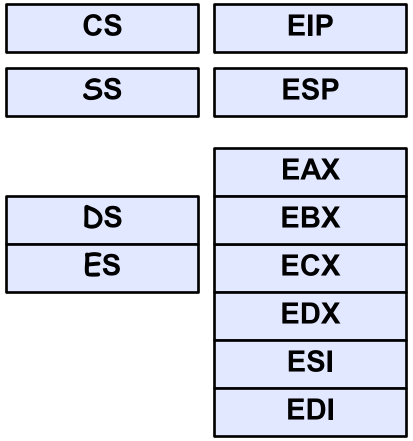
Simple address translation with Base and Bound

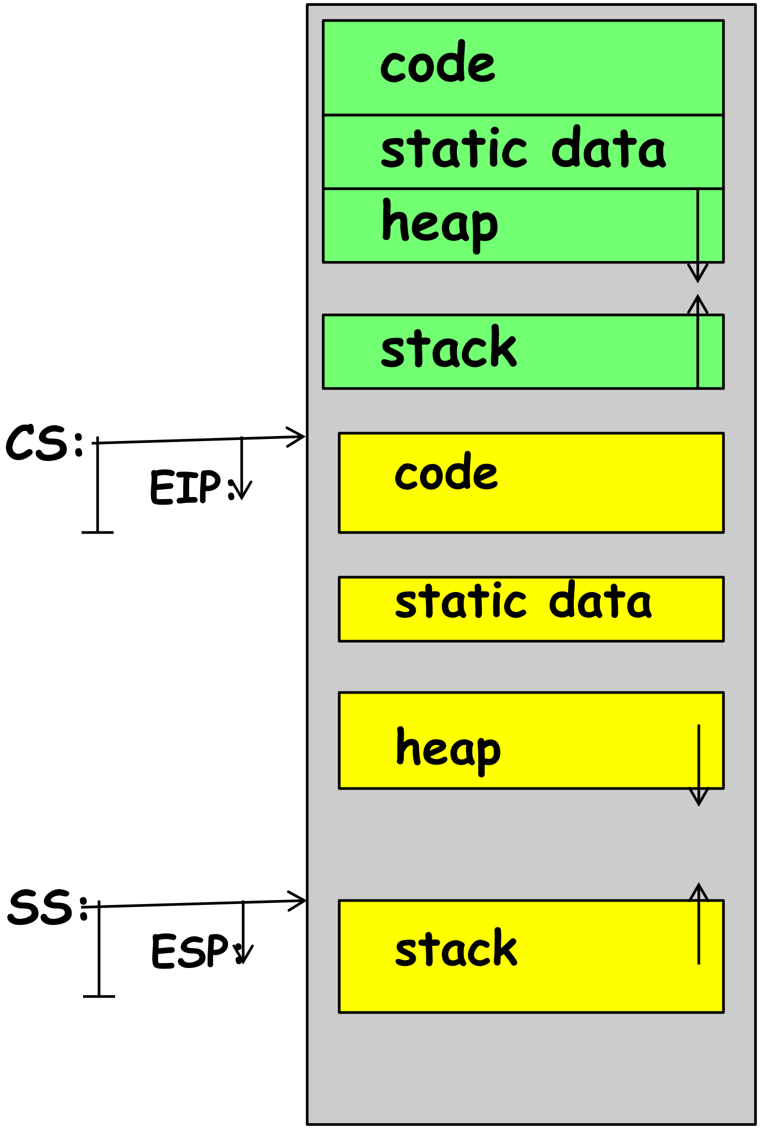


- Hardware relocation
- Can the program touch OS?
- Can it touch other programs?

x86 – segments and stacks

Processor Registers

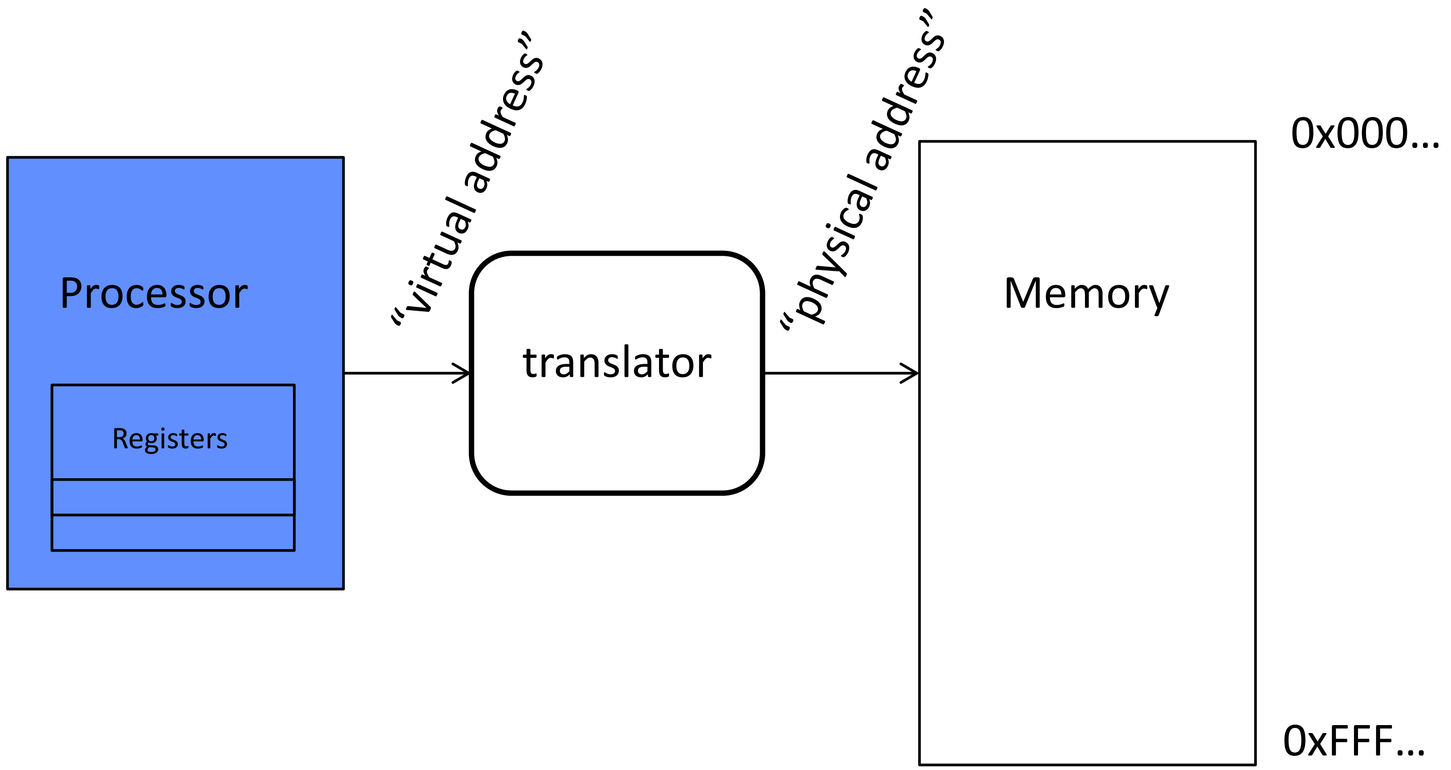




Start address, length and access rights associated with each segment register

Another idea: Address Space Translation

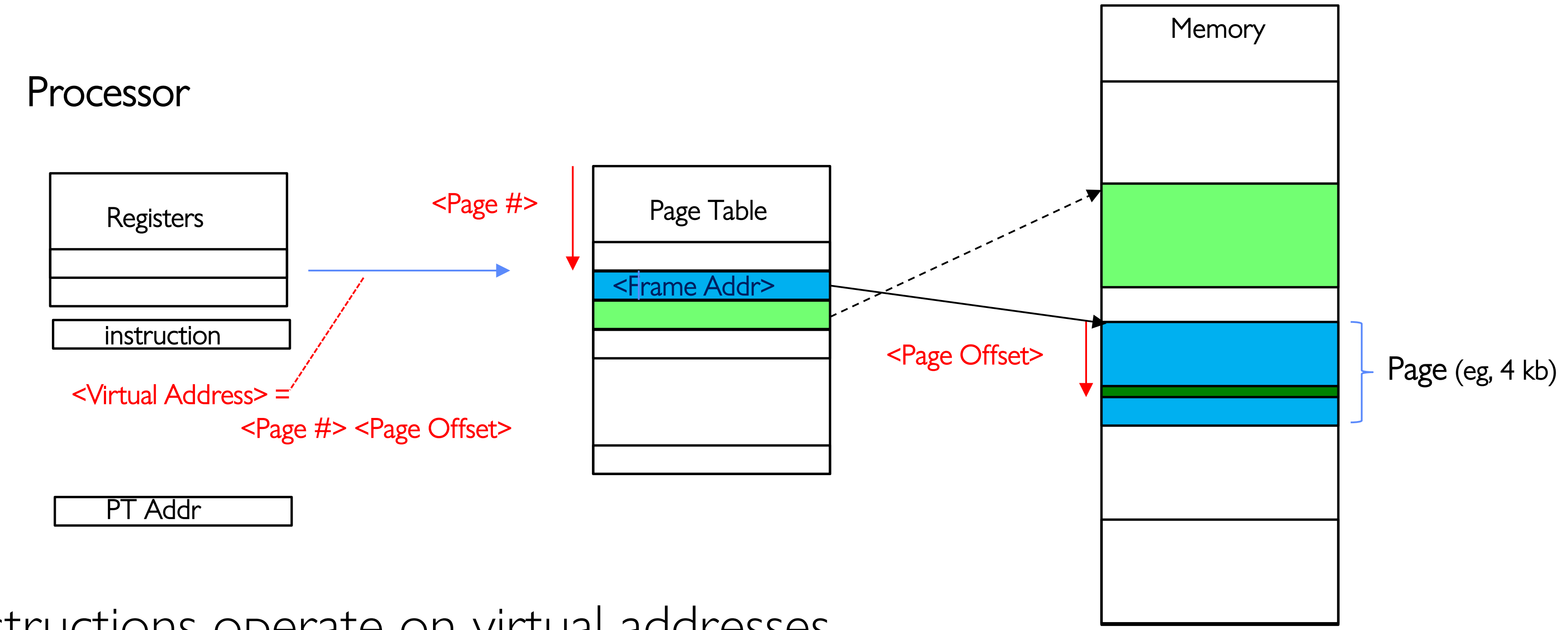
- Program operates in an address space that is distinct from the physical memory space of the machine



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 …

Paged Virtual Address

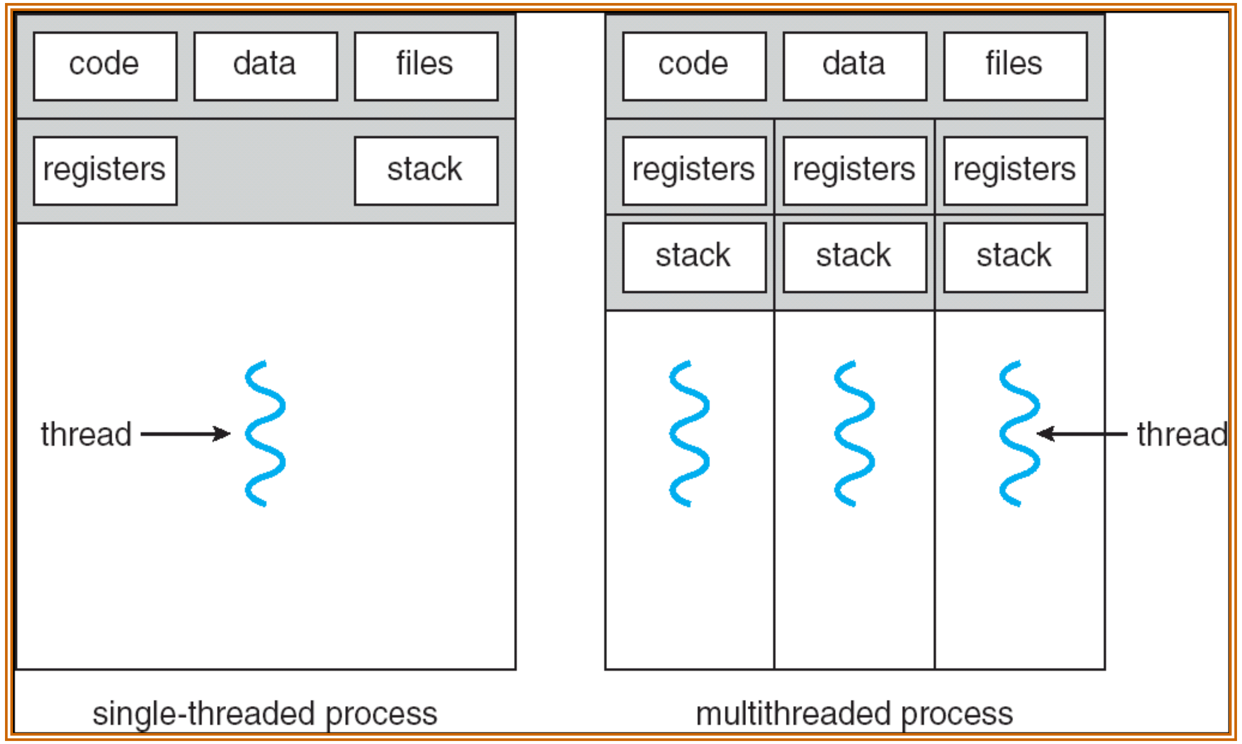


- Instructions operate on virtual addresses
  - Instruction address, load/store data address
- Translated to a physical address through a Page Table by the hardware
- Any Page of address space can be in any (page sized) frame in memory
  - Or not-present (access generates a page fault)
- Special register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

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



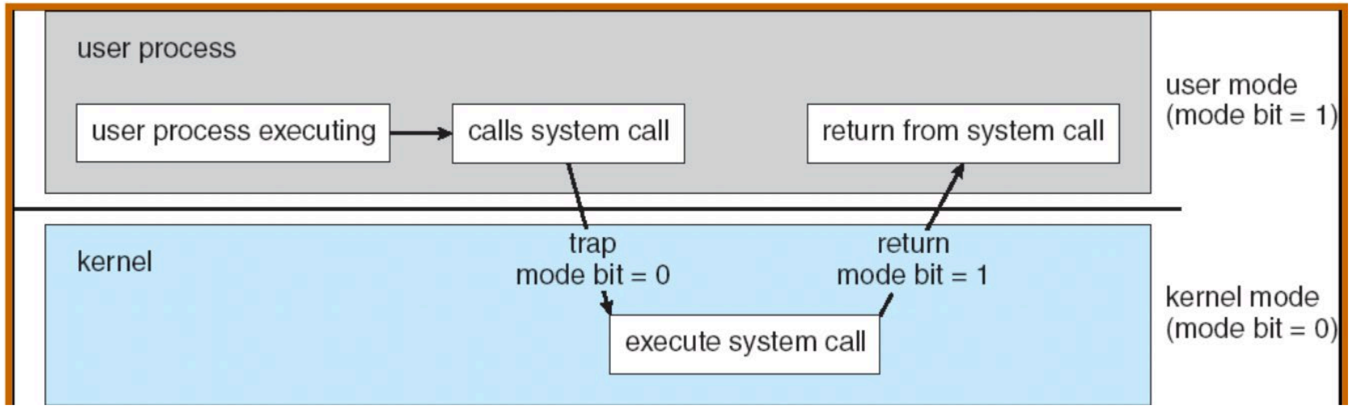
- Threads encapsulate concurrency:
  - "Active" component
- Address spaces encapsulate protection:
  - "Passive" component
  - Keeps buggy programs from crashing the system
- Why have multiple threads per address space?
  - Parallelism: take advantage of actual hardware parallelism (e.g. multicore)
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

Protection and Isolation

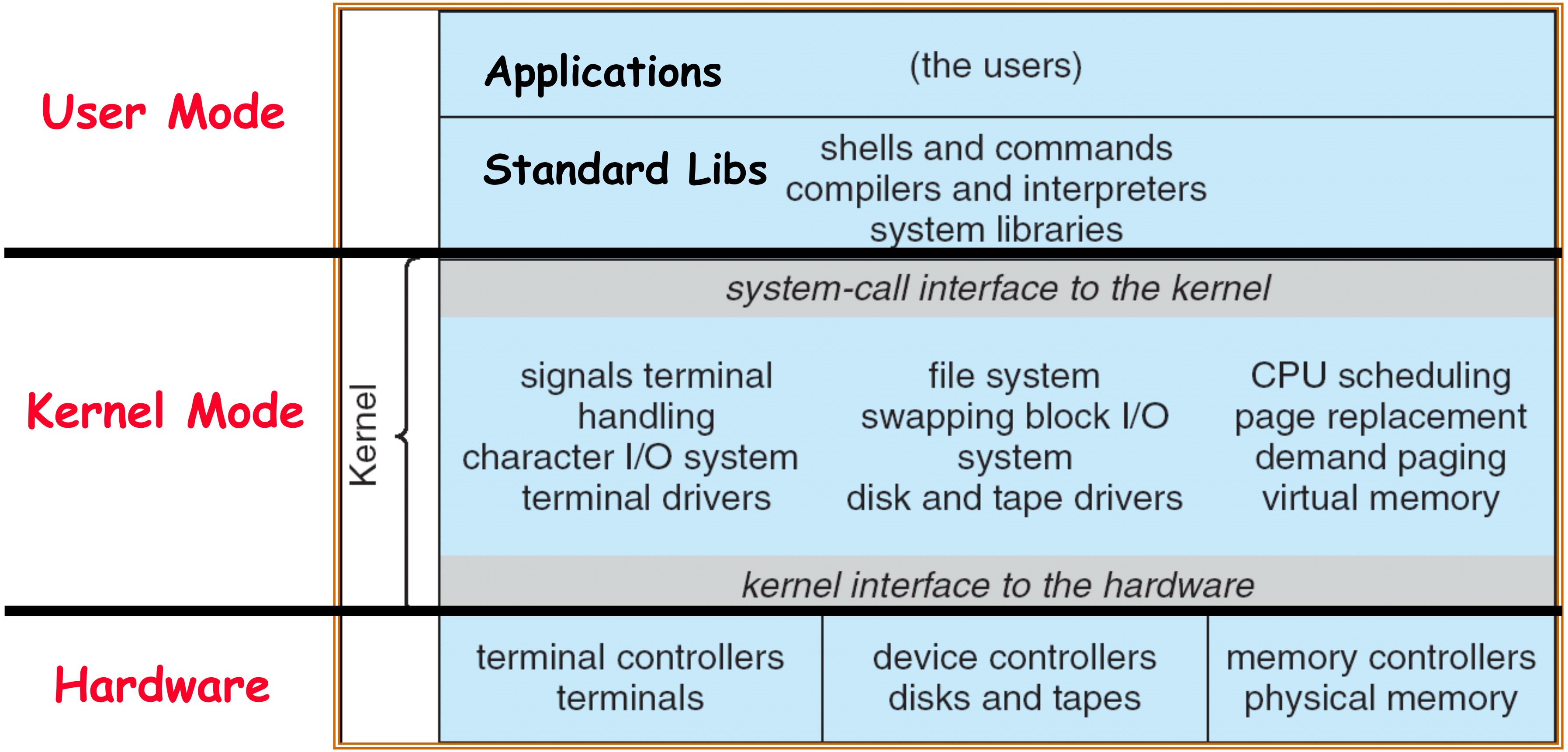
- Why Do We Need Processes??
  - Reliability: bugs can only overwrite memory of process they are in
  - Security and privacy: malicious or compromised process can't read or write other process' data
  - (to some degree) Fairness: enforce shares of disk, CPU
- Mechanisms:
  - Address translation: address 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

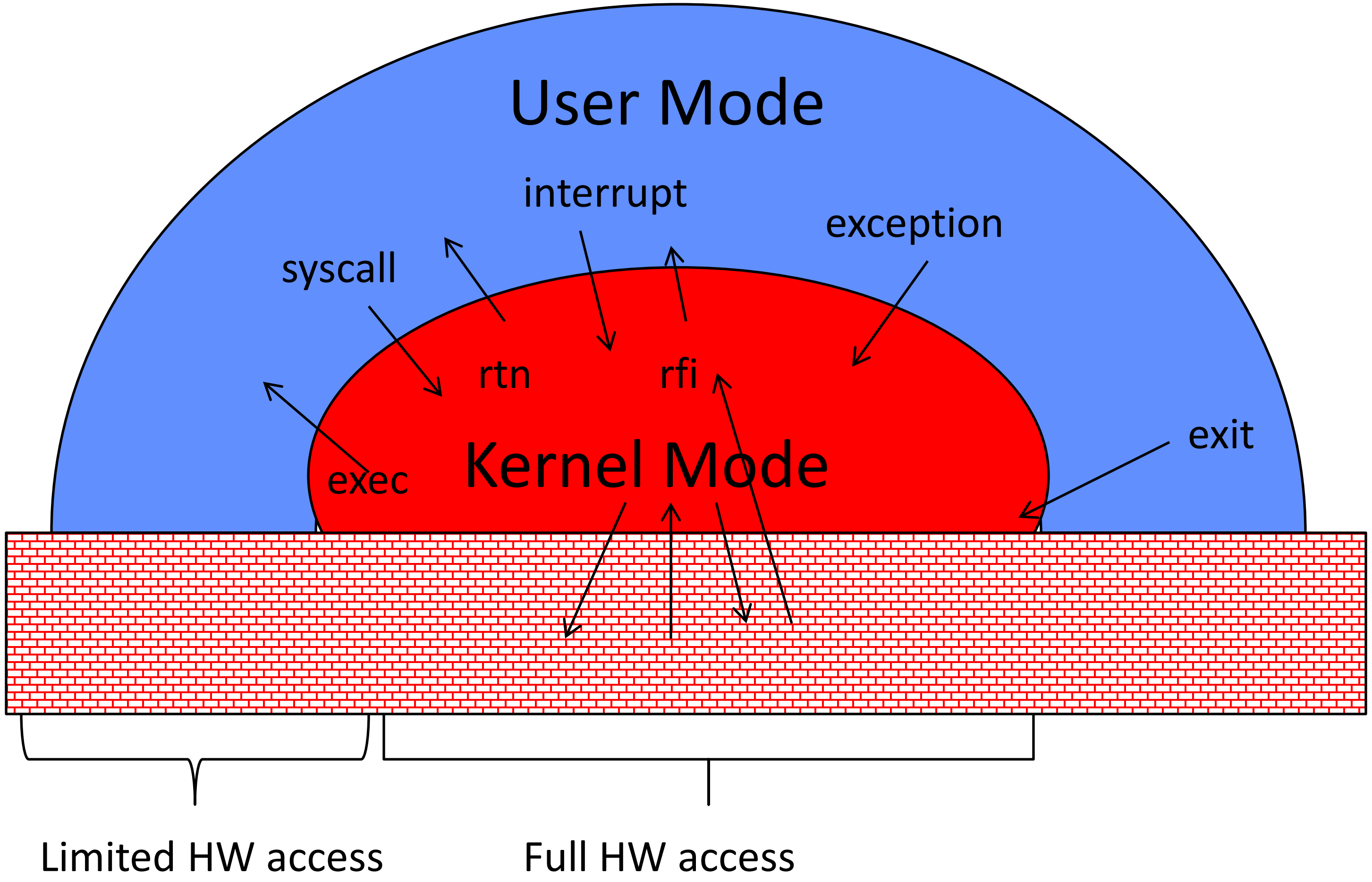
- Hardware provides at least two modes (at least 1 mode bit):
  1. Kernel Mode (or "supervisor" mode)
  2. User Mode
- Certain operations are prohibited when running in user mode
  - Changing the page table pointer, disabling interrupts, interacting directly w/ hardware, writing to kernel memory
- Carefully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



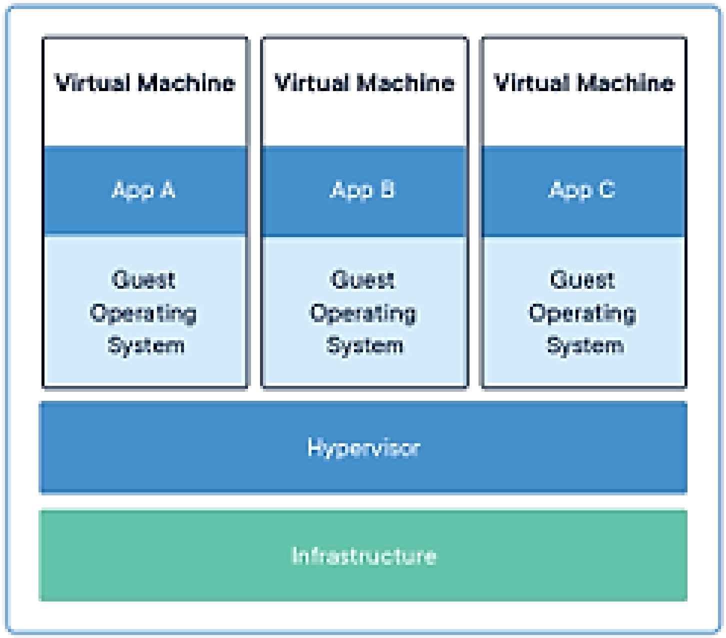
For example: UNIX System Structure

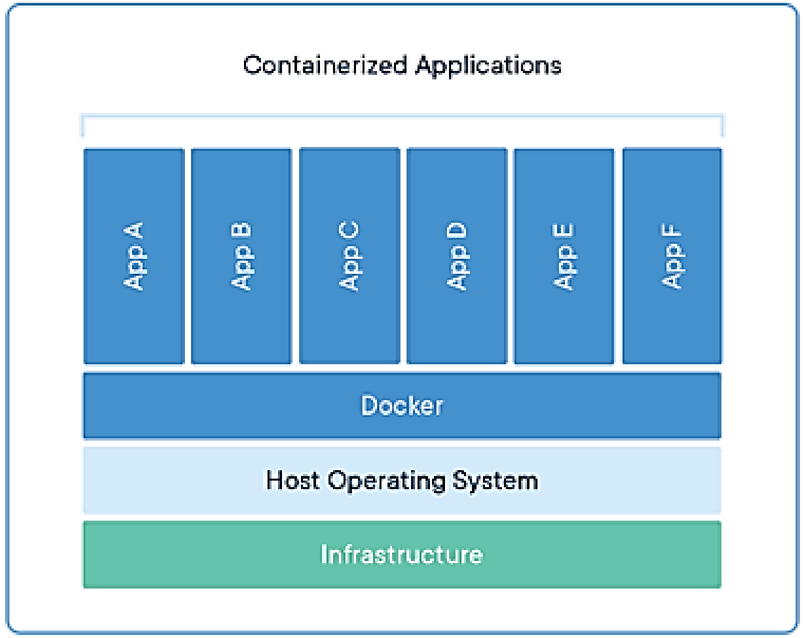


User/Kernel (Privileged) Mode



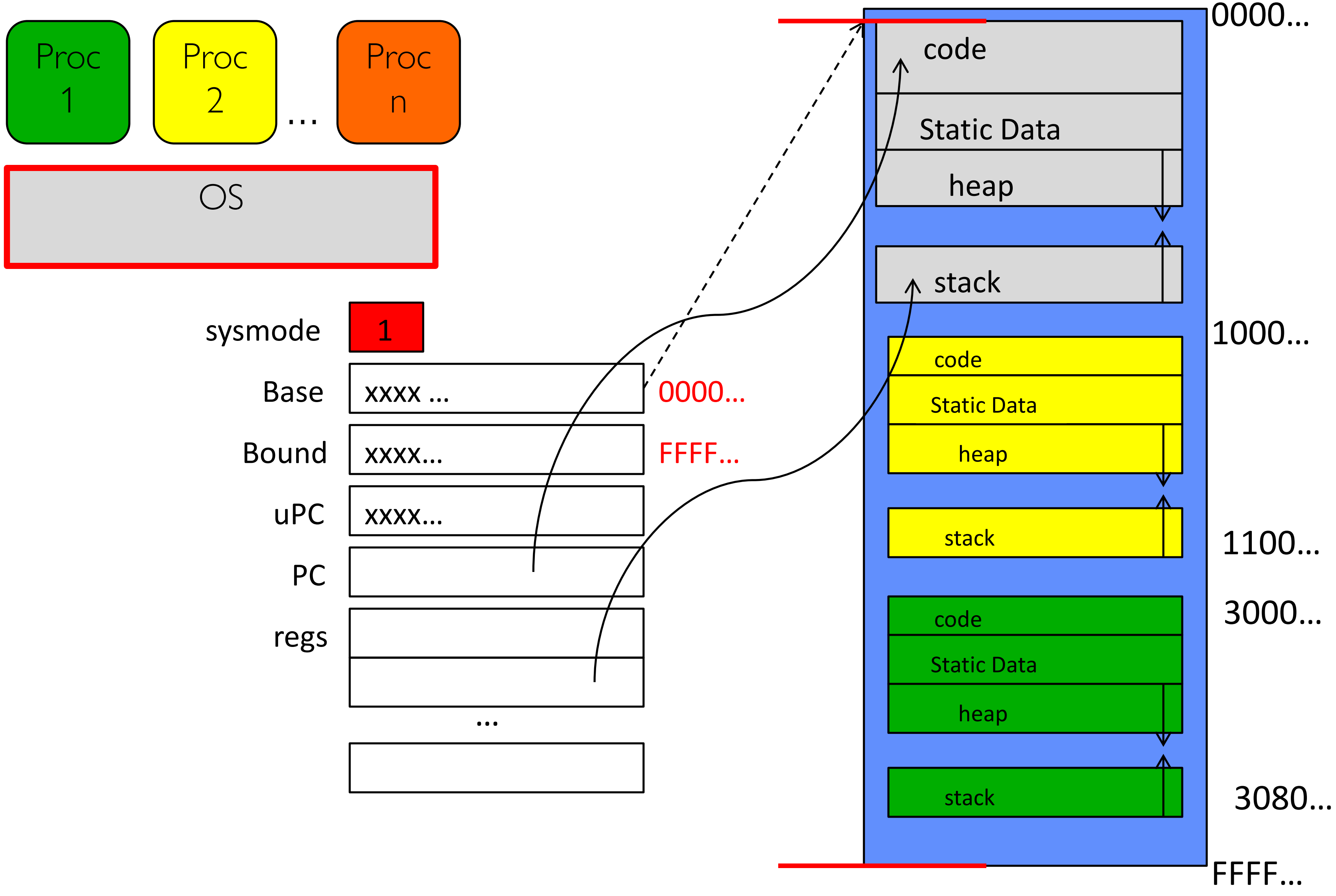
Additional Layers of Protection for Modern Systems



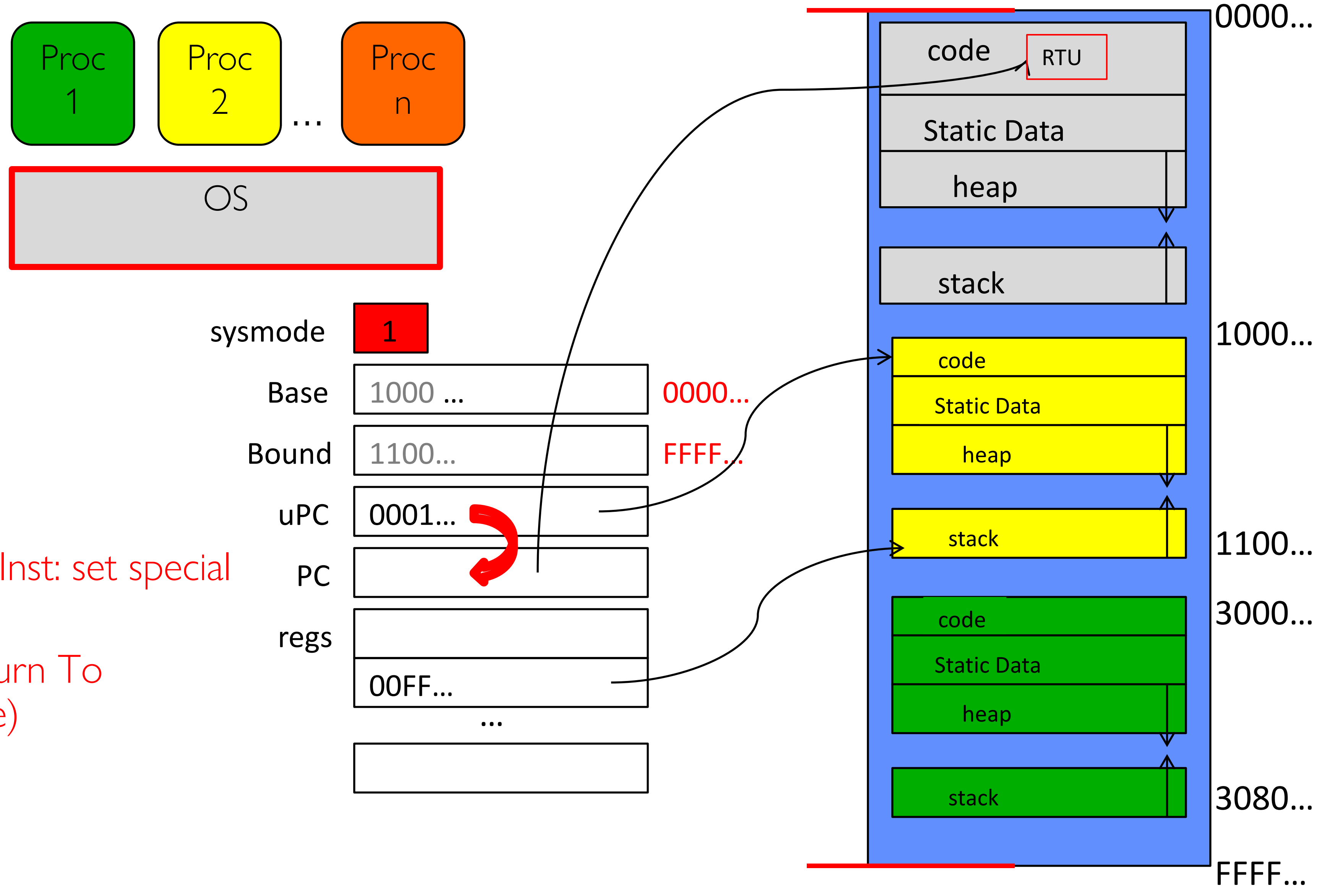


- Additional layers of protection through virtual machines or containers
  – Run a complete operating system in a virtual machine
  – Package all the libraries associated with an app into a container for execution
- More on these ideas later in the class

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

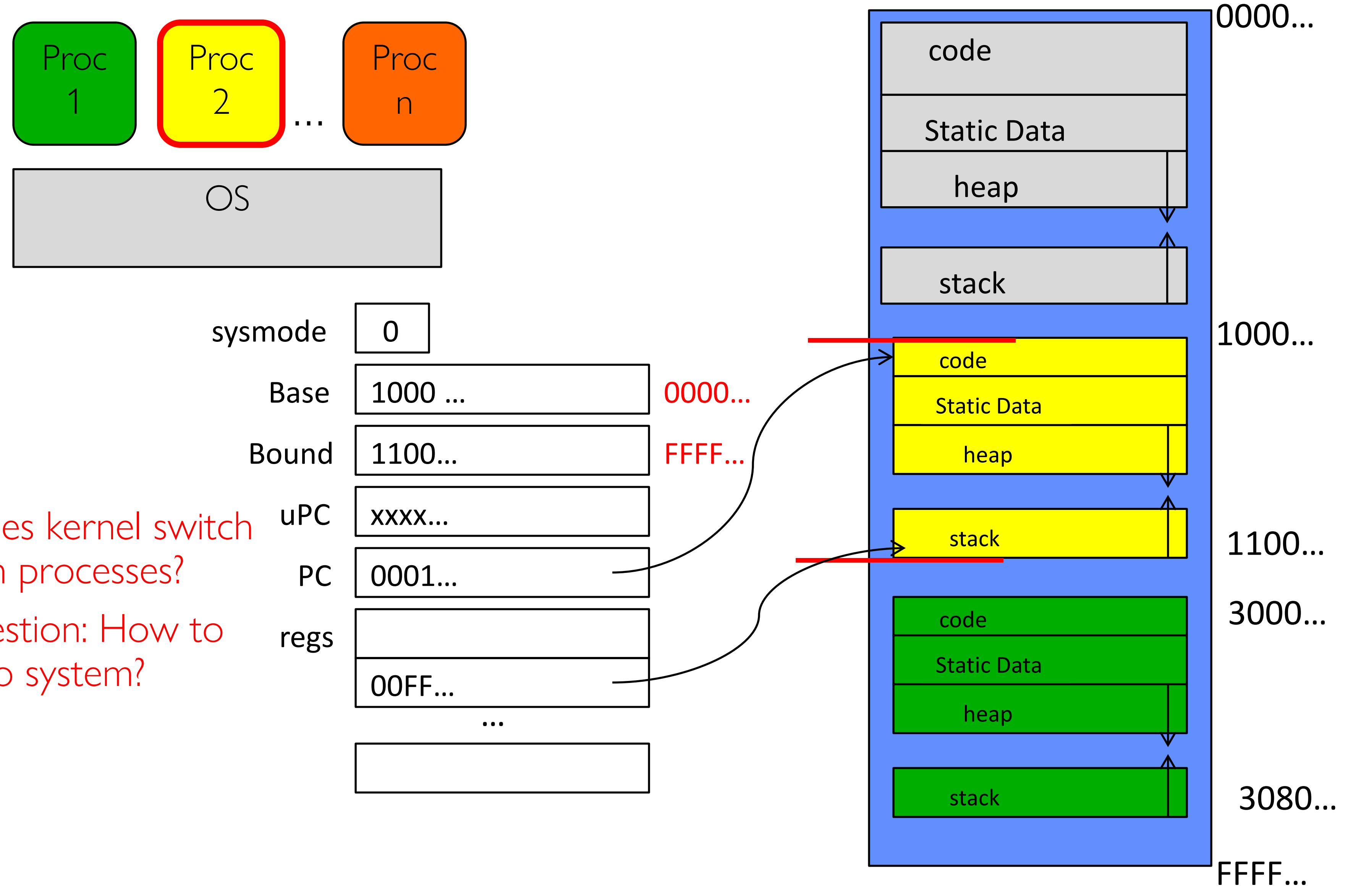


Simple B&B: OS gets ready to execute process



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

Simple B&B: User Code Running



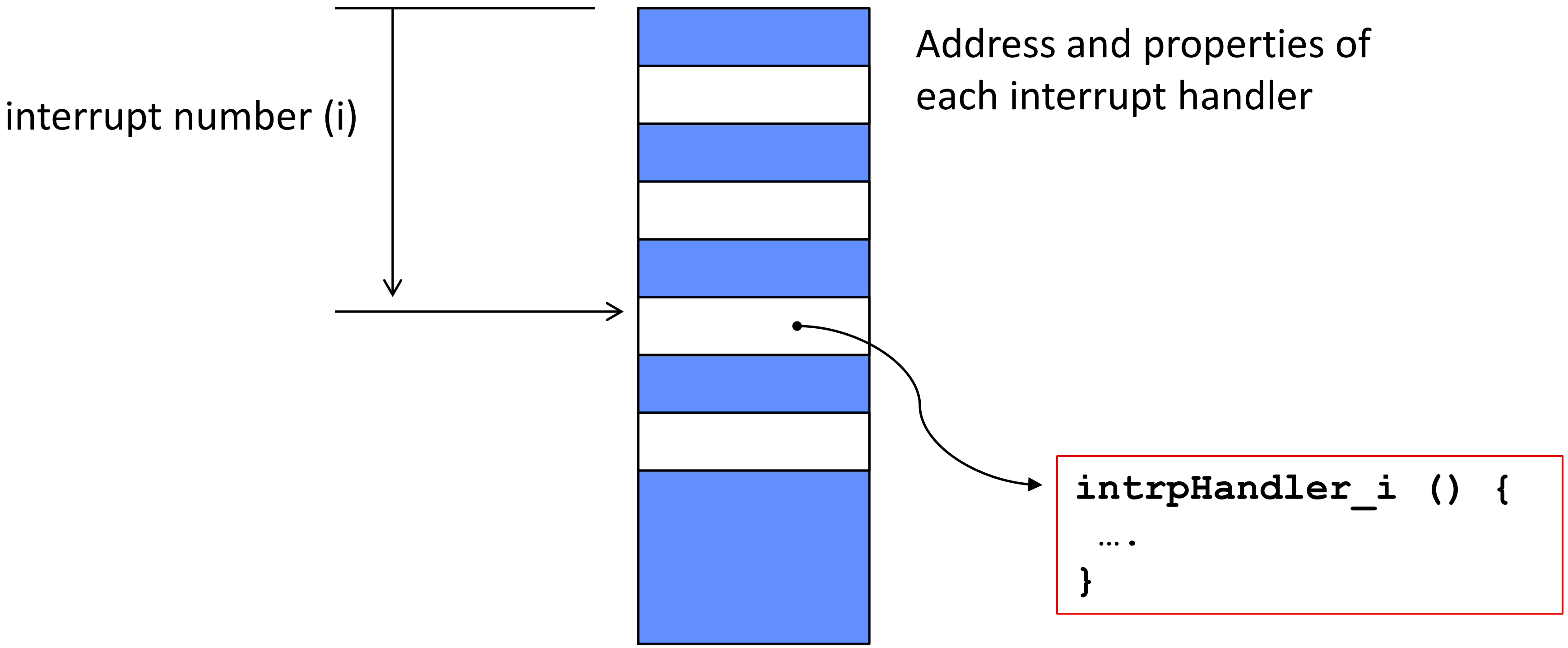
- How does kernel switch between processes?
- First question: How to return to system?

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?

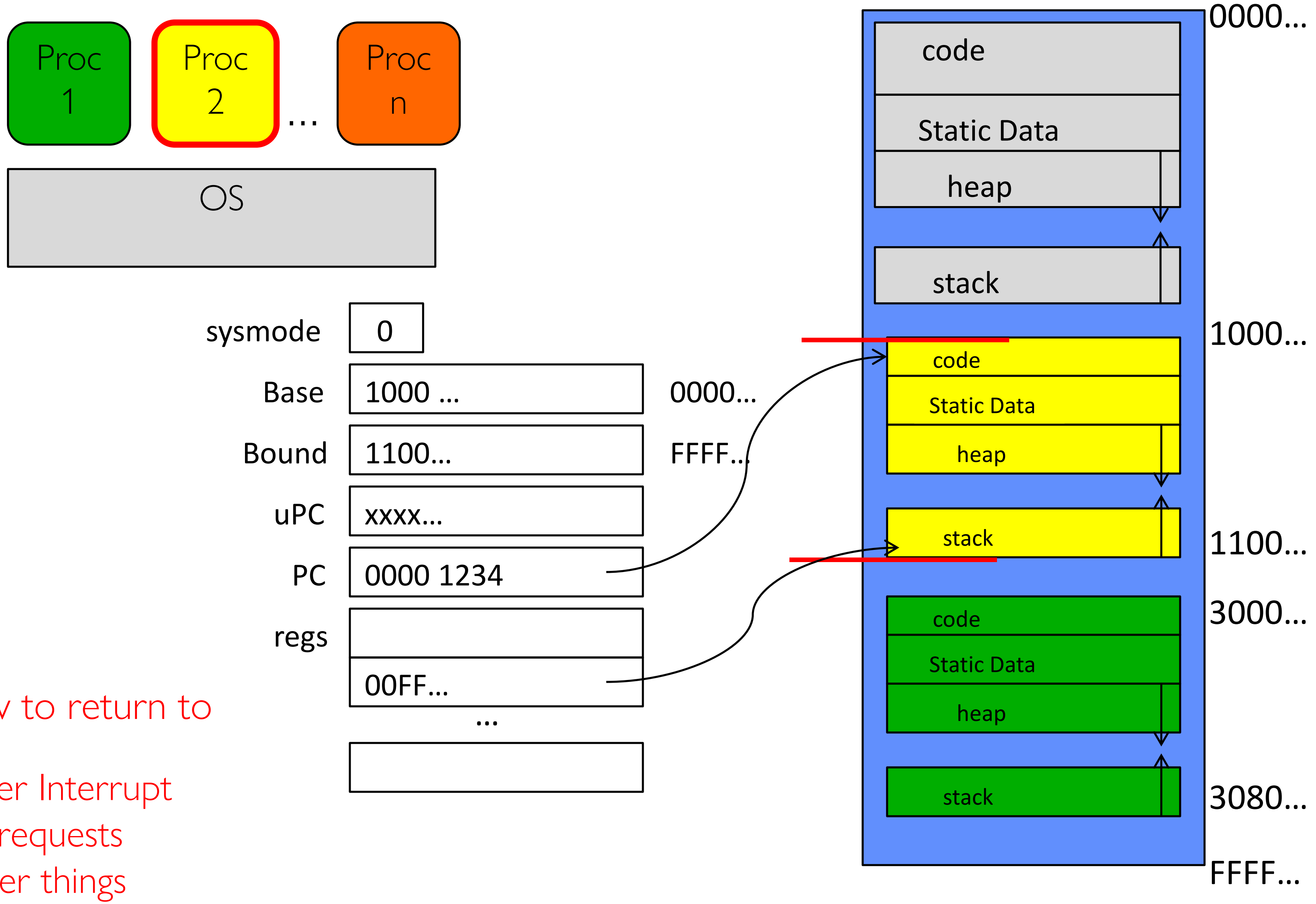
How do we get the system target address of the "unprogrammed control transfer?"

Interrupt Vector



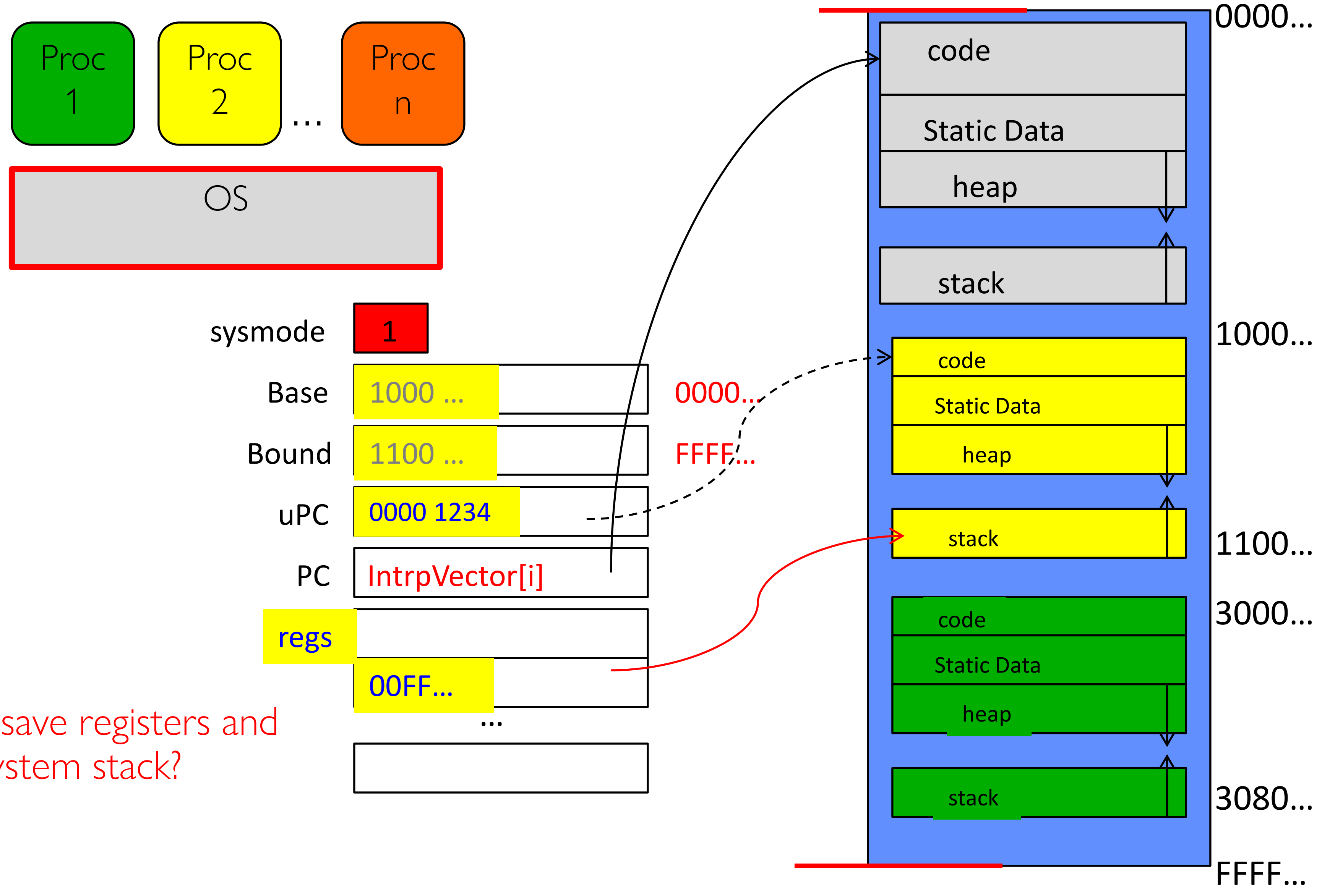
- Where else do you see this dispatch pattern?

Simple B&B: User => Kernel



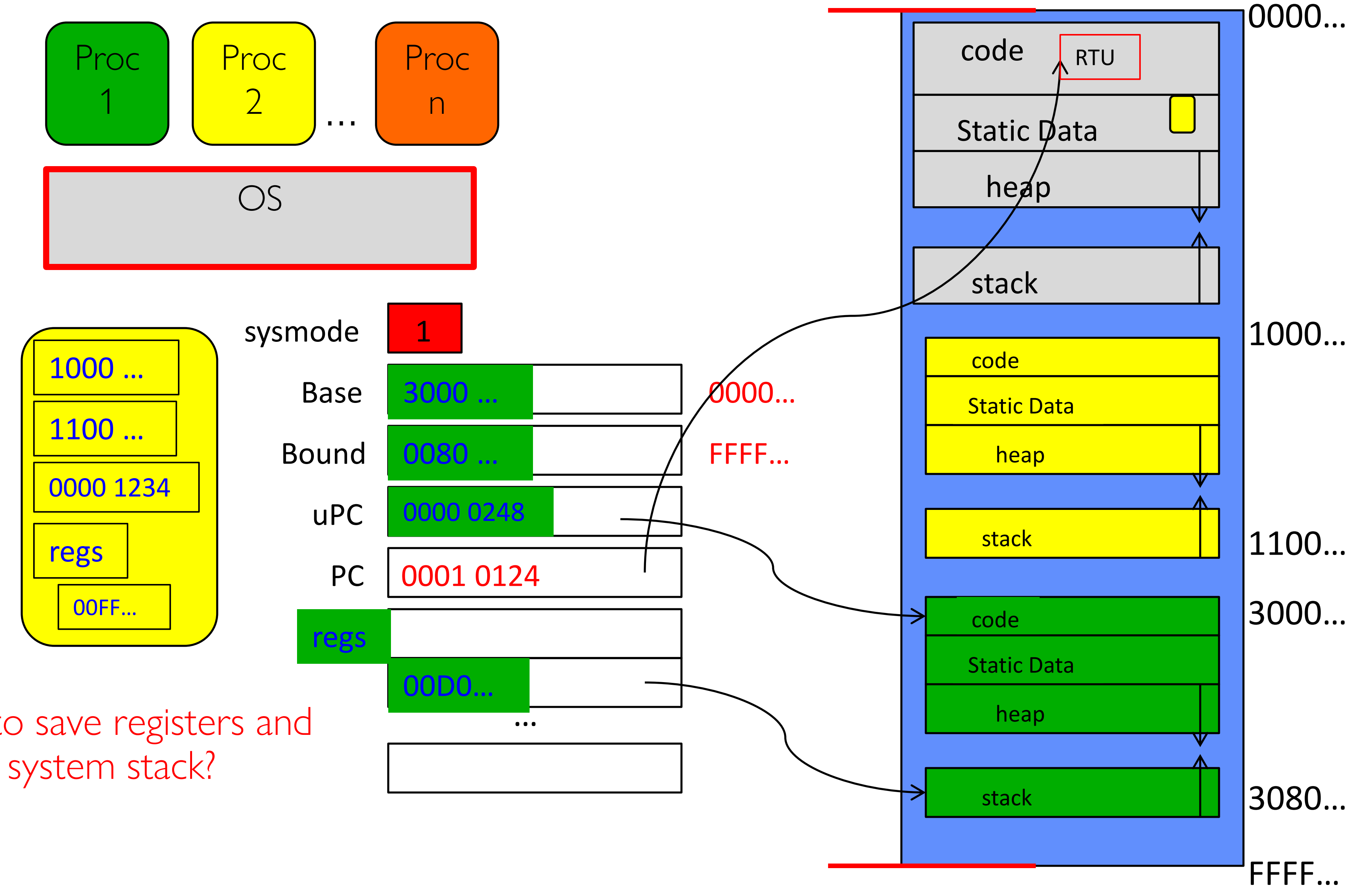
- So: How to return to system?
  - Timer Interrupt
  - I/O requests
  - Other things

Simple B&B: Interrupt



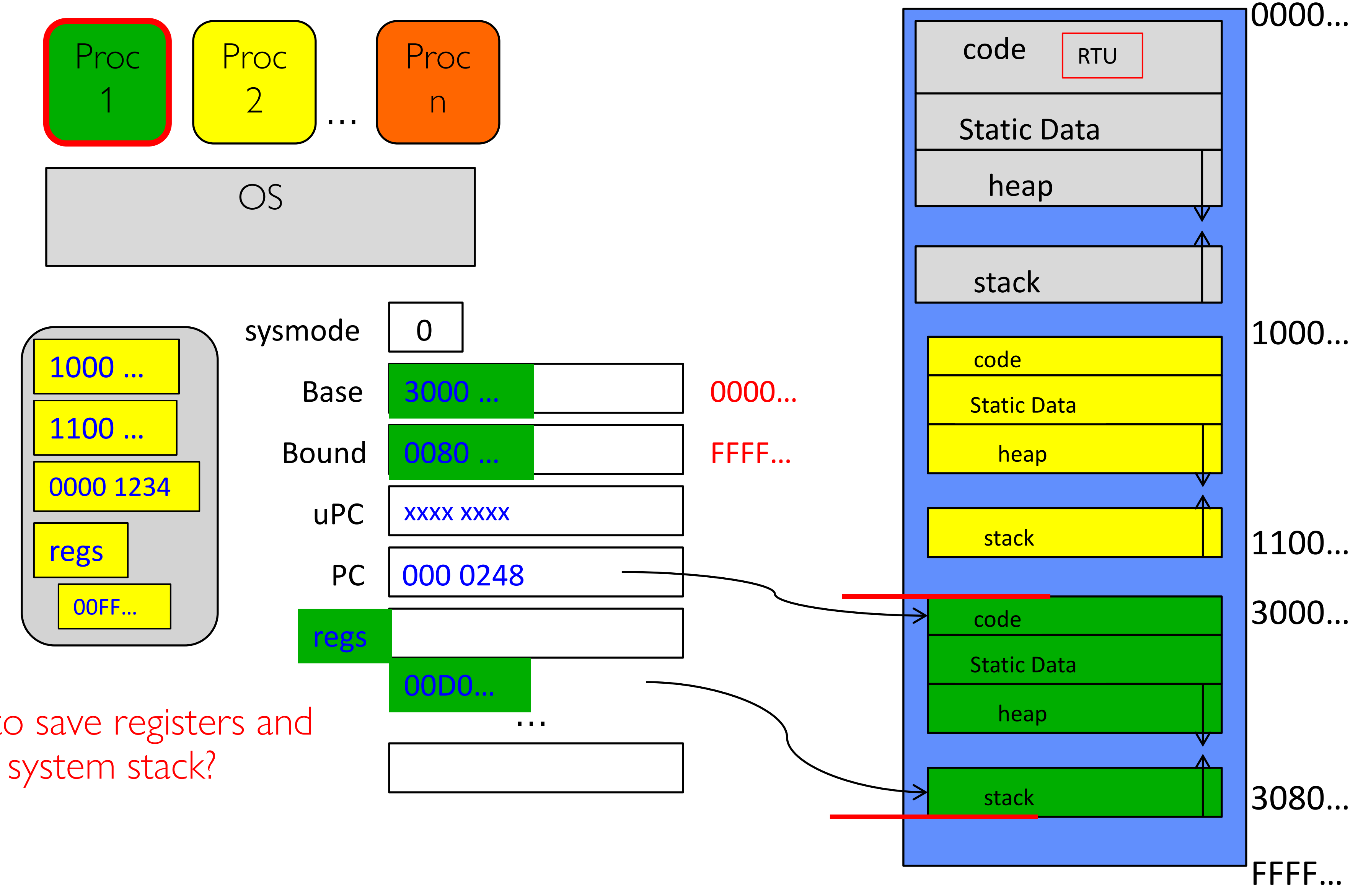
- How to save registers and set up system stack?

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