# SE350: Operating Systems

Lecture 2: OS Concepts

# Outline

- Brief history of OS's
- Four fundamental OS concepts
  - Thread
  - Address space
  - Process
  - Dual-mode operation/protection

# Very Brief History of OS

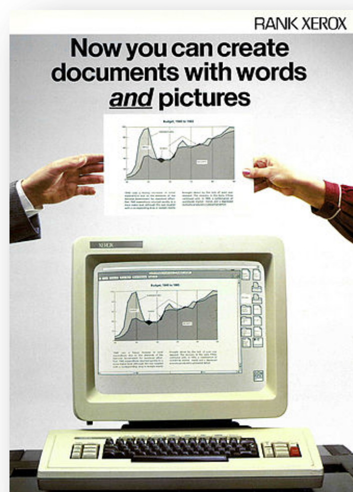
- Several distinct phases:
  - Hardware expensive, humans cheap
    - Eniac, … Multics

"I think there is a world market for maybe five computers." – *Thomas Watson, chairman of IBM, 1943*

*Thomas Watson was often called "the worlds greatest salesman" by the time of his death in 1956*

# Very Brief History of OS

- Several distinct phases:
  - Hardware expensive, humans cheap
    - Eniac, … Multics
  - Hardware cheaper, humans expensive
    - PCs, workstations, rise of GUIs
  - Hardware very cheap, humans very expensive
    - Ubiquitous devices, widespread networking




# Very Brief History of OS

- Several distinct phases:
  - Hardware expensive, humans cheap
    - Eniac, … Multics
  - Hardware cheaper, humans expensive
    - PCs, workstations, rise of GUIs
  - Hardware very cheap, humans very expensive
    - Ubiquitous devices, widespread networking
- Rapid change in hardware leads to changing OS
  - Batch ⇒ multiprogramming ⇒ timesharing ⇒ GUI ⇒ ubiquitous devices
  - Gradual migration of features into smaller machines
- Today
  - Small OS: 100K lines / Large: 20M lines (10M browser!)
  - 100-1000 people-years

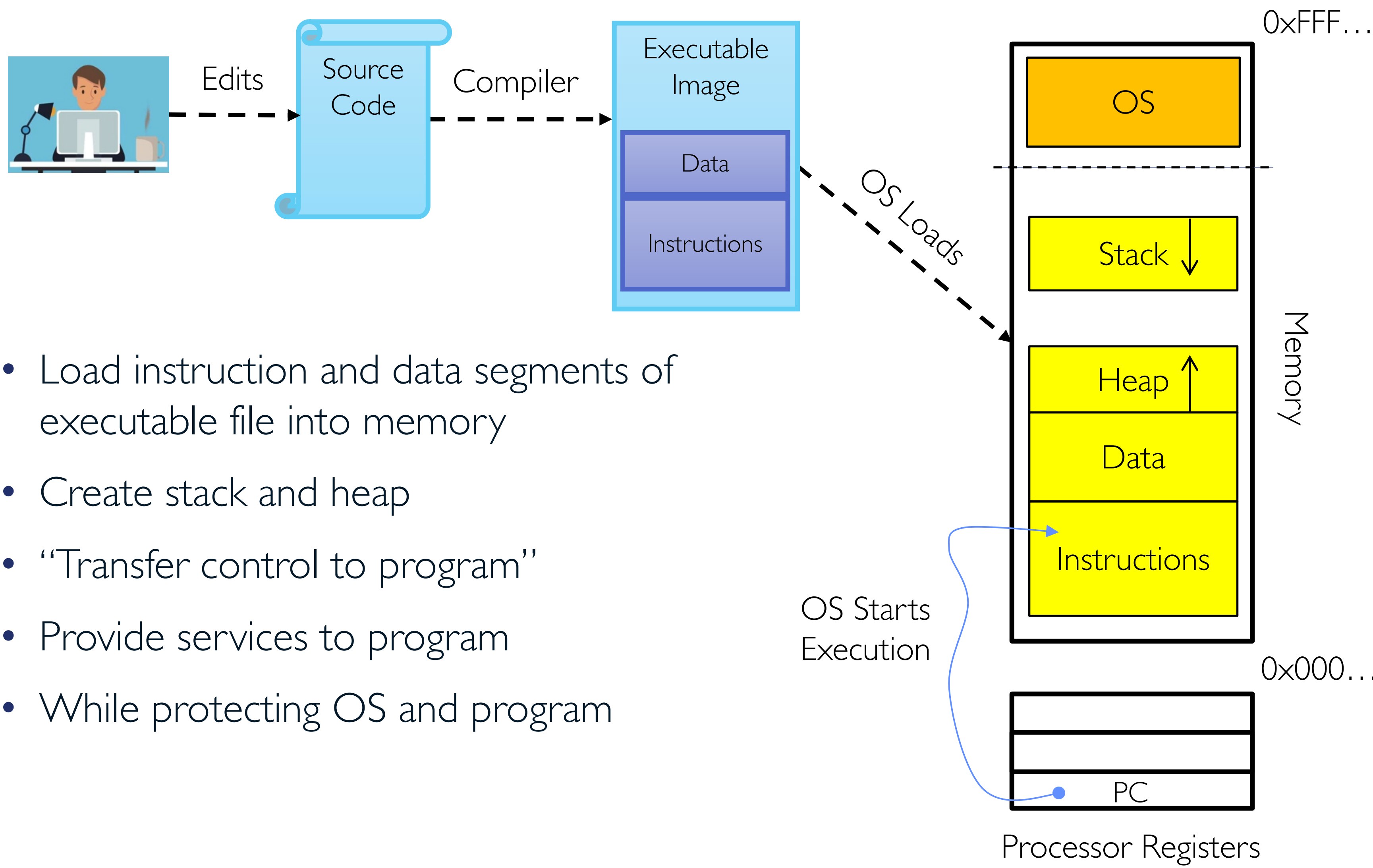
# OS Archaeology

- Due to high cost of building OS from scratch, most modern OS's have long lineage
- Multics $\Rightarrow$ AT&T Unix $\Rightarrow$ BSD Unix $\Rightarrow$ Ultrix, SunOS, NetBSD,…
- Mach (micro-kernel) + BSD $\Rightarrow$ NextStep $\Rightarrow$ XNU $\Rightarrow$ Apple OS X, iPhone iOS
- MINIX $\Rightarrow$ Linux $\Rightarrow$ Android, Chrome OS, RedHat, Ubuntu, Fedora, Debian, Suse,…
- CP/M $\Rightarrow$ QDOS $\Rightarrow$ MS-DOS $\Rightarrow$ Windows 3.1 $\Rightarrow$ NT $\Rightarrow$ 95 $\Rightarrow$ 98 $\Rightarrow$ 2000 $\Rightarrow$ XP $\Rightarrow$ Vista $\Rightarrow$ 7 $\Rightarrow$ 8 $\Rightarrow$ 10 $\Rightarrow$ …

# Today: Four Fundamental OS Concepts

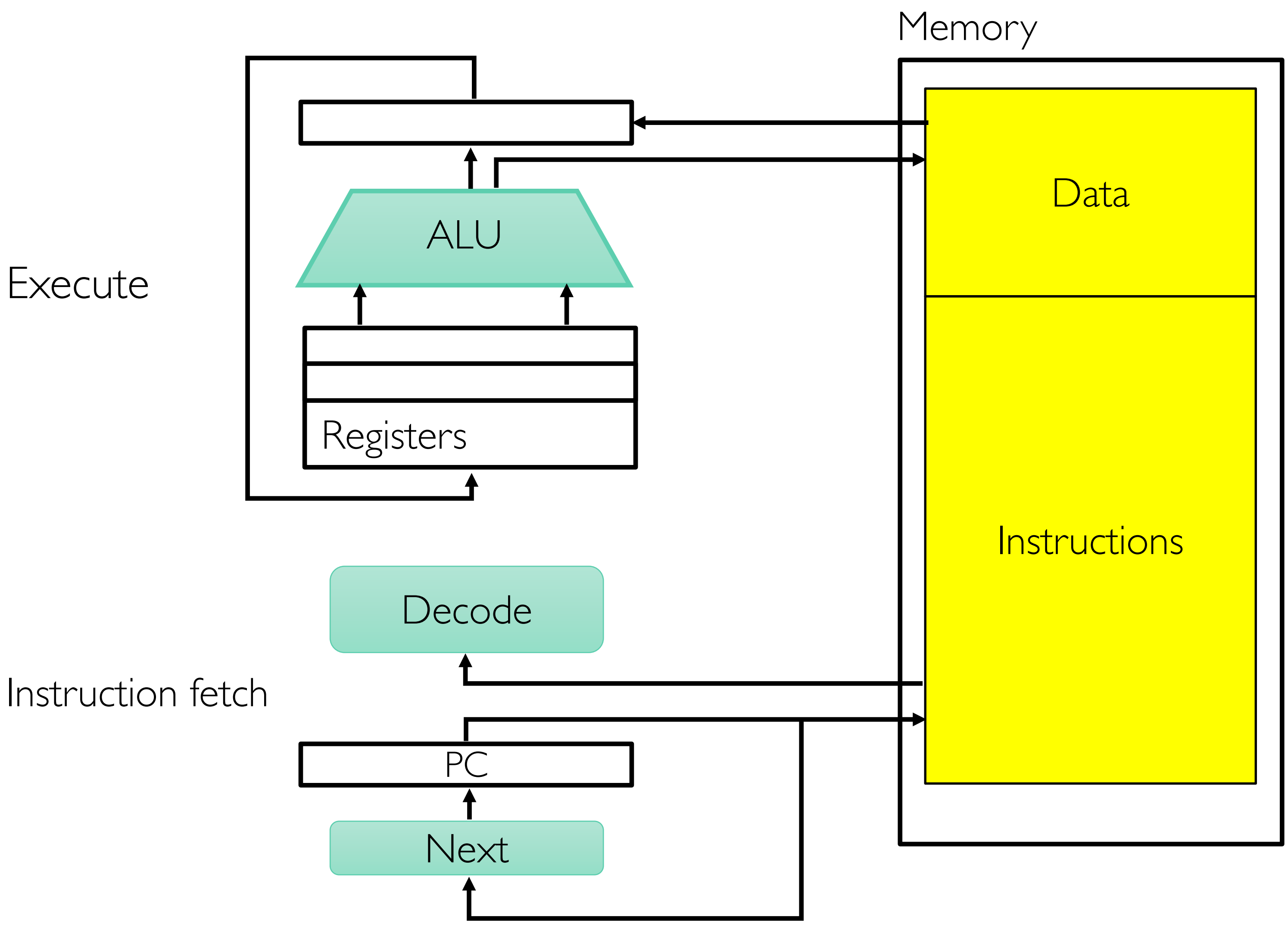
- Thread
  - Single unique execution context which fully describes program state
  - Program counter, registers, execution flags, stack
- Address space (with translation)
  - Address space which is distinct from machine's physical memory addresses
- Process
  - Instance of executing program consisting of address space and 1+ threads
- Dual-mode operation/protection
  - Only "system" can access certain resources
  - OS and hardware are protected from user programs
  - User programs are isolated from one another by controlling translation from program virtual addresses to machine physical addresses

# OS Bottom Line: Run Programs

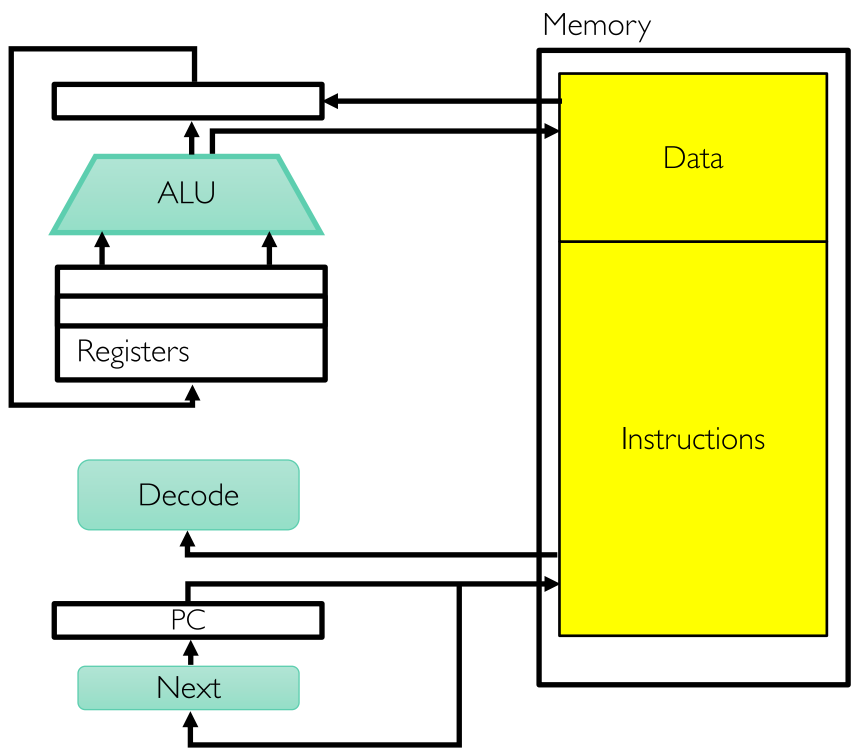



- Load instruction and data segments of executable file into memory
- Create stack and heap
- "Transfer control to program"
- Provide services to program
- While protecting OS and program

# Instruction Cycle: Fetch, Decode, Execute



# What Happens During Program Execution?




- Execution sequence:
  - Fetch instruction at PC
  - Decode
  - Execute (possibly using registers)
  - Write results to registers/memory
  - PC ← *Next*(PC)
  - Repeat

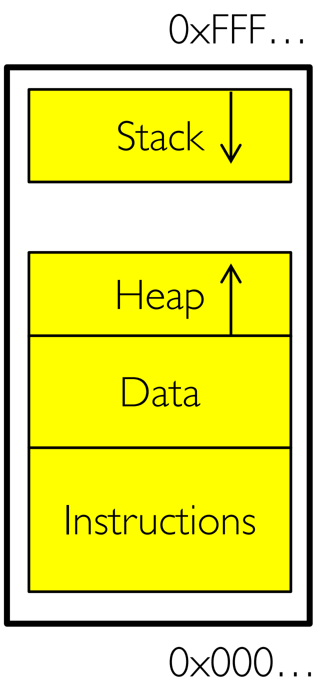
Next instruction or jump to new address …

# Thread (1$^{st}$ OS Concept)

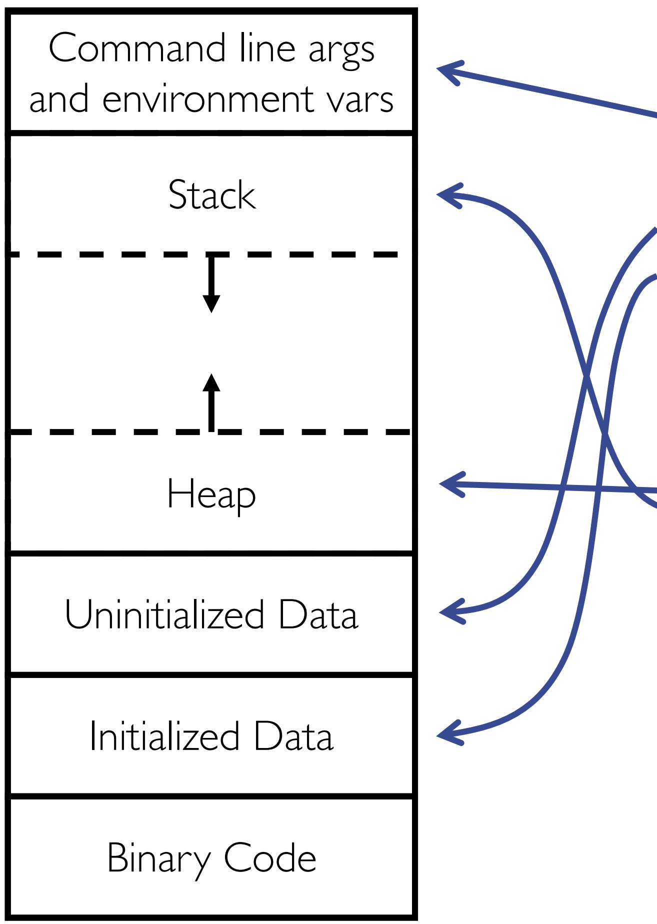
- Thread is single unique execution context
  - Program counter (PC), registers, execution flags, stack
- Thread is executing on processor when it resides in processor's registers
- Registers hold root state of thread (the rest is "in memory")
- Registers are defined by instruction set architecture (ISA) or by compiler
  - Stack pointer (SP) holds address of top of stack
    - Other conventions: frame pointer, heap pointer, data
  - PC register holds the address of executing instruction in the thread

# Address Space ($2^{nd}$ OS Concept)

- Address space is set of accessible addresses and state associated with them
  - For 32-bit processor: $2^{32}$ = ~4 billion addresses
- What happens when you read or write to address?
  - Perhaps nothing
  - Perhaps acts like regular memory
  - Perhaps ignores writes
  - Perhaps causes I/O operation
    - (Memory-mapped I/O)
  - Perhaps causes exception (fault)

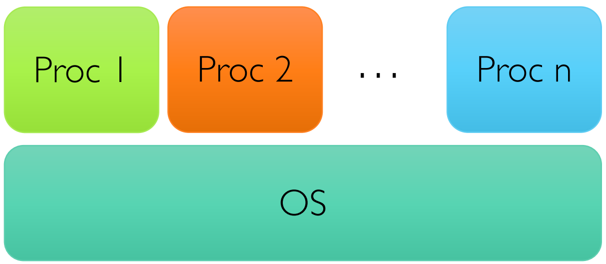


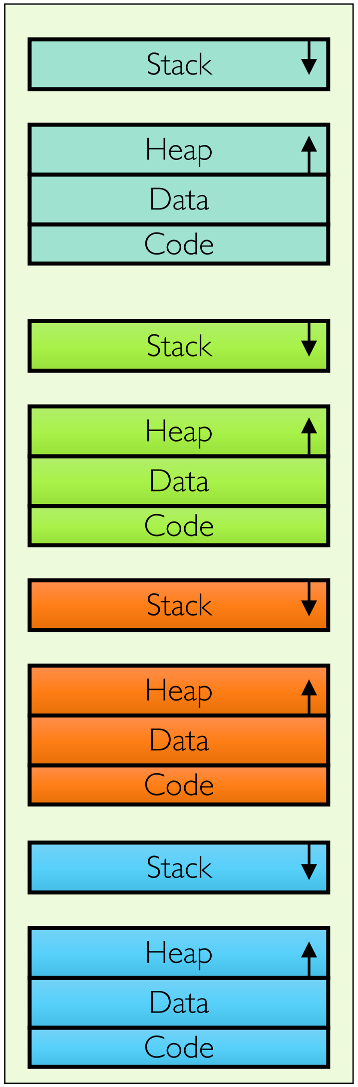
# Address Space Layout of C Programs



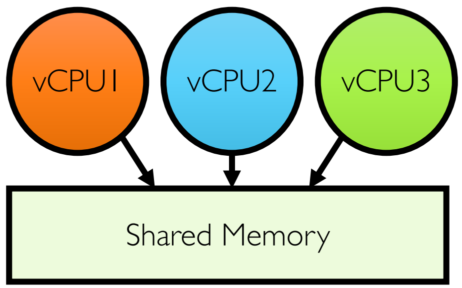

```c
#include <stdio.h>
#include <stdlib.h>

int x;
int y = 15;

int main(int argc, char *argv[]) {

    int *values;
    int I;

    values = (int *)malloc(sizeof(int)*5);

    for (i = 0; i < 5; i++)
        values[i] = i;

    return 0;
}
```

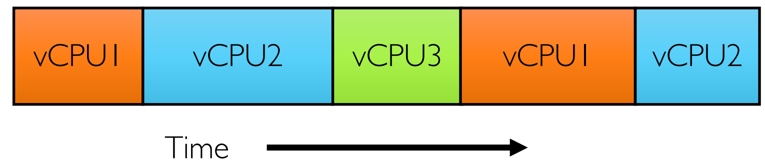
# Multiprogramming: Multiple Threads



# Time Sharing




- How can we give illusion of multiple processors with single processor?
  - Multiplex in time!
- Each virtual "CPU" needs structure to hold
  - PC, SP, and rest of registers (integer, floating point, …)
- How do we switch from one vCPU to next?
  - Save PC, SP, and registers in current state block
  - Load PC, SP, and registers from new state block
- What triggers switch?
  - Timer, voluntary yield, I/O, …

# The Basic Problem of Concurrency

- The basic problem of concurrency involves resources
  - Hardware: single CPU, single DRAM, single I/O devices
  - Multiprogramming API: processes think they have exclusive access to shared resources
- OS should coordinate all activity
  - Multiple processes, I/O interrupts, …
  - How can it keep all these things straight?
- Basic idea is to use virtual machine abstraction
  - Simple machine abstraction for processes
  - Multiplex these abstract machines
- Dijkstra did this for the "THE system"
  - Few thousand lines vs 1 million lines in OS 360 (1K bugs)

# Properties of This Simple Multiprogramming Technique

- All vCPUs share same non-CPU resources
  - I/O devices, memory, …
- Consequence of sharing
  - Each thread can access data of every other thread (good for sharing, bad for protection)
  - Threads can share instructions (good for sharing, bad for protection)
  - Can threads overwrite OS functions?
- This (unprotected) model is common in
  - Embedded applications
  - Windows 3.1/Early Macintosh (switch only with yield)
  - Windows 95-ME (switch with both yield and timer)

# Protection

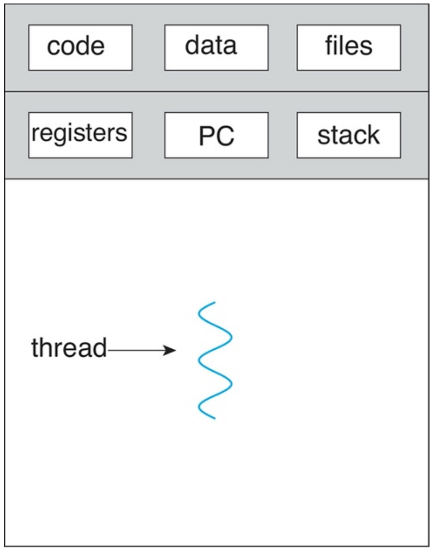
- OS must protect itself from user programs
  - Reliability: compromising OS generally causes it to crash
  - Security: limit scope of what processes can do
  - Privacy: limit each process to data it is permitted to access
  - Fairness: enforce appropriate share of resources (CPU time, memory, I/O, etc)
- It must protect user programs from one another
- Primary mechanism is to limit translation from program address space to physical memory space
  - Can only touch what is mapped into process address space
- There are additional mechanisms as well
  - Privileged instructions, in/out instructions, special registers
  - syscall processing, subsystem implementation
    - (e.g., file access rights, etc)

# Process (3rd OS Concept)

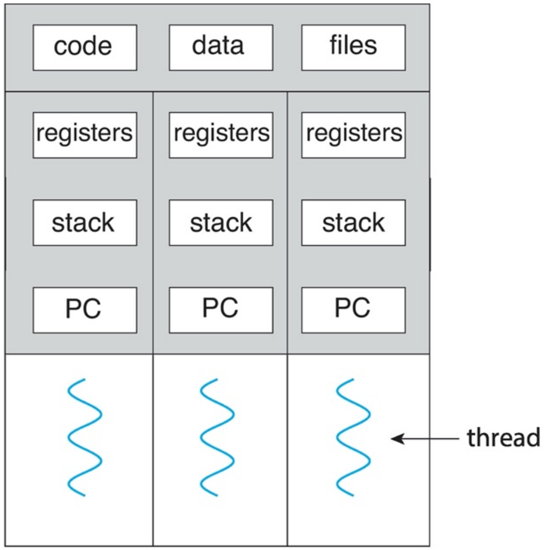
- Process: execution environment with restricted rights
  - Address space with one or more threads
  - Owns memory (address space)
  - Owns file descriptors, file system context, …
  - Encapsulates one or more threads sharing process resources
- Why processes?
  - Protected from each other!
  - OS Protected from them
  - Memory protection
  - Threads more efficient than processes (later)
  - Fundamental tradeoff between protection and efficiency
    - Communication easier within a process
    - Communication harder between processes
- Application instance consists of one or more processes

# Single and Multithreaded Processes

- Threads encapsulate concurrency and are active components
- Address spaces encapsulate protection and are passive part
  - Keeps buggy program from trashing system
- Why have multiple threads per address space?
  - Processes are expensive to start, switch between, and communicate between




single-threaded process



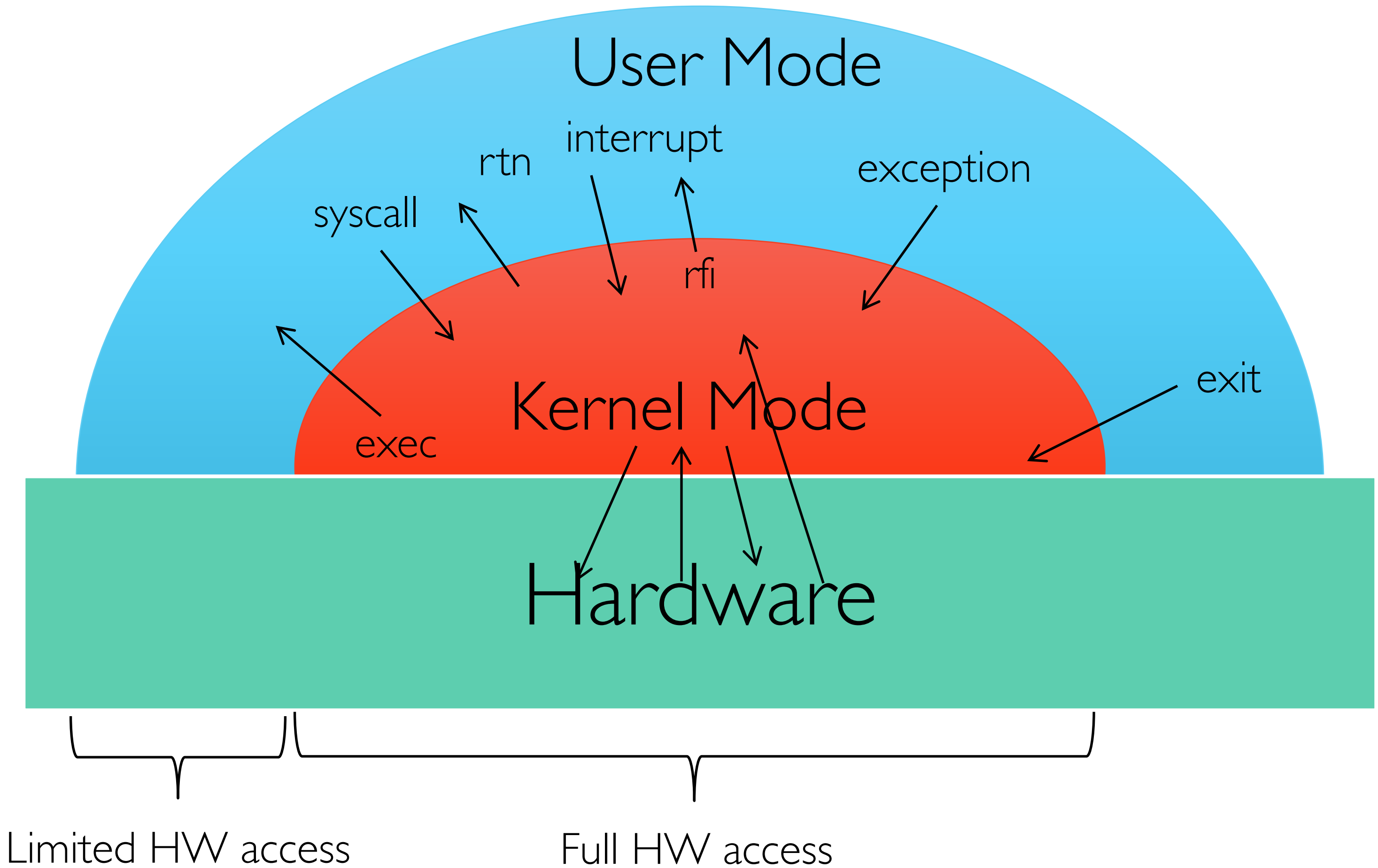

multithreaded process

# Dual-Mode Operation (4th OS Concept)

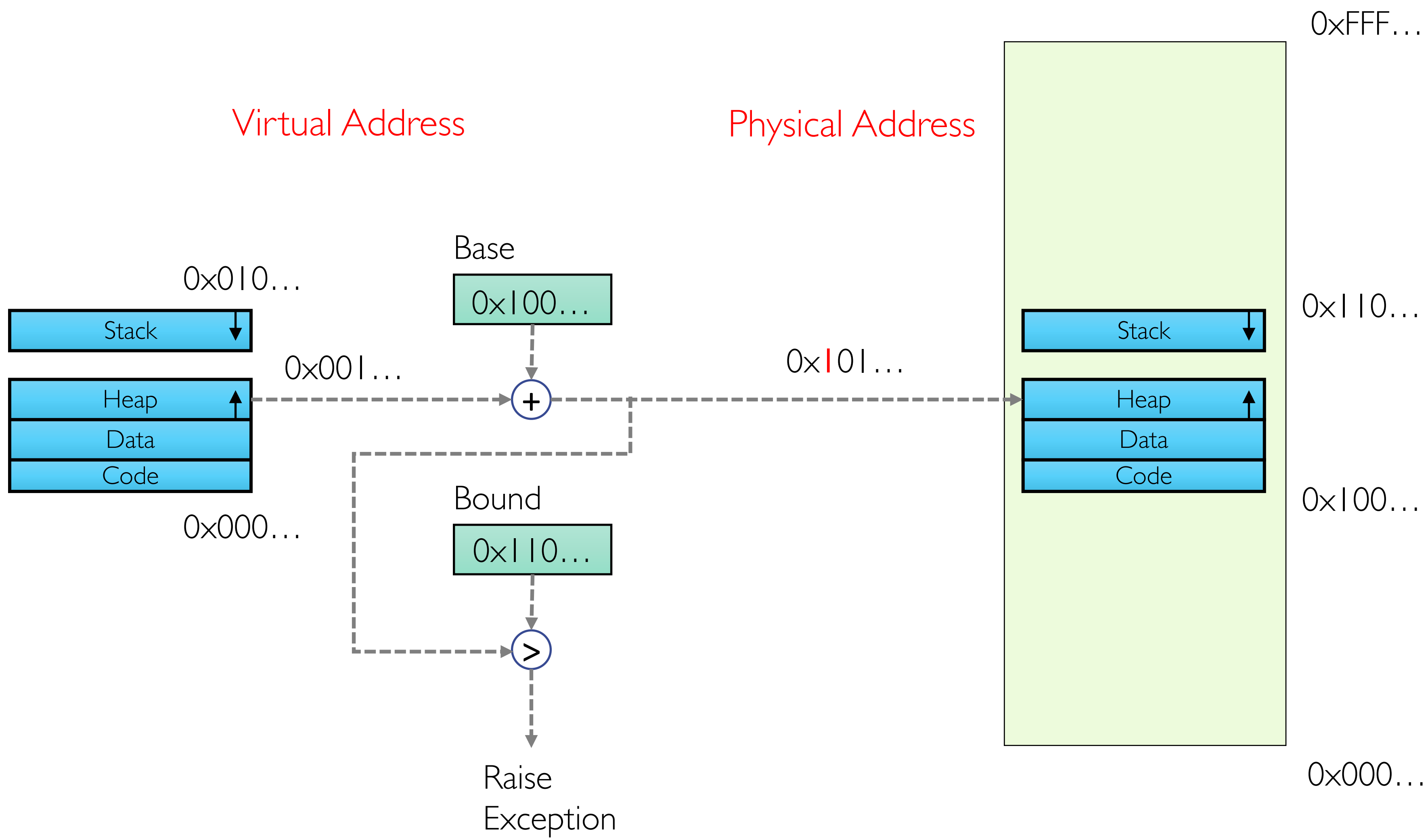
- Hardware provides at least two modes
  - Kernel mode (or "supervisor" or "protected")
  - User mode, which is how normal programs are executed

- How can hardware 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 to kernel transition sets system mode AND saves user PC
    - OS code carefully puts aside user state then performs necessary actions
  - Kernel to user transition clears system mode AND restores user PC
    - E.g., rfi: return-from-interrupt

# User/Kernel (Privileged) Mode



# Simple Memory Protections: Base and Bound (B&B)

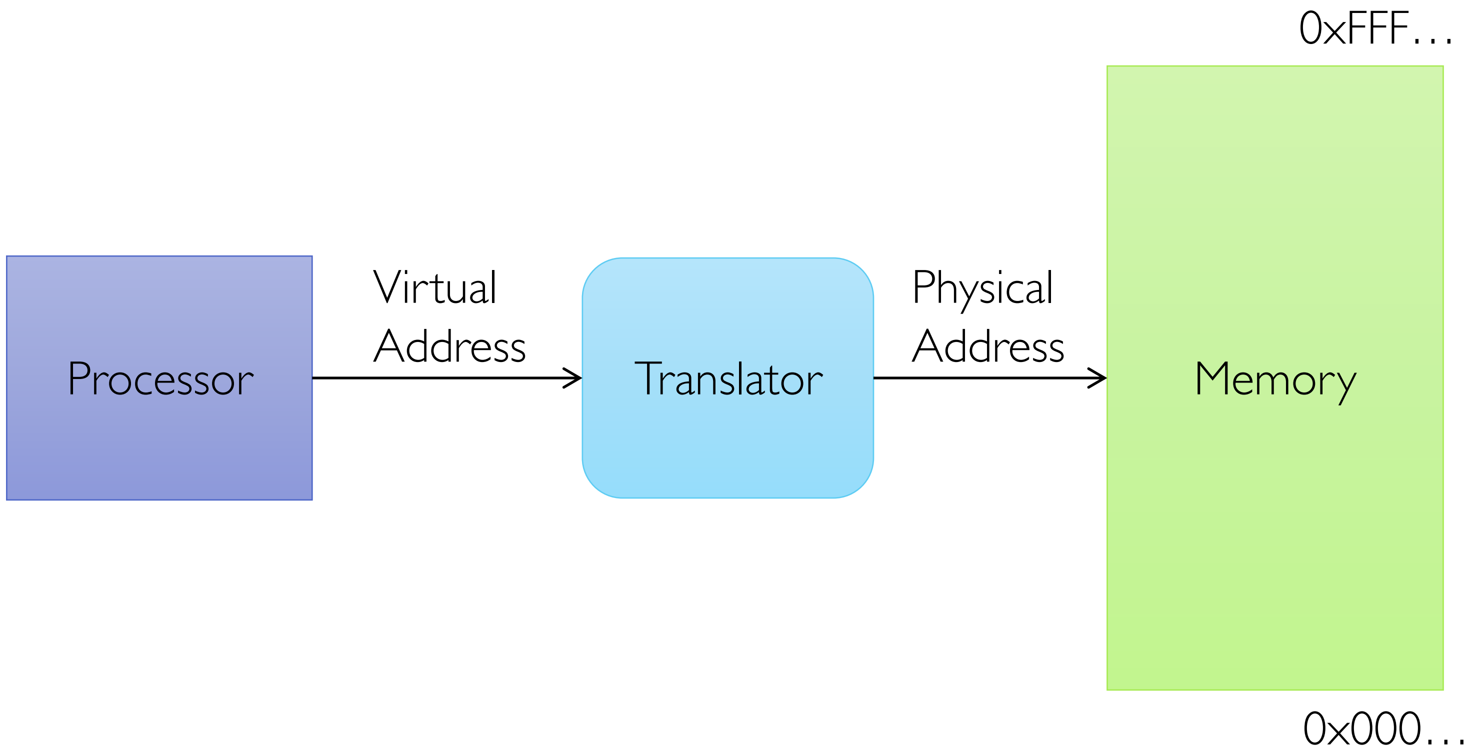


# Towards Virtual Addresses

- What are upsides of B&B?
  - OS protection and program isolation
  - Low overhead address translation
- What are downsides of B&B?
  - Expandable heap?
  - Expandable stack?
  - Memory sharing between processes?
  - Non-relative addresses – hard to move memory around
  - Memory fragmentation

# Address Space Translation

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

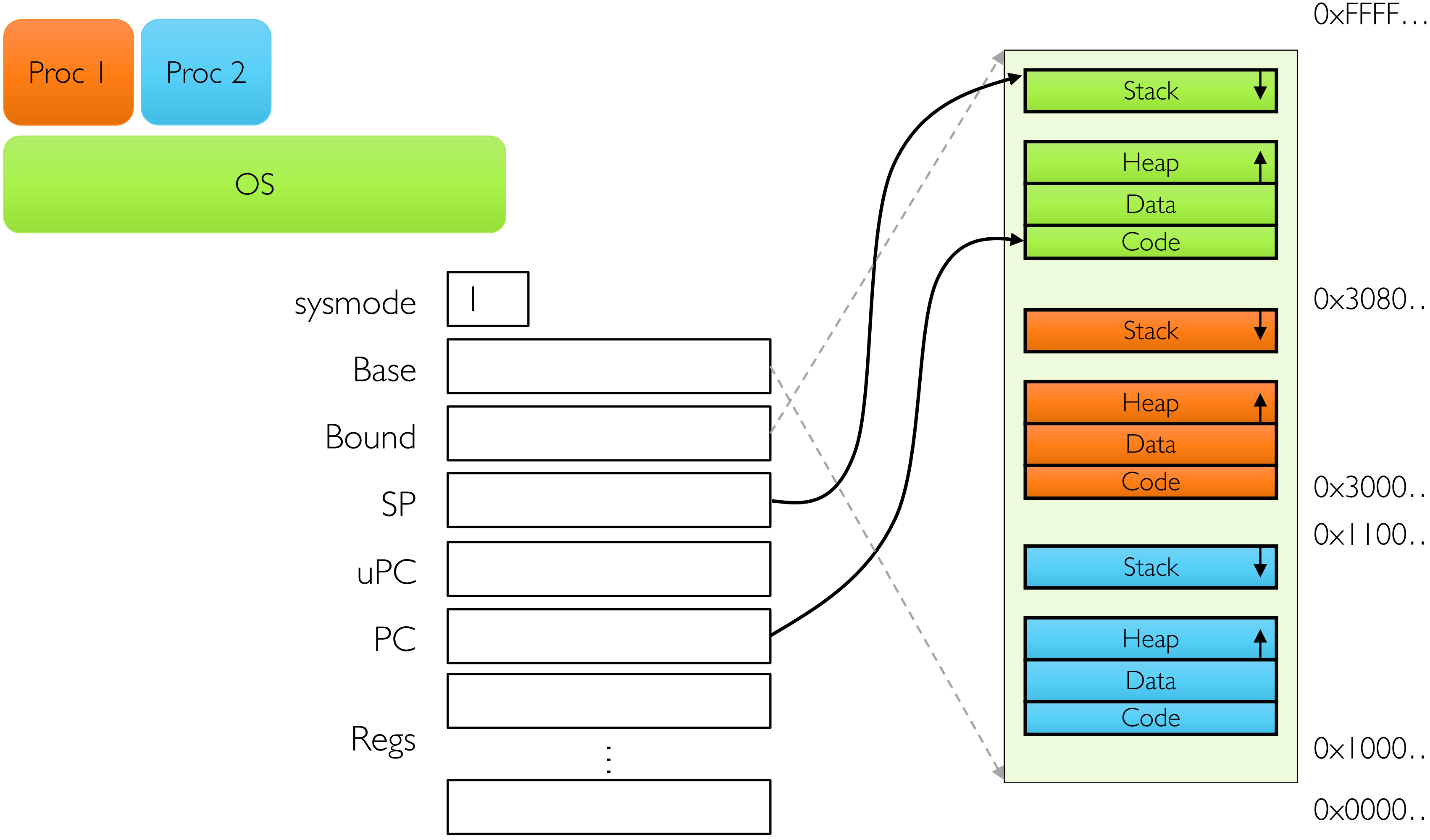


# Virtual Address Example

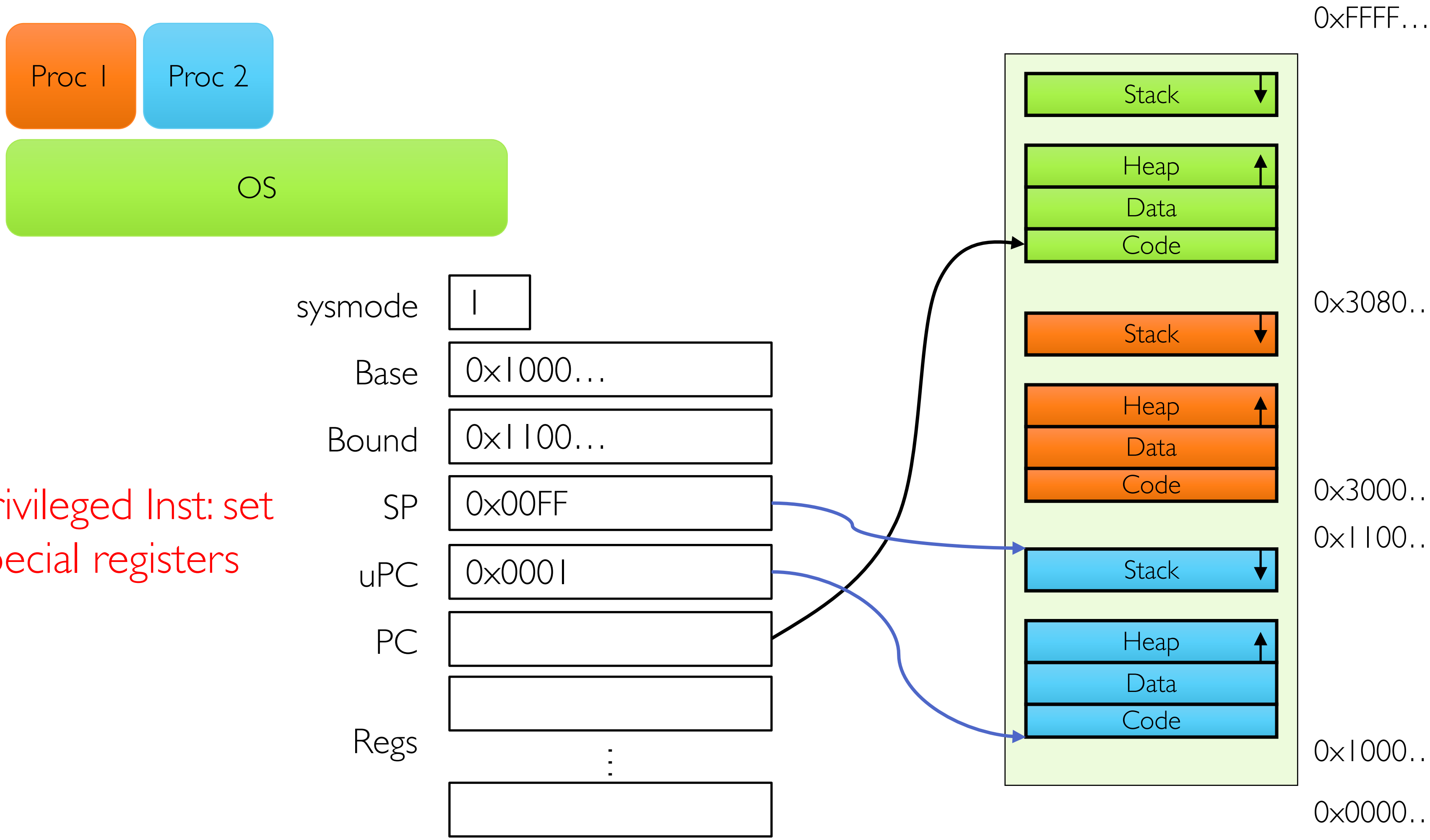
```
int staticVar = 0;         // a static variable
int main() {
    staticVar += 1;
    usleep(5000000);       // sleep for 5 seconds
    printf("static address: %x, value: %d\n", &staticVar, staticVar);
}
```

- What happens if we run two instances of this program at the same time?
- What if we took the address of a procedure local variable in two copies of the same program running at the same time?

# Putting it All Together: OS Loads Process (with B&B)

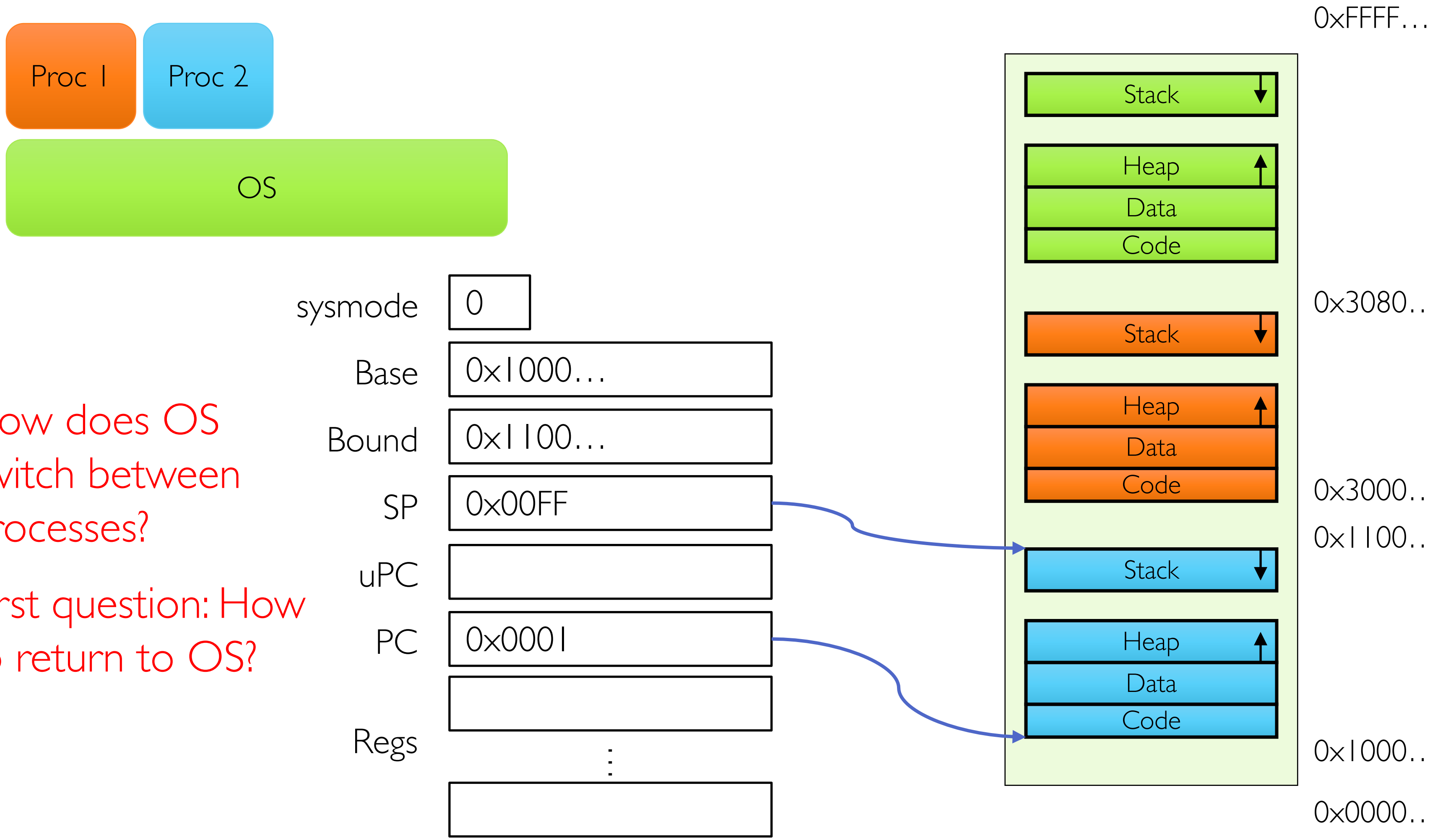


# OS Gets Ready to Execute Process (with B&B)




- Privileged Inst: set special registers

# User Code Running (with B&B)



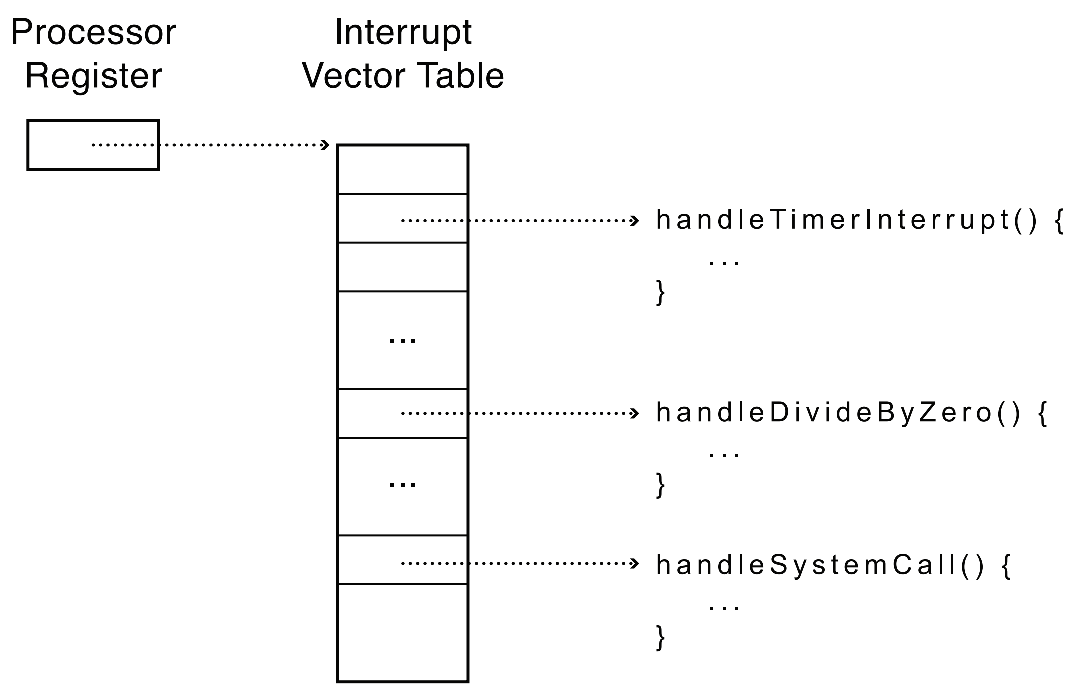

- How does OS switch between processes?
- First question: How to return to OS?

# Three Types of Mode Transfer

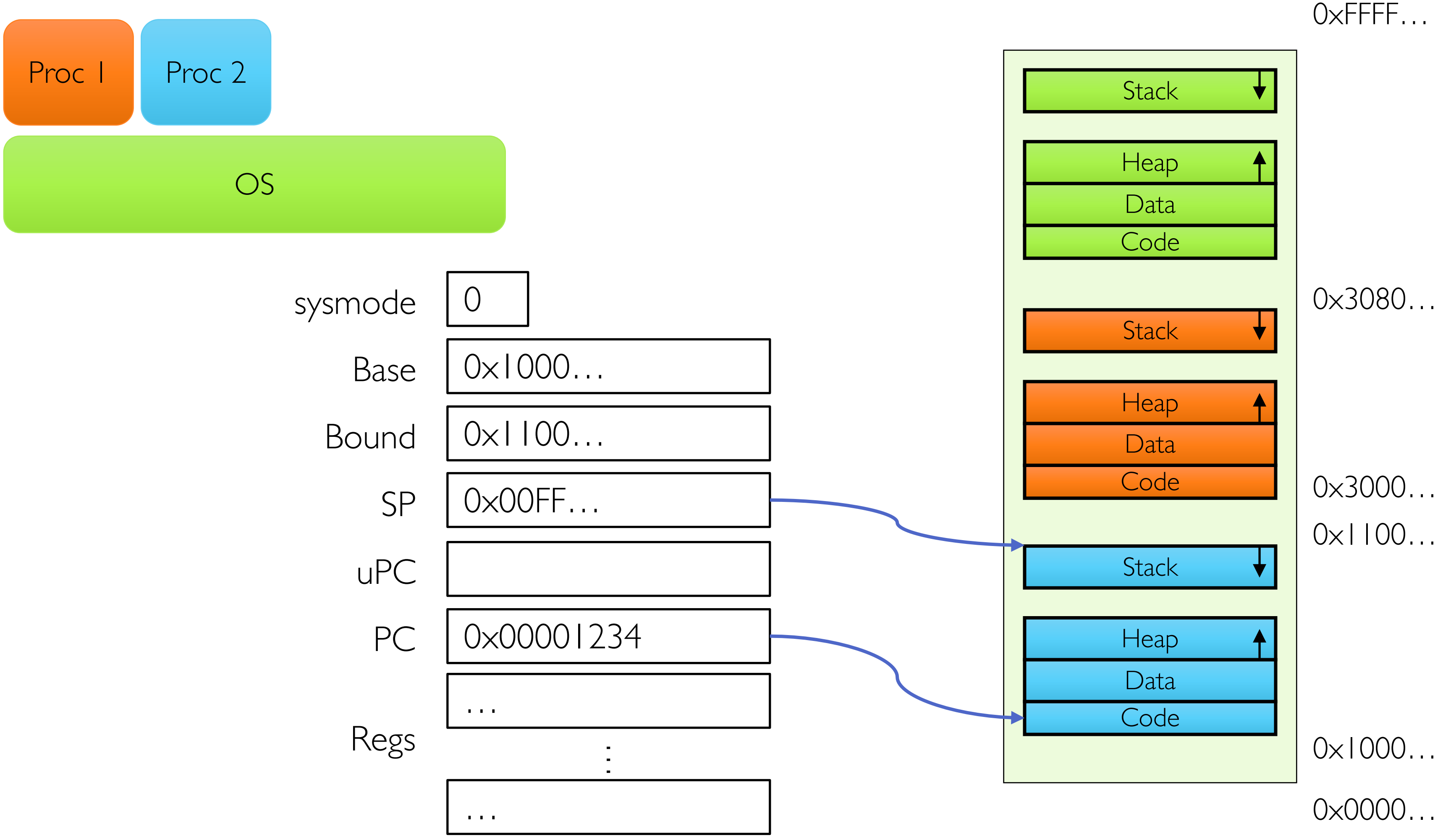
- Syscall
  - Process requests system service, e.g., `exit`
    - Like function call, but outside process
  - Process does not have address of system function to call
    - Like a Remote Procedure Call (RPC) – for later
  - OS marshalls syscall id and args in registers and exec syscall
- Interrupt
  - 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 UNPROGRAMMED CONTROL TRANSFER
- How do we get address of unprogrammed control transfer?

# Interrupt Vector

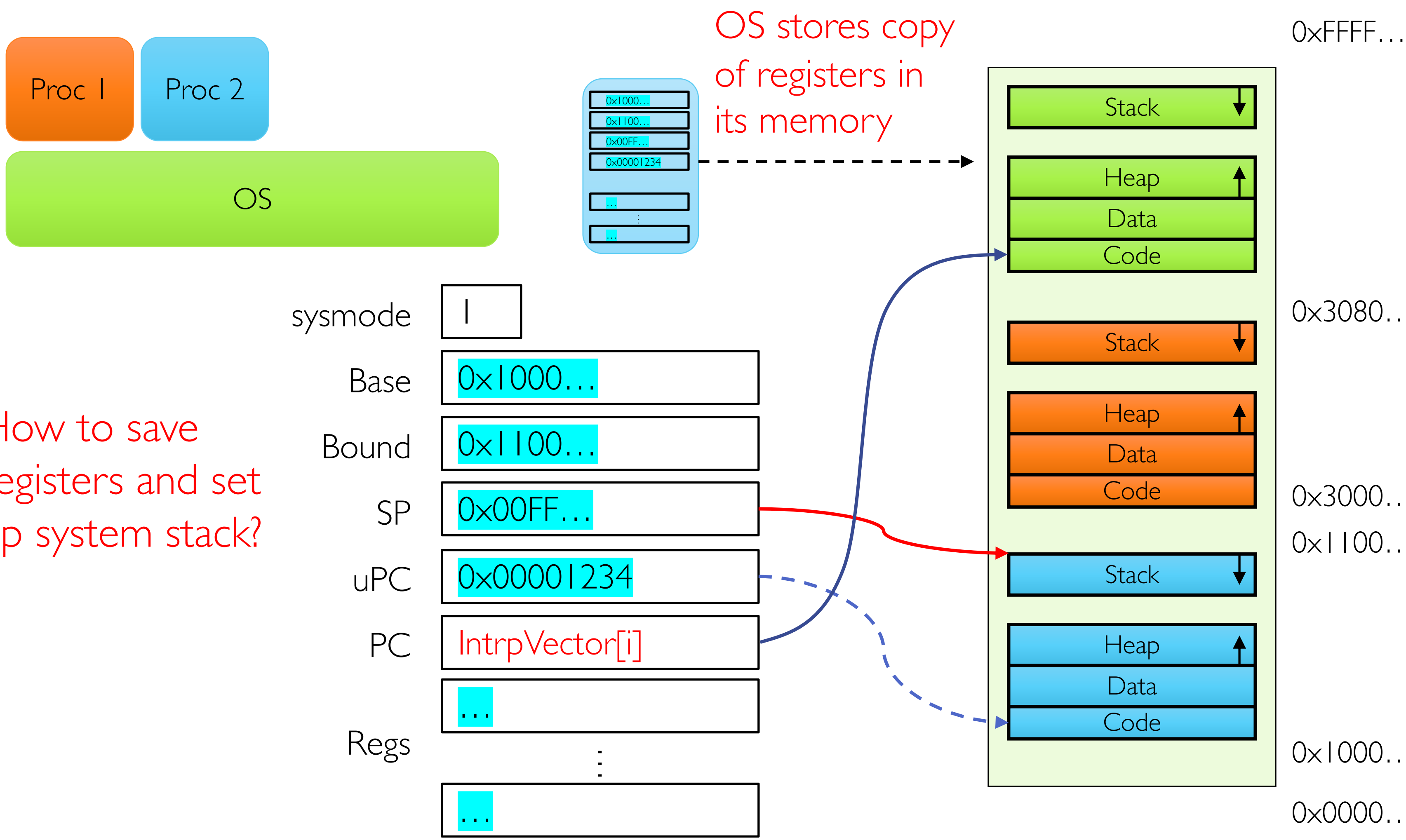
- Table set up by OS pointing to code to run on different events



# User to Kernel Switch (with B&B)



# Interrupt (with B&B)

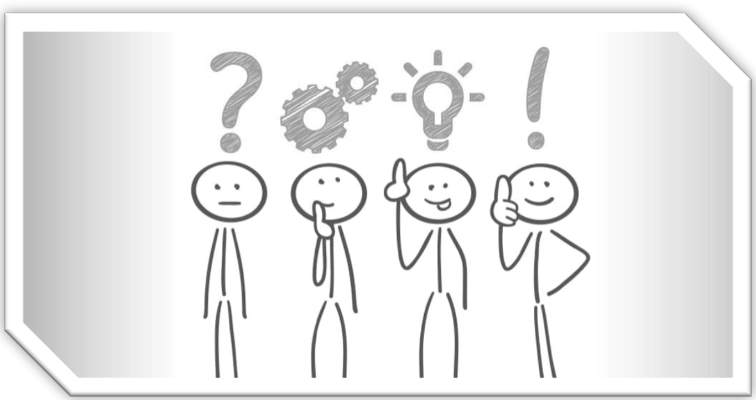



- How to save registers and set up system stack?

# Summery: Four Fundamental OS Concepts

- Thread
  - Single unique execution context which fully describes program state
  - Program counter, registers, execution flags, stack
- Address space (with translation)
  - Address space which is distinct from machine's physical memory addresses
- Process
  - Instance of executing program consisting of address space and 1+ threads
- Dual-mode operation/protection
  - Only "system" can access certain resources
  - OS and hardware are protected from user programs
  - User programs are isolated from one another by controlling translation from program virtual addresses to machine physical addresses

# Questions?



# Acknowledgment

- Slides by courtesy of Anderson, Culler, Stoica, Silberschatz, Joseph, and Canny