Four Fundamental OS Concepts

Lecture 2

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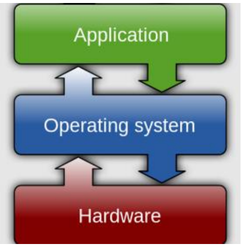
https://teaching.hkaiser.org/spring2026/csc4103/

Admistratrivia

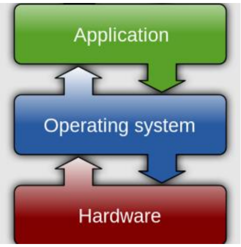
Homework and Early Drop Deadline

- Assignment 0: due January 26th, 11:59pm
- Project 0: due February 9th, 11:59pm
- You should be working on both already!
  - Get familiar with all the CSC4103 tools, set up environment, submitting to autograder via git
- Early drop deadline: January 21st



Group Projects are Looming

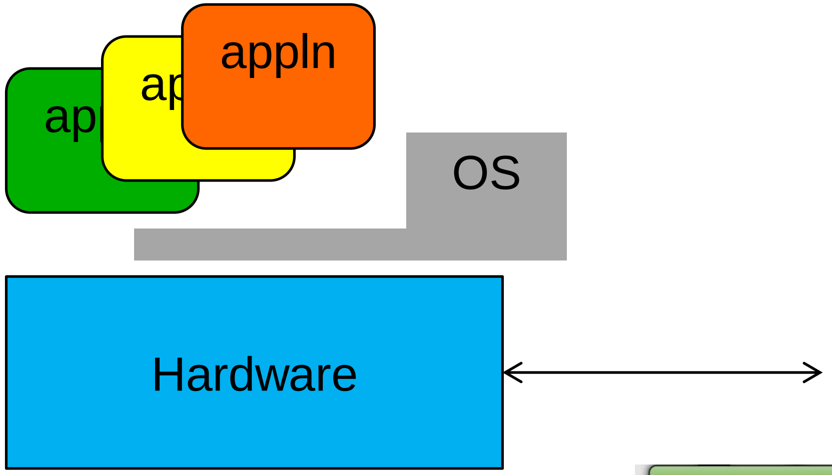
- Group Formation is due Friday January 23rd
  - Send email with preferences, each group will consist of four students (three students in exceptional cases)
  - I will assign remaining students arbitrarily
- Start working through Study Guide 0: C/x86
  - Answer all questions!

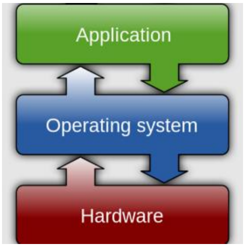


Four Fundamental OS Concepts

Recall: What is an Operating System?

- Special layer of software that provides application software access to hardware resources
  - Convenient abstraction of complex hardware devices
  - Protected access to shared resources
  - Security and authentication
  - Communication



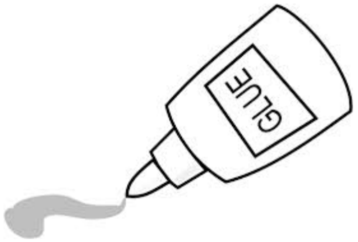


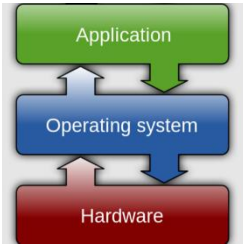
Recall: What is an Operating System?

- 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





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- Thread: Execution Context
  - Program Counter, Registers, Execution Flags, Stack
- Address Space (with Translation)
  - Program's view of memory is distinct from physical machine
- Process: Instance of a Running Program
  - Address space + one or more threads + …
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  - Only the "system" can access certain resources
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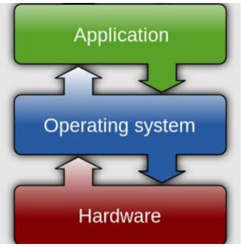
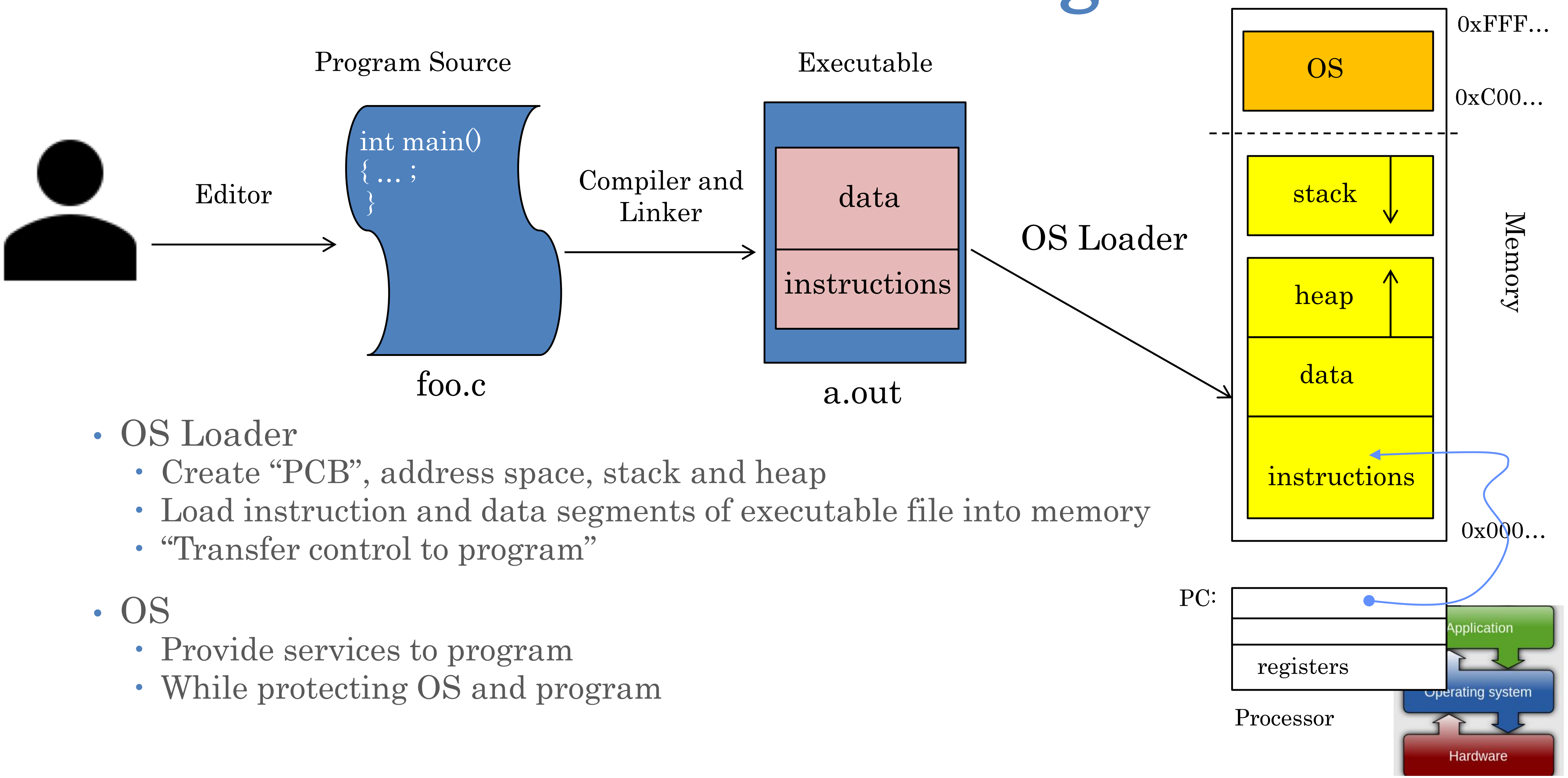


OS Bottom Line: Run Programs



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

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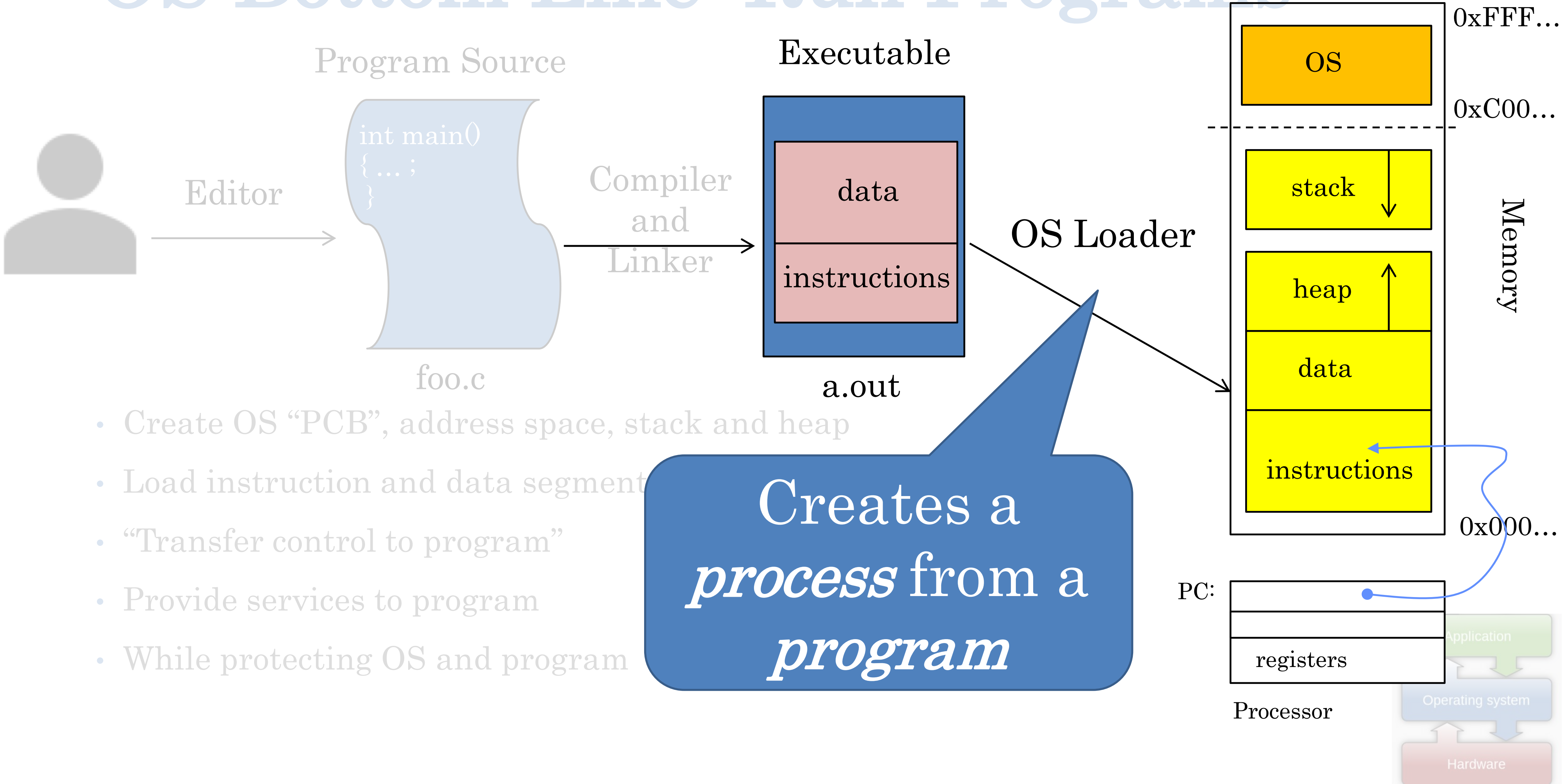

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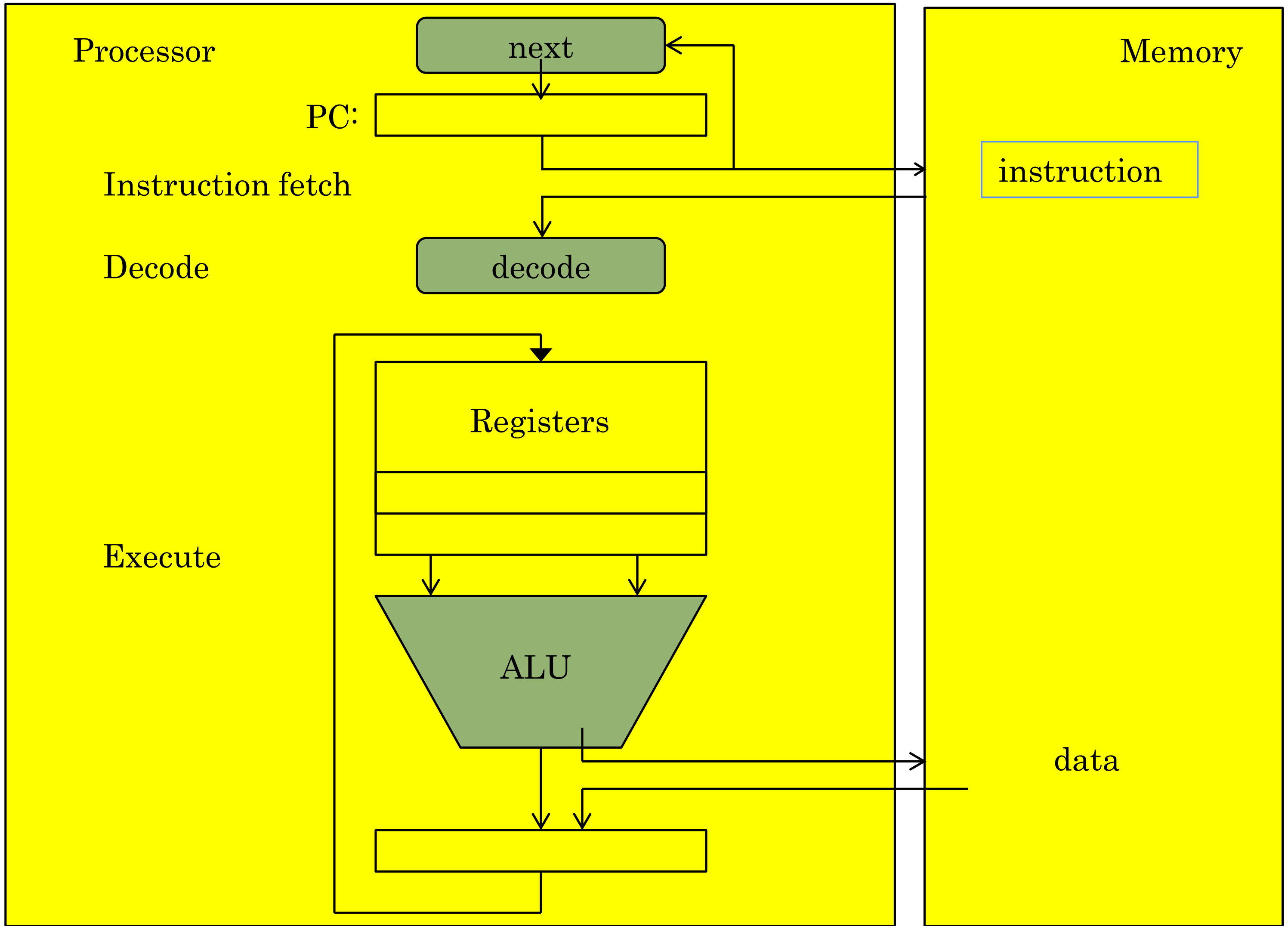
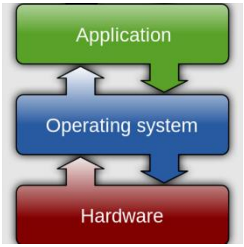
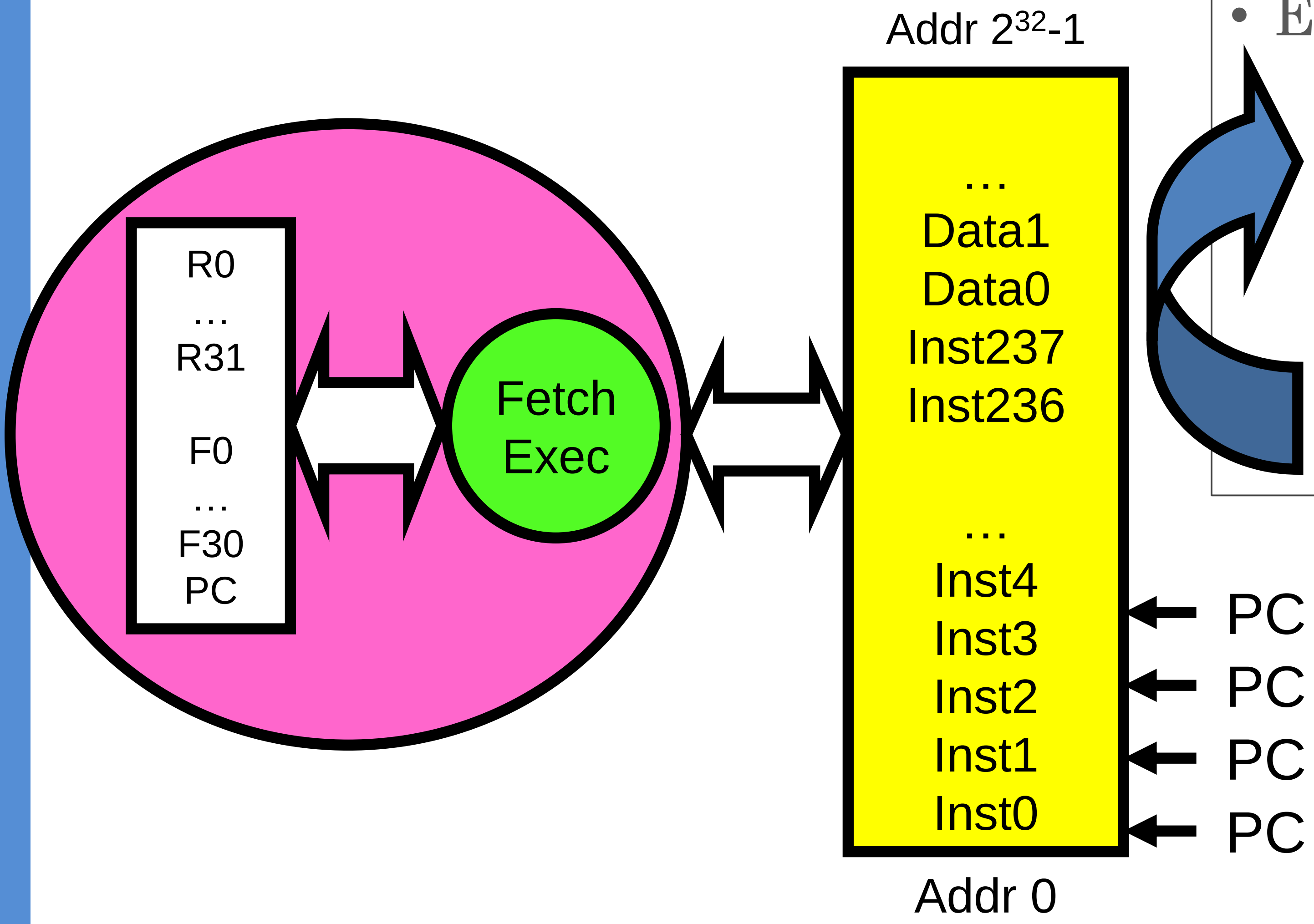
Recall: CPU Instruction Cycle

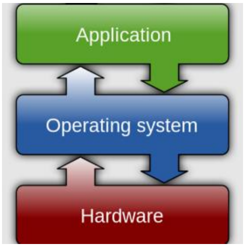




Review: How Programs Execute



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



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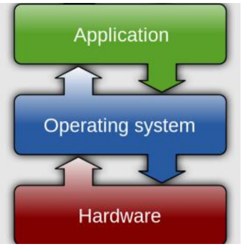
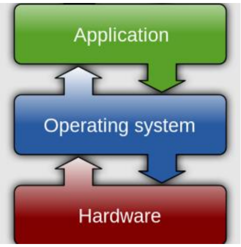
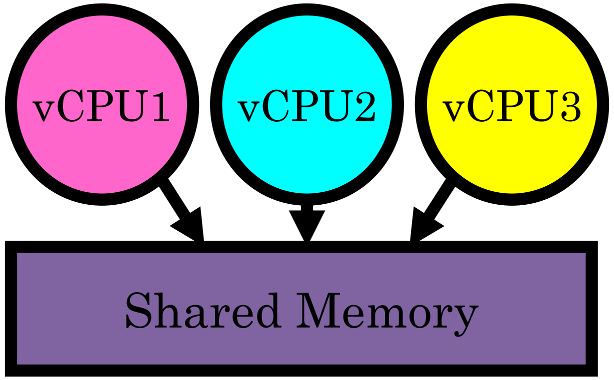


Key OS Concept: Thread

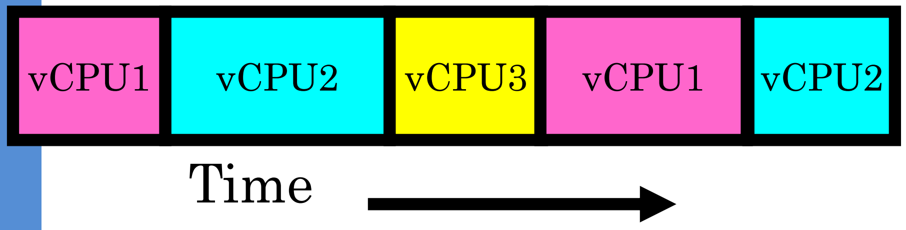
- Definition: A single, unique execution context
  - Program counter, registers, stack, execution state
- A thread is the OS abstraction for a CPU core
  - A “virtual CPU” of sorts
- Registers hold the root state of the thread:
  - Including program counter – pointer to the currently executing instruction
  - The rest is “in memory”
- Registers point to thread state in memory:
  - Stack pointer to the top of the thread’s (own) stack



Illusion of Multiple Processors

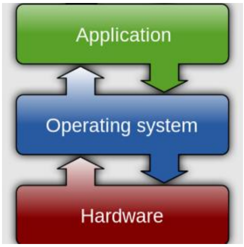


On a single physical CPU:



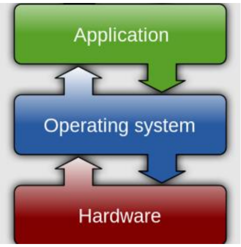
- Threads are **virtual cores**
- Multiple threads: **Multiplex** hardware in time
- **A thread is *executing* on a processor when it is resident in that processor's registers**

- Each virtual core (thread) has PC, SP, Registers
- Where is it?
  - On the real (physical) core, or
  - Saved in memory – called the Thread Control Block (TCB)

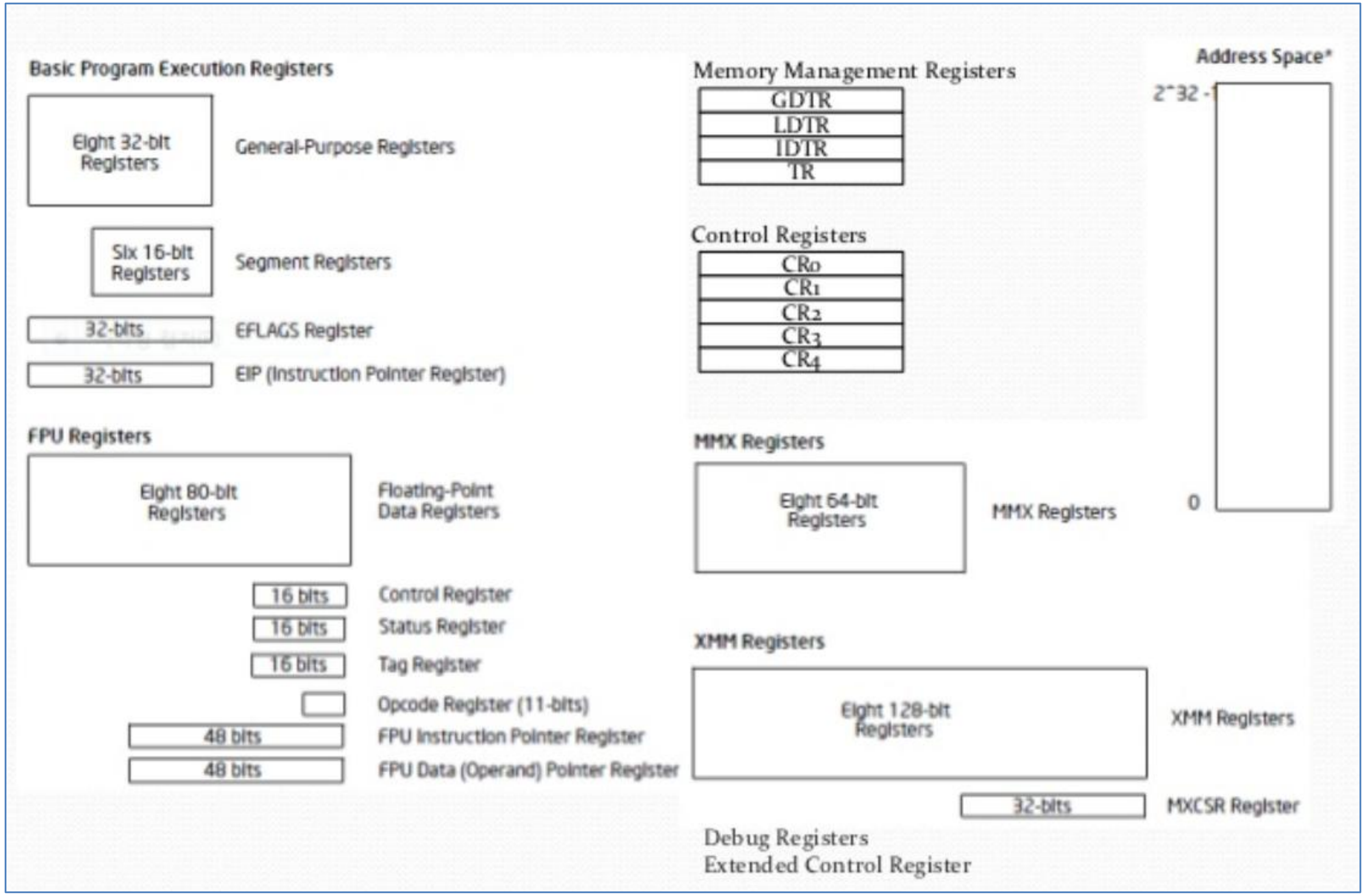


OS Object Representing a Thread

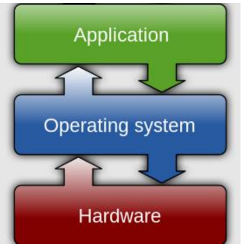
- Traditional term: Thread Control Block (TCB)
- Holds contents of registers when thread is not running…
- … And other information the kernel needs to keep track of the thread and its state.



Registers: x86



Complex memory architecture with specialized registers and "segments"



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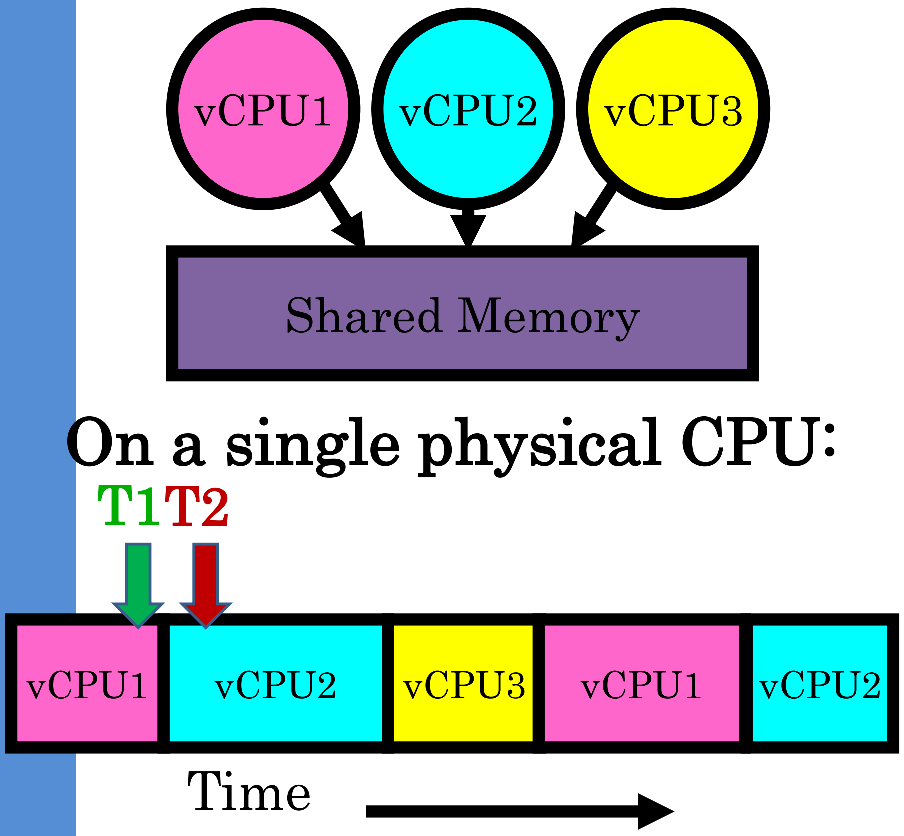
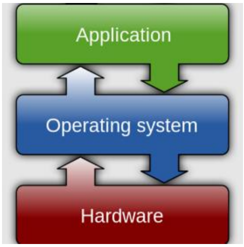
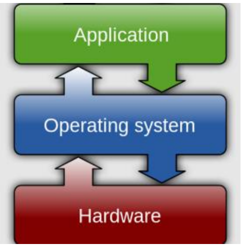


- At T1: vCPU1 on real core
- At T2: vCPU2 on real core
- What happened?
  - OS ran [how?]
  - Saved PC, SP, … in vCPU1's thread control block
  - Loaded PC, SP, … from vCPU2's thread control block
- This is called **context switch**



Very Simple Multiprogramming

- All vCPUs share non-CPU resources
  - Memory, I/O Devices
- Each thread can read/write memory
  - Including data of others
  - And the 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



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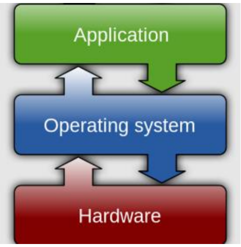
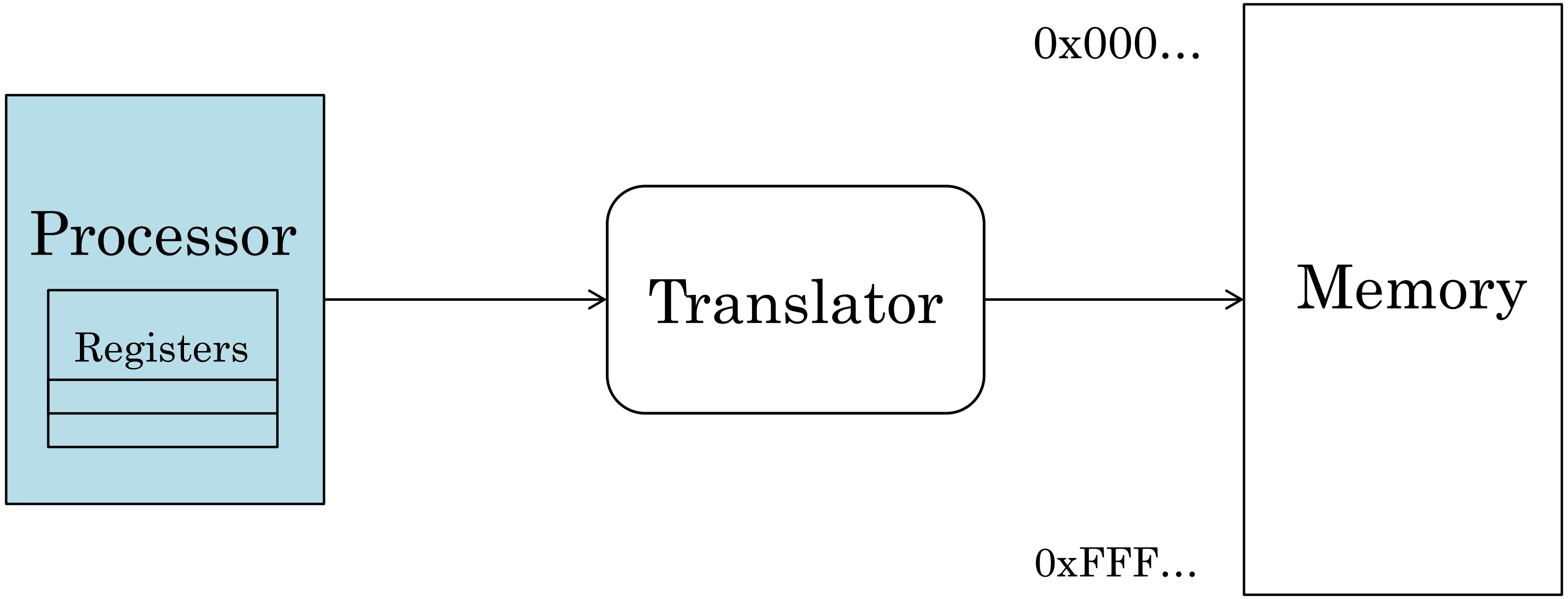
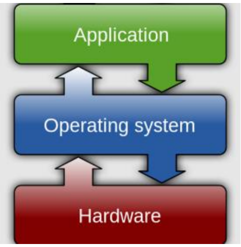


Key OS Concept: Address Space

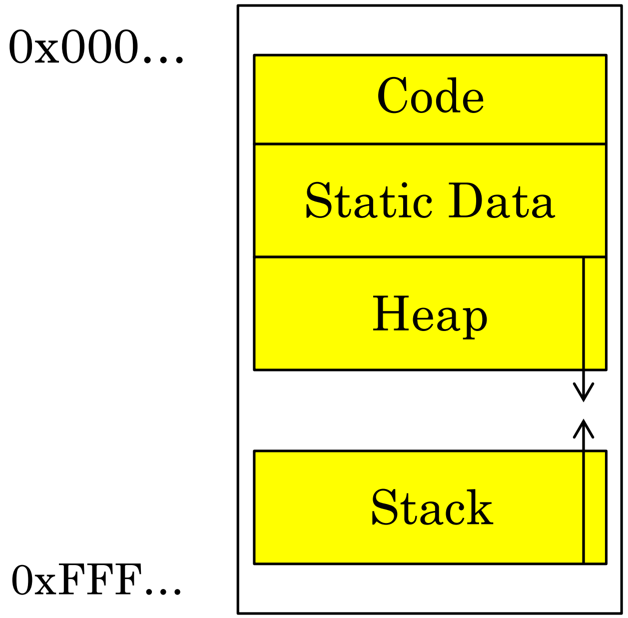
- Program operates in an address space that is distinct from the physical memory space of the machine

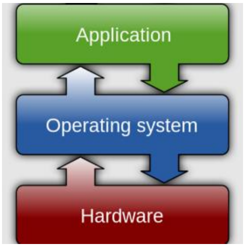




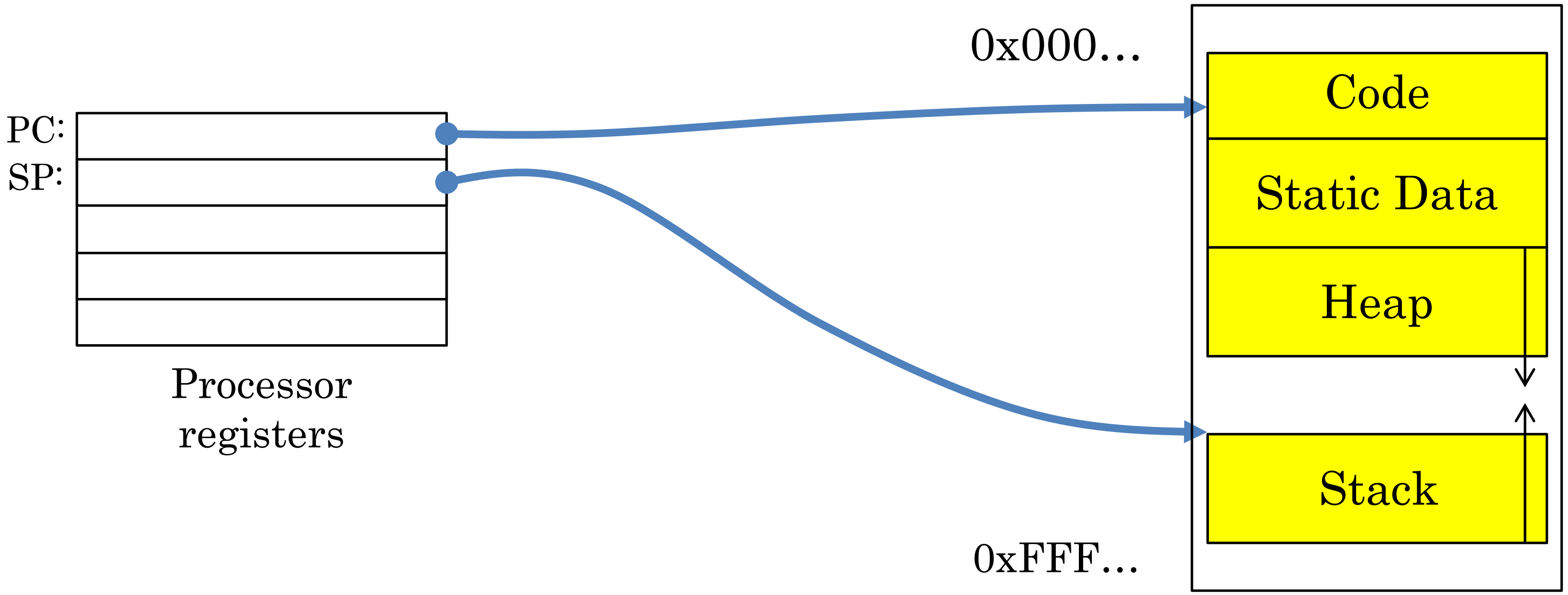
Address Space

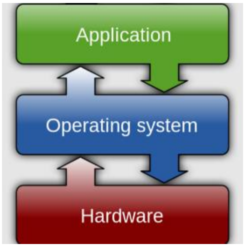
- Definition: Set of accessible addresses and the state associated with them
  - 2^{32} = ~4 billion on a 32-bit machine
- What happens when you read or write to an address?
  - Perhaps acts like regular memory
  - Perhaps causes I/O operation
    - (Memory-mapped I/O)
  - Causes program to abort (segfault)?
  - Communicate with another program
  - …





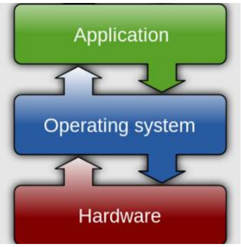
Typical Address Space Structure





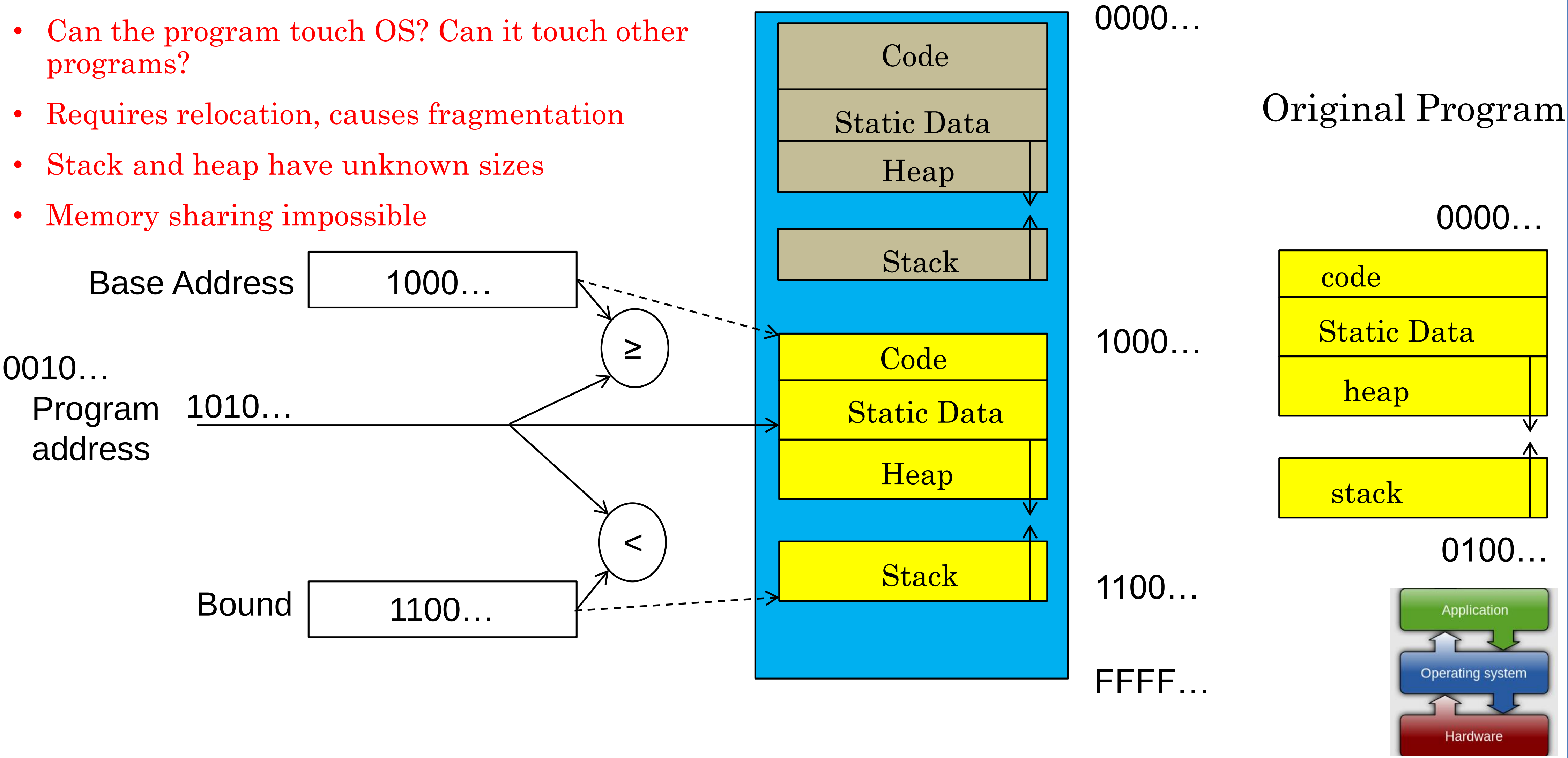
Address Space

- What can the hardware do to help the OS protect itself from programs? And programs from each other?
  - Prevent processes from reading or writing to physical addresses it should not have access to!
  - Allow processes to read and write to physical addresses it should have access to!

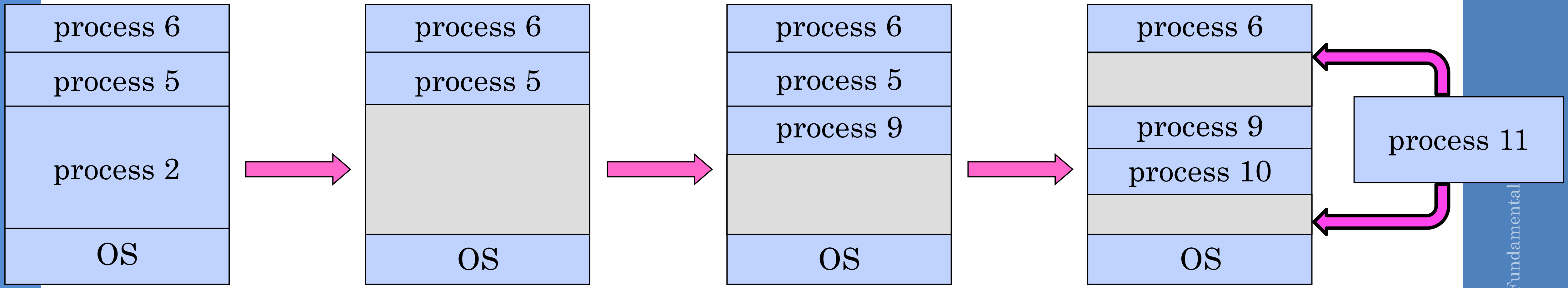


Base and Bound (no Translation)

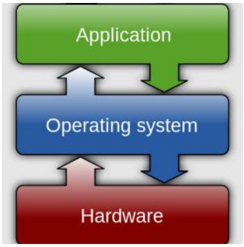
- Can the program touch OS? Can it touch other programs?
- Requires relocation, causes fragmentation
- Stack and heap have unknown sizes
- Memory sharing impossible



Issues with Simple Base and Bound

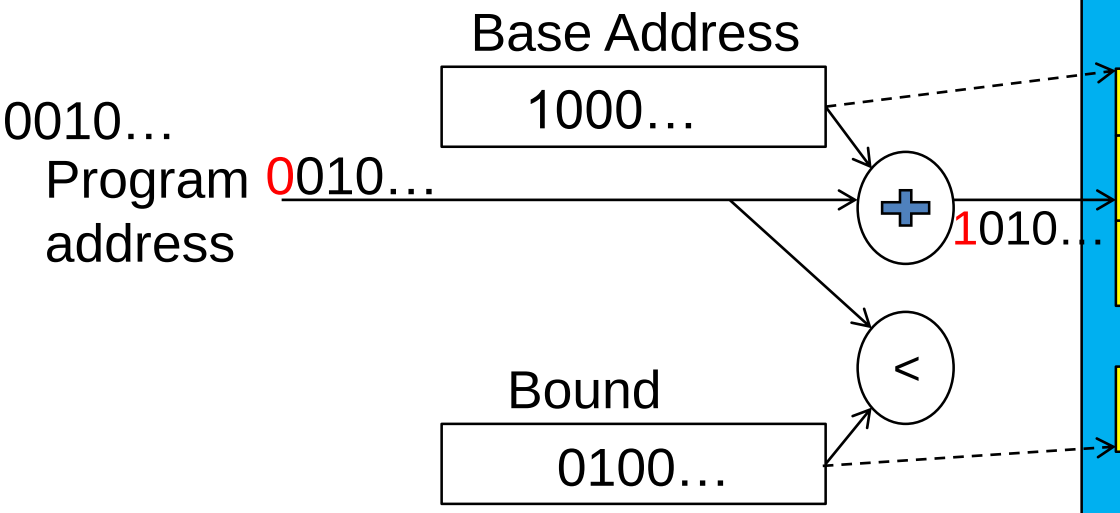


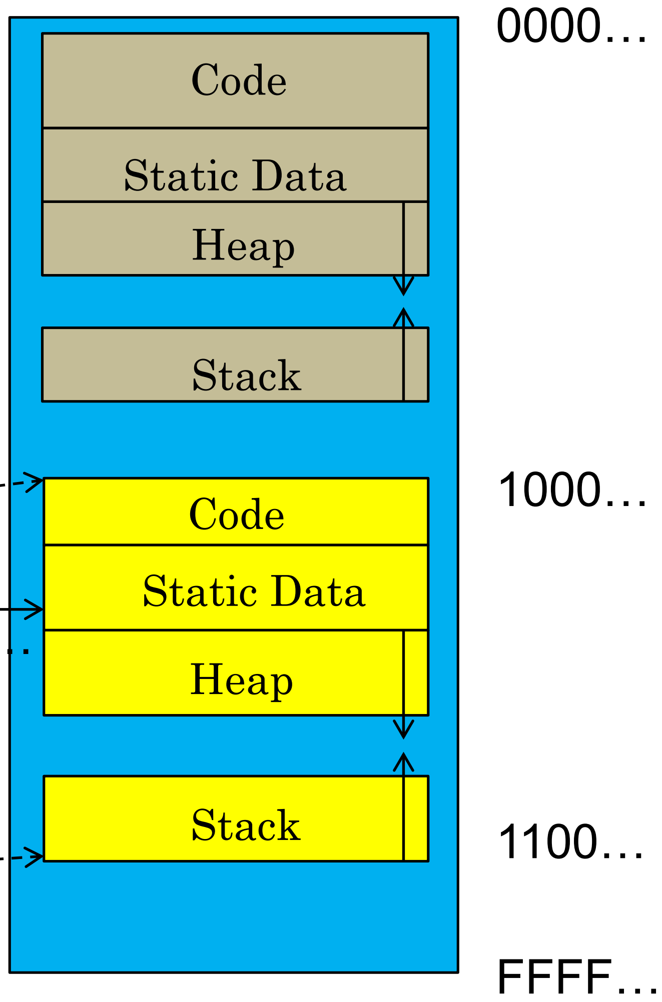
- Fragmentation problem over time
- Hard to do interprocess sharing
  - E.g., to share code

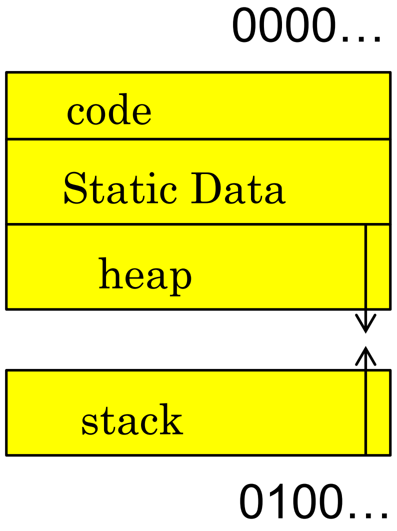


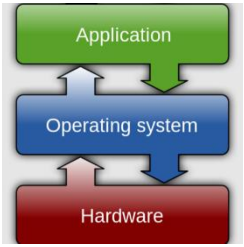
Base and Bound (with Translation)

- Can the program touch OS? Can it touch other programs?
- Fragmentation still an issue!
- Still no sharing!
- Stack and heaps are of variable size!



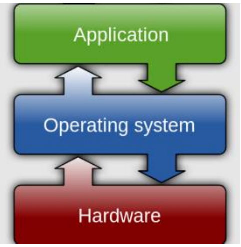






Paged Virtual Address Space

- What if we break the entire virtual address space into equally sized chunks (i.e., pages) and have a base and bound for each?
- All pages are of the same size, so it's easy to place each page in memory!
- Hardware translates addresses using a page table
  - Each page has a separate base
  - The "bound" is the page size
  - Special hardware register stores pointer to page table



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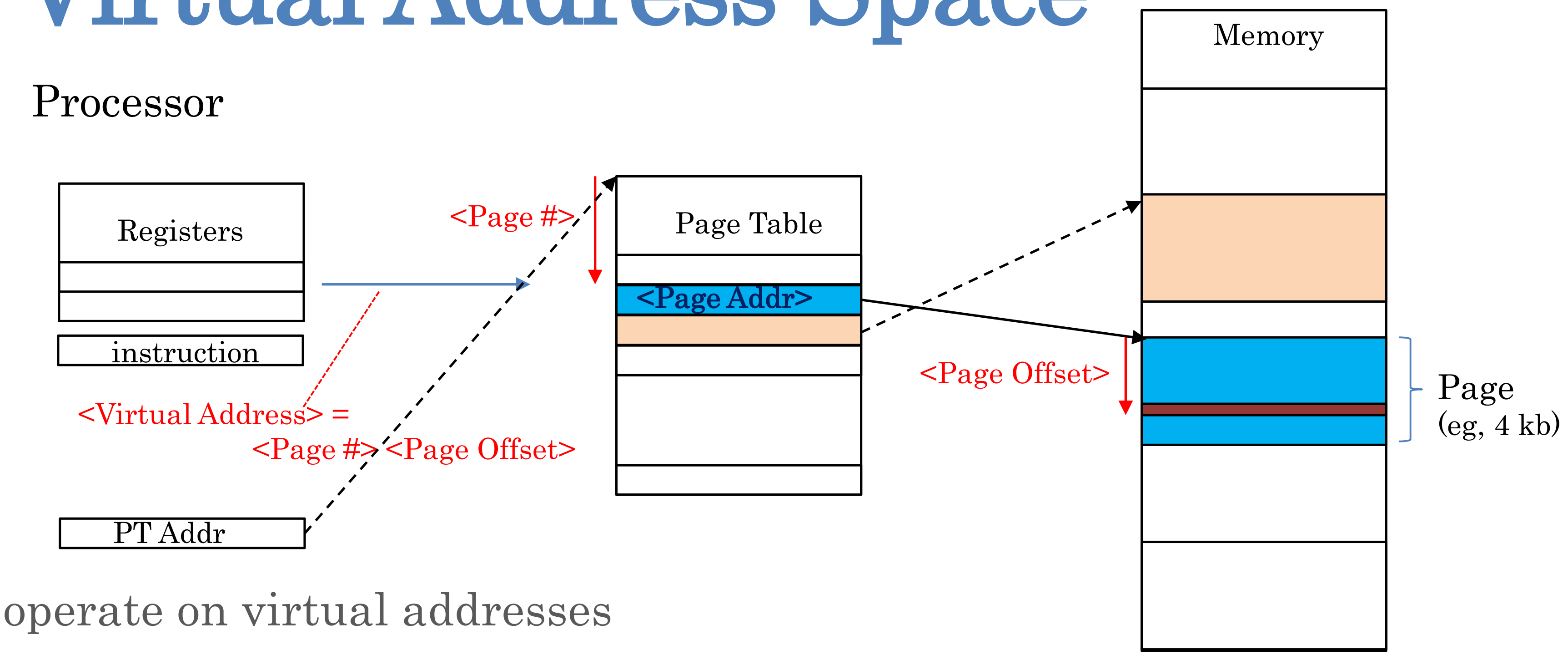
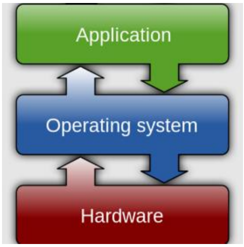


- Instructions operate on virtual addresses
- Virtual addresses translated at runtime to physical addresses via a page table
- Special register holds page table base address of current process' page table



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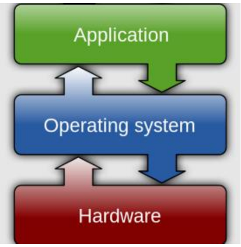
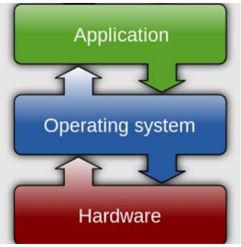


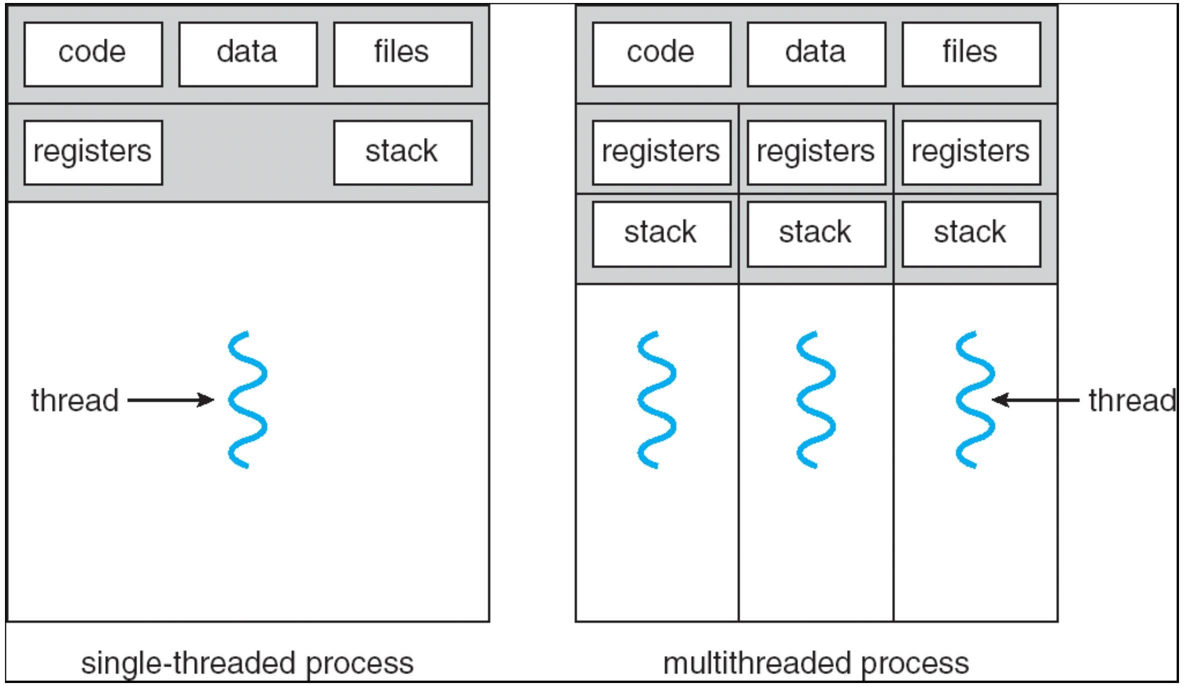
Key OS Concept: Process

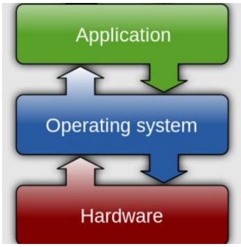
- Definition: execution environment with restricted rights
  - One or more threads executing in a single virtual address space (own page table)
  - Owns file descriptors, network connections, etc.
- Instance of a running program
  - When you run an executable, it runs in its own process
  - Application: one or more processes working together
- Protected from each other; OS protected from them
- In modern OSes, anything that runs outside of the kernel runs in a process
  - Even many of the OS services run in separate processes



Single and Multithreaded Processes

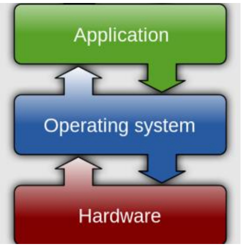
- Threads encapsulate concurrency
  - "Active" component
- Address space encapsulate protection:
  - "Passive" component
  - Keeps bugs from crashing the entire system
- Why have multiple threads per address space?





Protection and Isolation

- Why?
  - 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!



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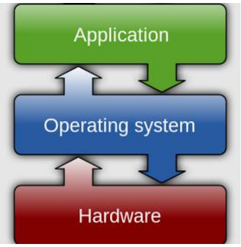
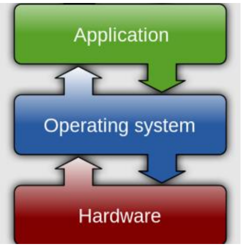


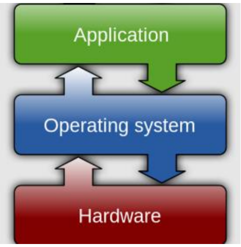
Dual-Mode Operation

- One bit of state: processor is either in user mode or kernel mode
  - x86 has four privilege levels: rank 0 (kernel) … rank 3 (user)
- Certain actions are only permitted in kernel mode (privileged instructions), e.g.
  - Changing the page table pointer (memory protection)
  - Certain entries in the page table
  - Hardware I/O instructions
  - Disable interrupts (timers)
- State bit can't be changed directly, is flipped only during execution of special transfer operations



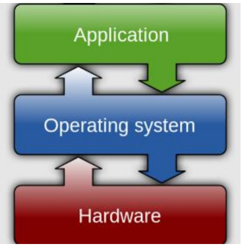
Dual-Mode Operation

- What hardware is needed to protect applications and users from one another?
- Privileged instructions
  - All potentially unsafe instructions are prohibited in user mode
- Memory protection
  - All memory accesses outside of a process's valid memory region are prohibited when executing in user mode
- Timer interrupts
  - Regardless of what a process does, the kernel must have a way to potentially regain control from the current process



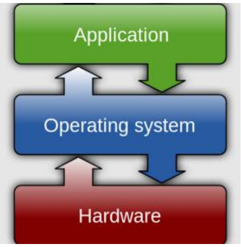
Dual-Mode Operation

- Processes (i.e., programs you run) execute in user mode
  - To perform privileged actions, processes request services from the OS kernel
  - Carefully controlled transition from user to kernel mode
- Kernel executes in kernel mode
  - Performs privileged actions to support running processes
  - … and configures hardware to properly protect them (e.g., address translation)
  - Return to user mode through special instructions
    - Return from interrupt

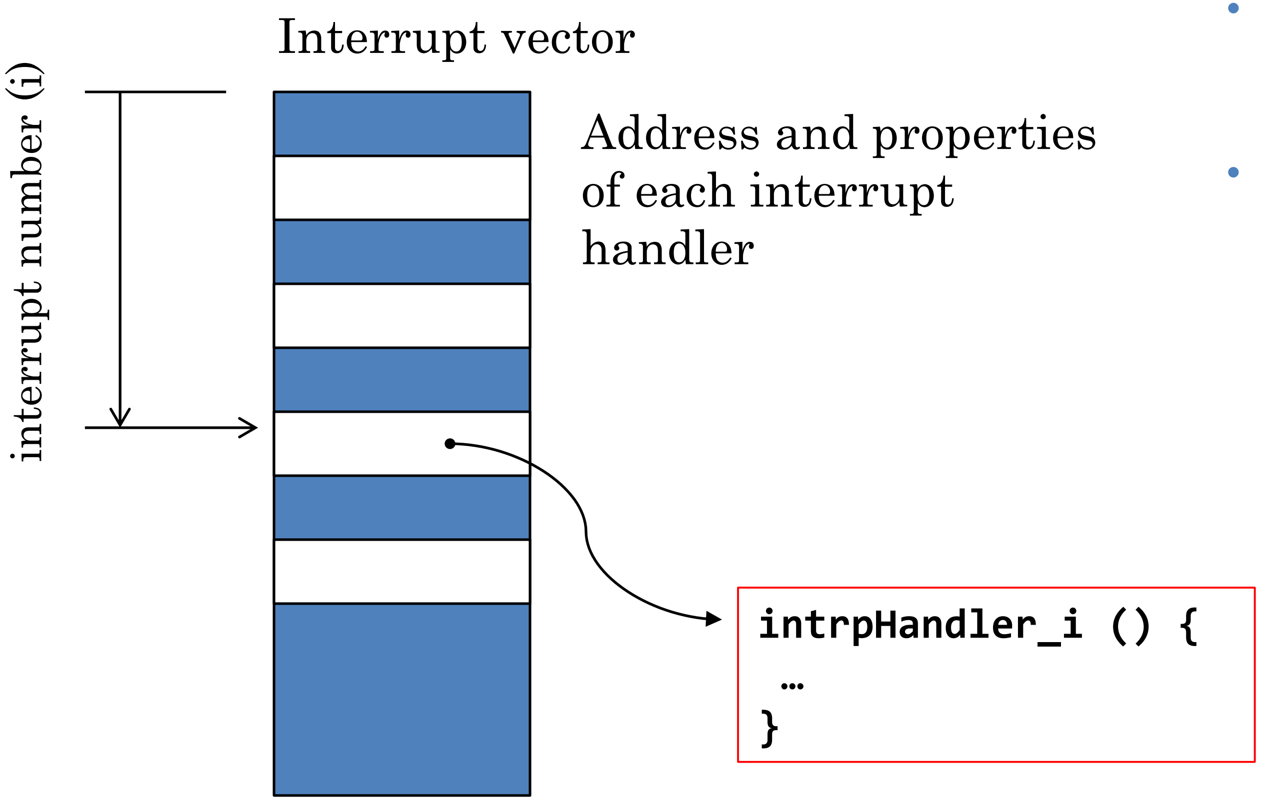


Three Types of User → Kernel Mode Transfer

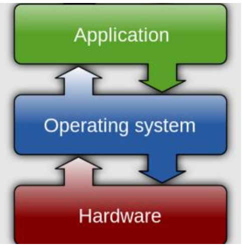
- System Call ("syscalls")
  - Process requests a system service (e.g., open a file)
  - Like a function call, but "outside" the process
- Interrupt
  - External asynchronous event, independent of the process
  - e.g., Timer, I/O device
- Trap (exception)
  - Internal synchronous event in process triggers context switch
  - E.g., Divide by zero, bad memory access (segmentation fault)
- CONTROL TRANSFER User -> Kernel mode
  - System calls constitute PROGRAMMED control transfer
  - Interrupts and traps are UNPROGRAMMED control transfer mechanisms
- User process can't jump to arbitrary instruction address in kernel!
  - Why not?



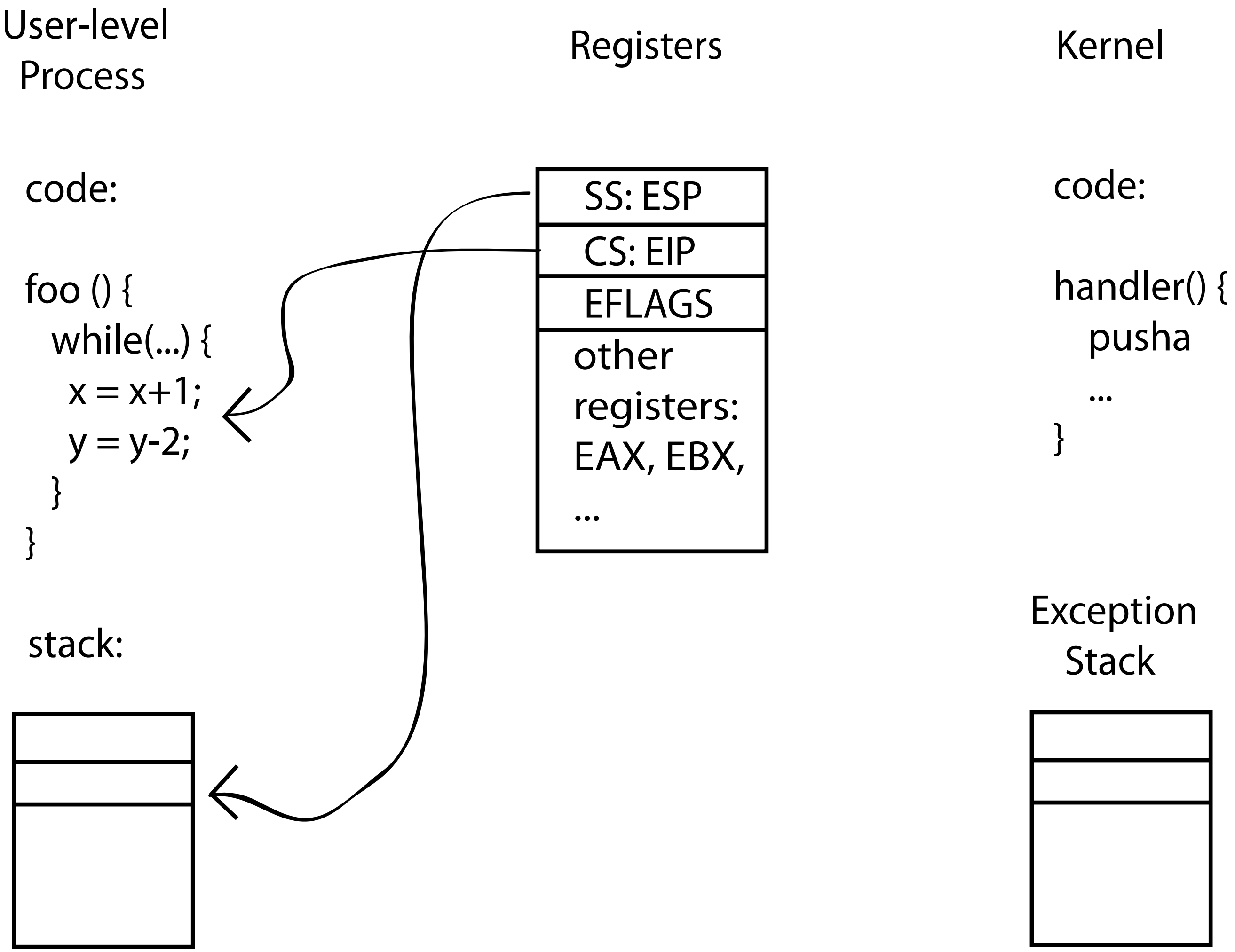
Where do User → Kernel Mode Transfers Go?

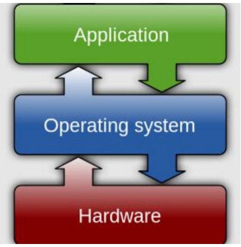


- Cannot let user programs specify the exact address!
- Solution: Interrupt Vector
  - OS kernel specifies a set of functions that are entry points to kernel mode
  - Appropriate function is chosen depending on the type of transition
    - Interrupt Number (i)
    - Type of interrupt
    - Type of trap
    - OS may do additional dispatch

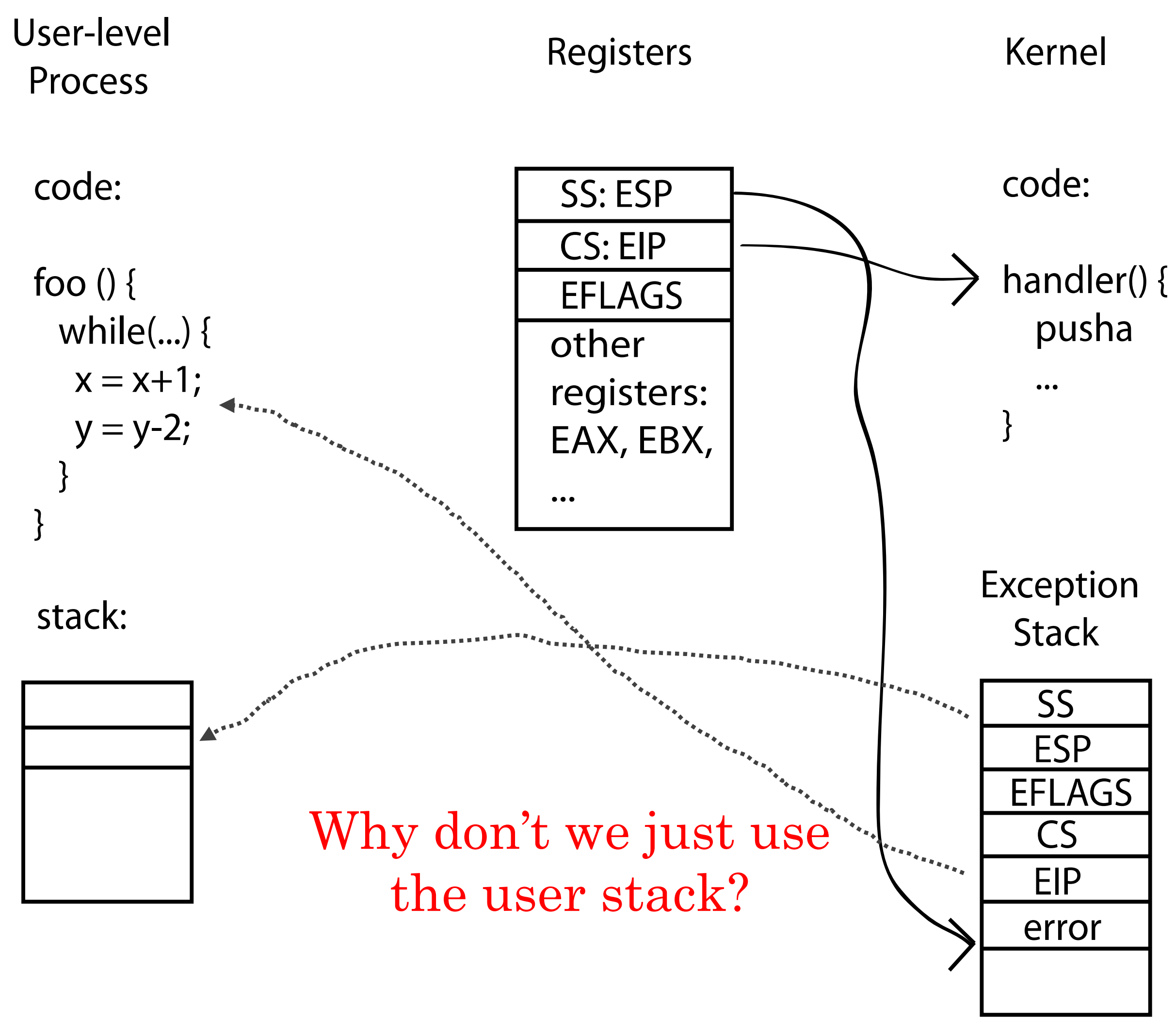


Example: Before Exception

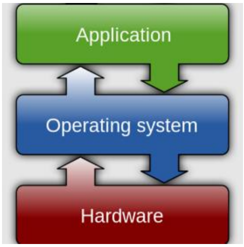




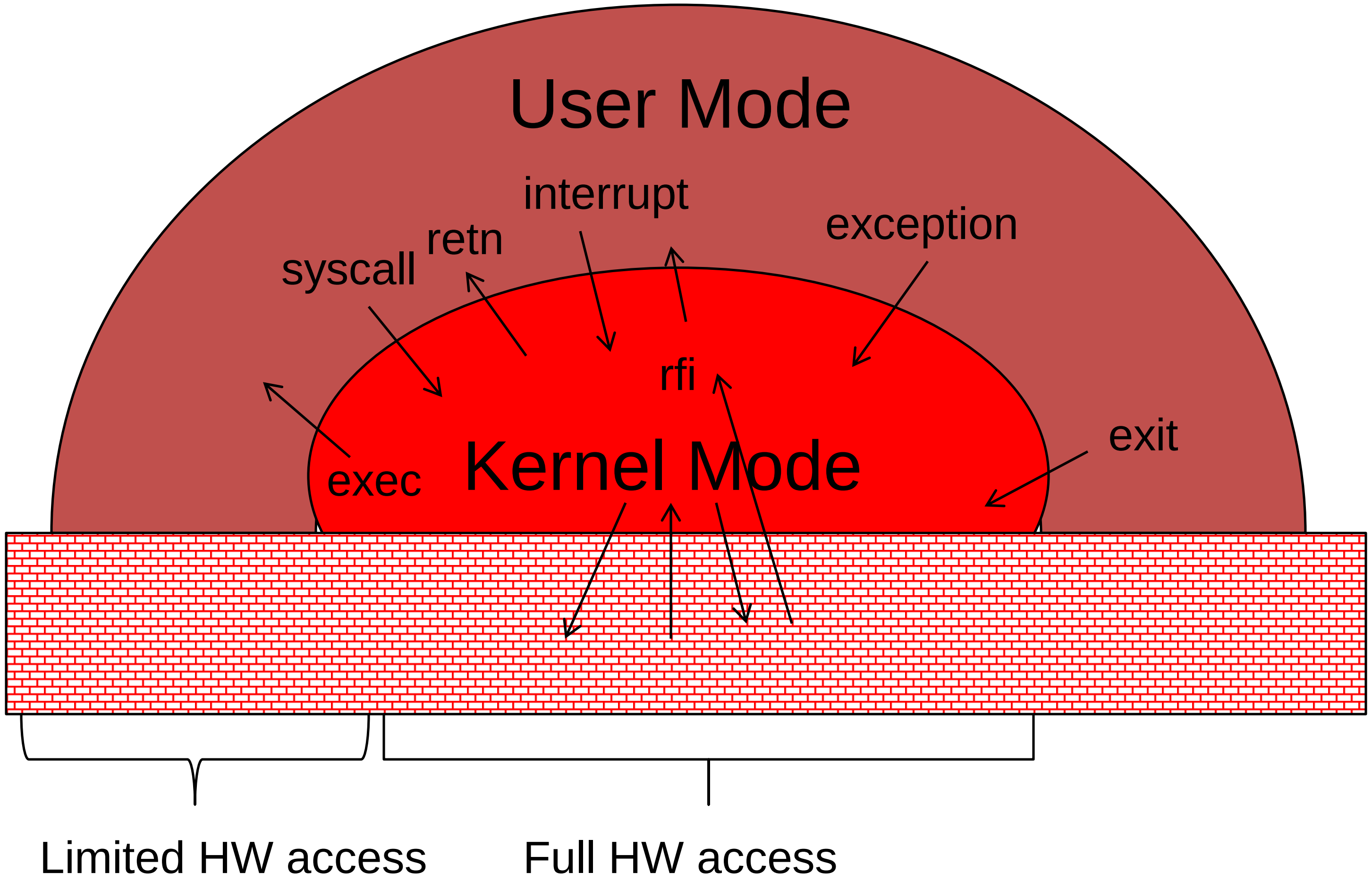
Example: After Exception

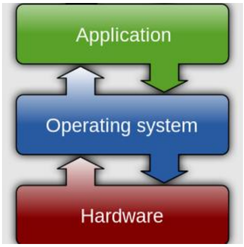


Why don't we just use the user stack?



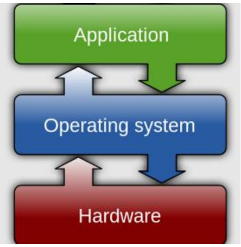
Life of a Process





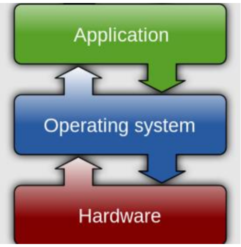
Implementing Safe User → Kernel Mode Transfers

- Carefully constructed kernel code packs up the user process state and sets it aside
- Must handle weird/buggy/malicious user state
  - Syscalls with null pointers, or otherwise invalid arguments
  - Return instruction out of bounds
  - User stack pointer out of bounds
- Should be impossible for buggy or malicious user program to cause the kernel to corrupt itself
- User program should not know that an interrupt has occurred (transparency)



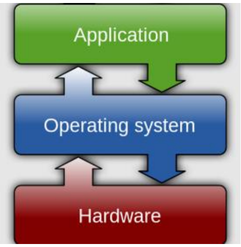
Kernel System Call Handler

- Vector through well-defined syscall entry points!
  - Table mapping system call number to handler
- Locate arguments
  - In registers or on user (!) stack
- Copy arguments
  - From user memory into kernel memory – carefully checking locations!
  - Protect kernel from malicious code evading checks
- Validate arguments
  - Protect kernel from errors in user code
- Copy results back
  - Into user memory – carefully checking locations!



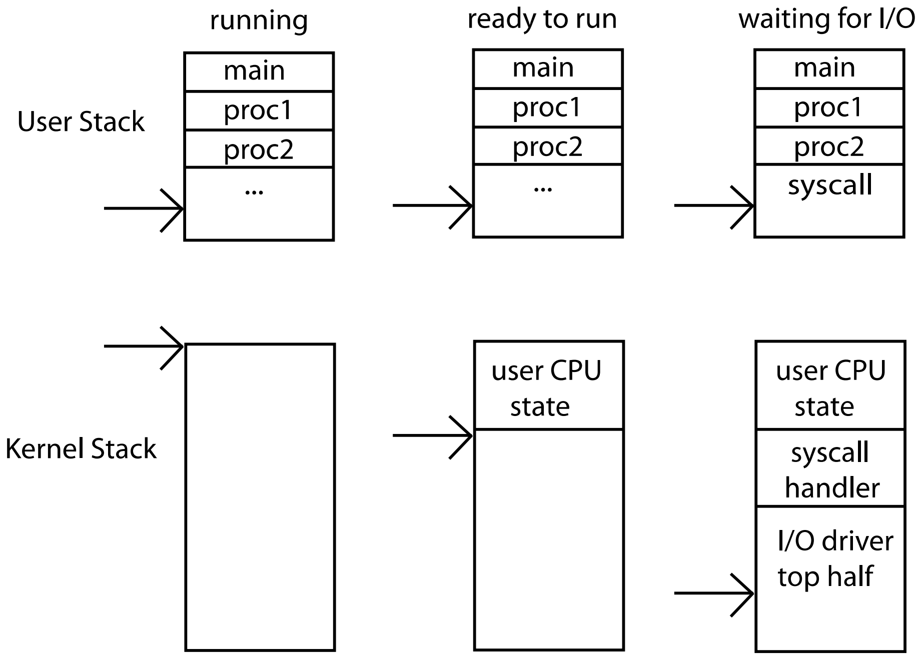
Kernel Stacks

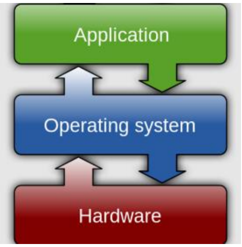
- Interrupt handlers want a stack
- System call handlers want a stack
- Can't just use the user stack [why?]
  - More convenient to store execution state of kernel if additional interrupt is required (i.e. waiting for I/O operation, etc.)
  - User-stack is in user-space
    - Other user-threads could maliciously modify entries the kernel put on the stack of the interrupted thread
  - Works regardless of state of user-process
    - User data could be corrupt or compromised



Kernel Stacks

- One Solution: two-stack model
  - Each thread has user stack and a kernel stack
  - Kernel stack stores user's registers during an exception
  - Kernel stack used to execute exception handler in the kernel

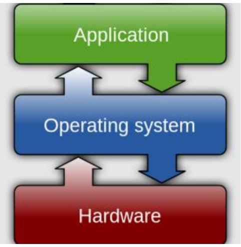




Hardware Support: Interrupt Control

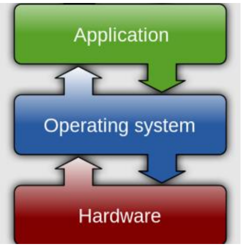
- Interrupt processing not visible to the user process:
  - Occurs between instructions, restarted transparently
  - No change to process state
  - Happens transparently to the process—user program does not know it was interrupted

- Interrupt Handler invoked with interrupts 'disabled'
  - Re-enabled upon completion
  - Non-blocking (run to completion, no waits)
  - Pack up task in a queue and pass off to an OS thread for hard work
    - wake up an existing OS thread



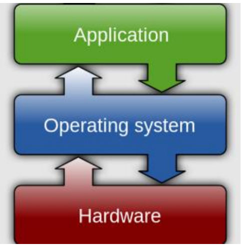
Hardware Support: Interrupt Control

- Interrupt processing not visible to the user process:
  - Occurs between instructions, restarted transparently
  - No change to process state
  - What can be observed even with perfect interrupt processing?
    - Execution time!
- Interrupt Handler invoked with interrupts 'disabled'
  - Re-enabled upon completion
  - Non-blocking (run to completion, no waits)
  - Pack up in a queue and pass off to an OS thread for hard work
    - wake up an existing OS thread



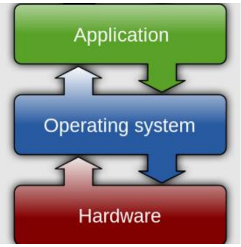
How do we take Interrupts Safely?

- Interrupt vector
  - Limited number of entry points into kernel
- Kernel interrupt stack
  - Handler works regardless of state of user code
- Interrupt masking
  - Handler is non-blocking
- Atomic transfer of control
  - "Single instruction"-like to change:
    - Program counter
    - Stack pointer
    - Memory protection
    - Kernel/user mode
- Transparent restartable execution
  - User program does not "know" interrupt occurred



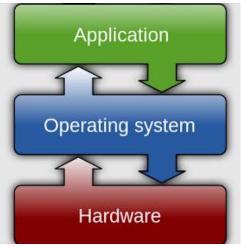
Kernel → User Mode Transfers

- "Return from interrupt" instruction
  - Drops mode from kernel to user privilege
  - Restores user PC and stack
- Transfer to user mode happens for:
  - Creation of a new process
  - Switching to a different process
  - User-level upcalls (signal handling, etc.)



Today: Four Fundamental OS Concepts

- Thread: Execution Context
  - Program Counter, Registers, Execution Flags, Stack
- Address Space (with Translation)
  - Program's view of memory is distinct from physical machine
- Process: Instance of a Running Program
  - Address space + one or more threads + …
- Dual-Mode Operation and Protection
  - Only the "system" can access certain resources
  - Combined with translation, isolates programs from each other

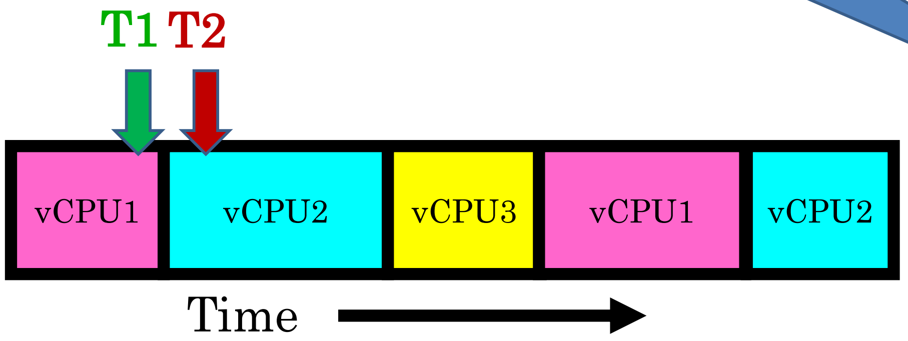


Now, let's put it all together!

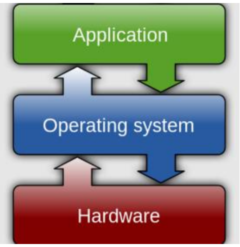
Illusion of Multiple Processors

Scheduling

On a single physical CPU:



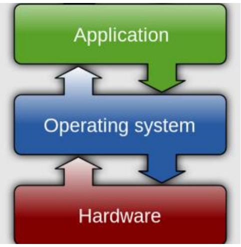
- At T1: vCPU1 on real core
- At T2: vCPU2 on real core
- How did the OS get to run?
  - Earlier, OS configured a hardware timer to periodically generate an interrupt
  - On the interrupt, the hardware switches to kernel mode and the OS's timer interrupt handler runs
  - Timer interrupt handler decides whether to switch threads or not according to a policy



Scheduling

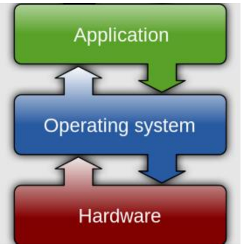
```
if ( readyProcesses(PCBs) ) {
        nextPCB = selectProcess(PCBs);
        run( nextPCB );
} else {
        run_idle_process();
}
```

- Scheduling: Mechanism for deciding which processes/threads receive the CPU
- Lots of different scheduling policies provide …
  - Fairness or
  - Realtime guarantees or
  - Latency optimization or …



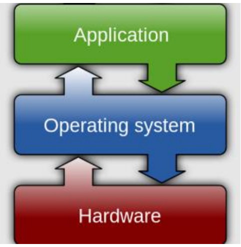
What's in a Process?

- Process Control Block (PCB): Kernel representation of each process
  - Process ID
  - Thread control block(s)
    - Program pointer, stack pointer, and registers for each thread
  - Page table (information for address space translation)
  - Necessary state to process system calls
    - Which files are open and which network connections are accessible to the process
  - All information that pertains to a process and has to be shared between all threads of said process
    - User information
    - File path of executable on disk
    - Current home directory of the process
    - Process privileges
    - Etc.

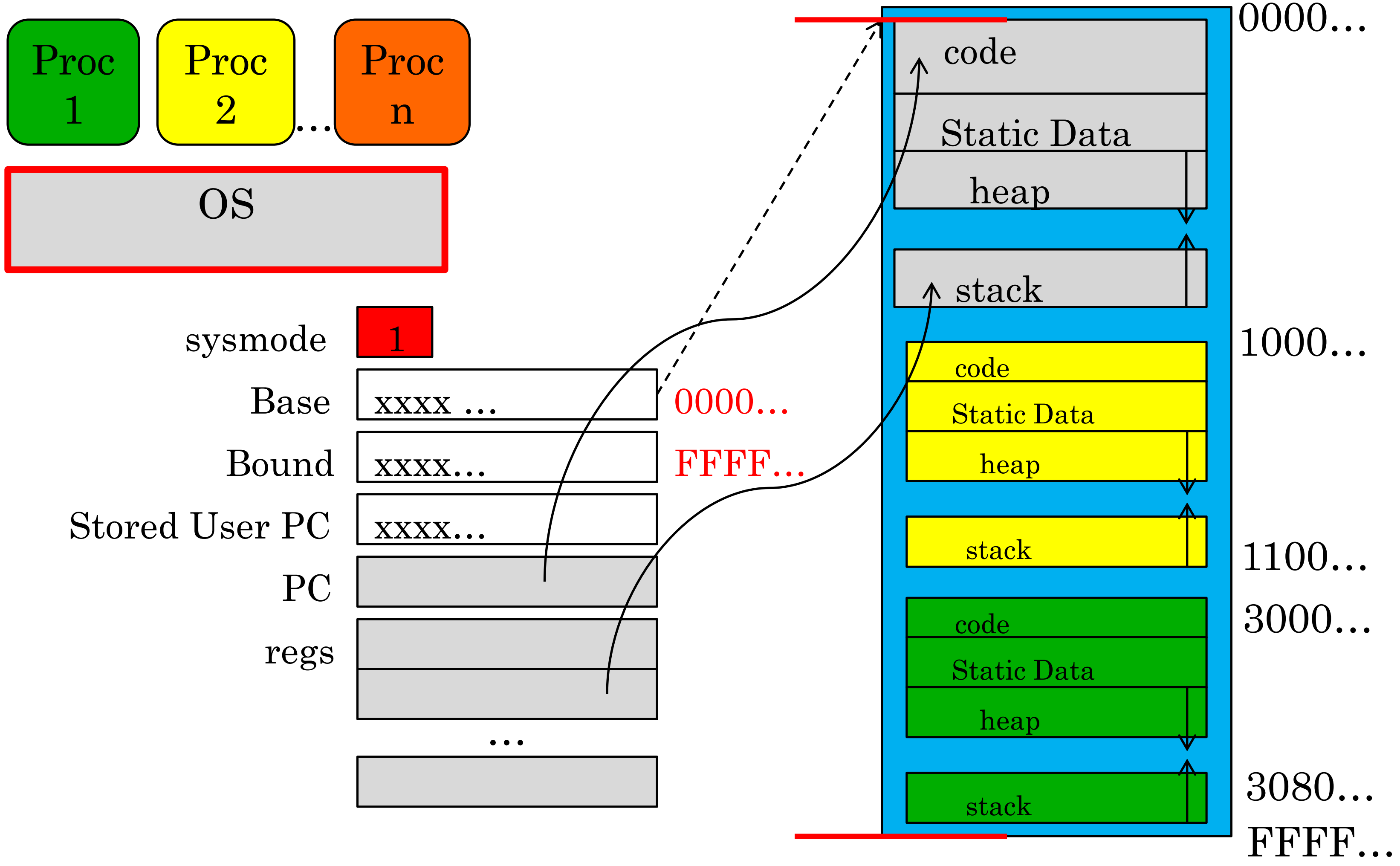


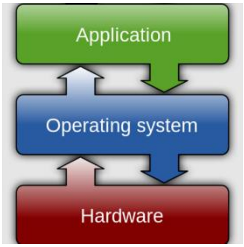
Mode Transfer and Translation

- Mode transfer should change address translation mapping
- Examples:
  - Ignore base and bound in kernel mode
  - Page tables:
    - Either switch to kernel page table…
    - Or mark some pages as only accessible in kernel mode

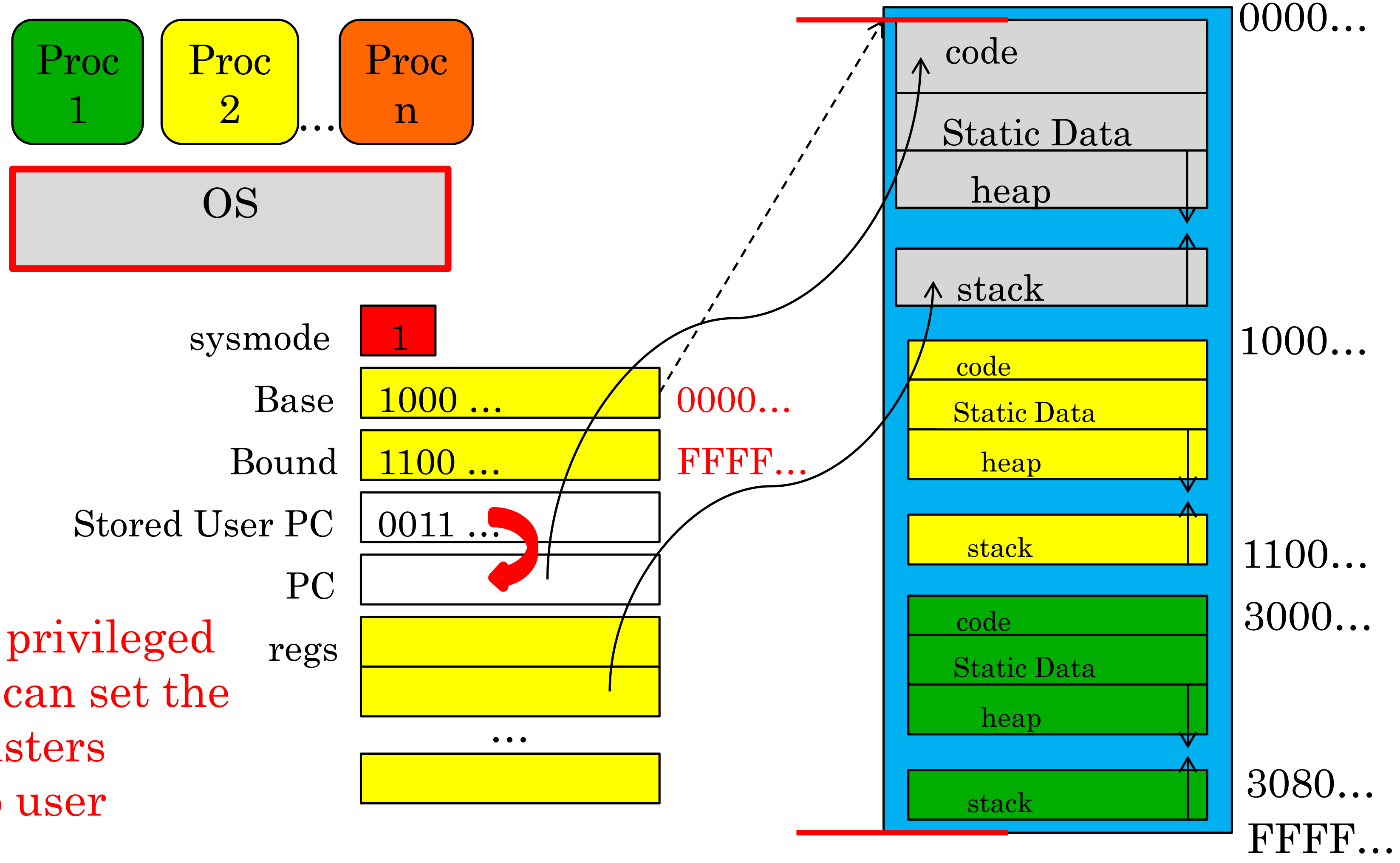


Base and Bound: OS Loads Process

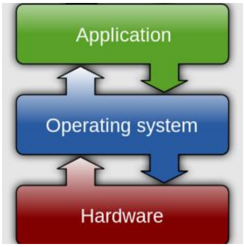




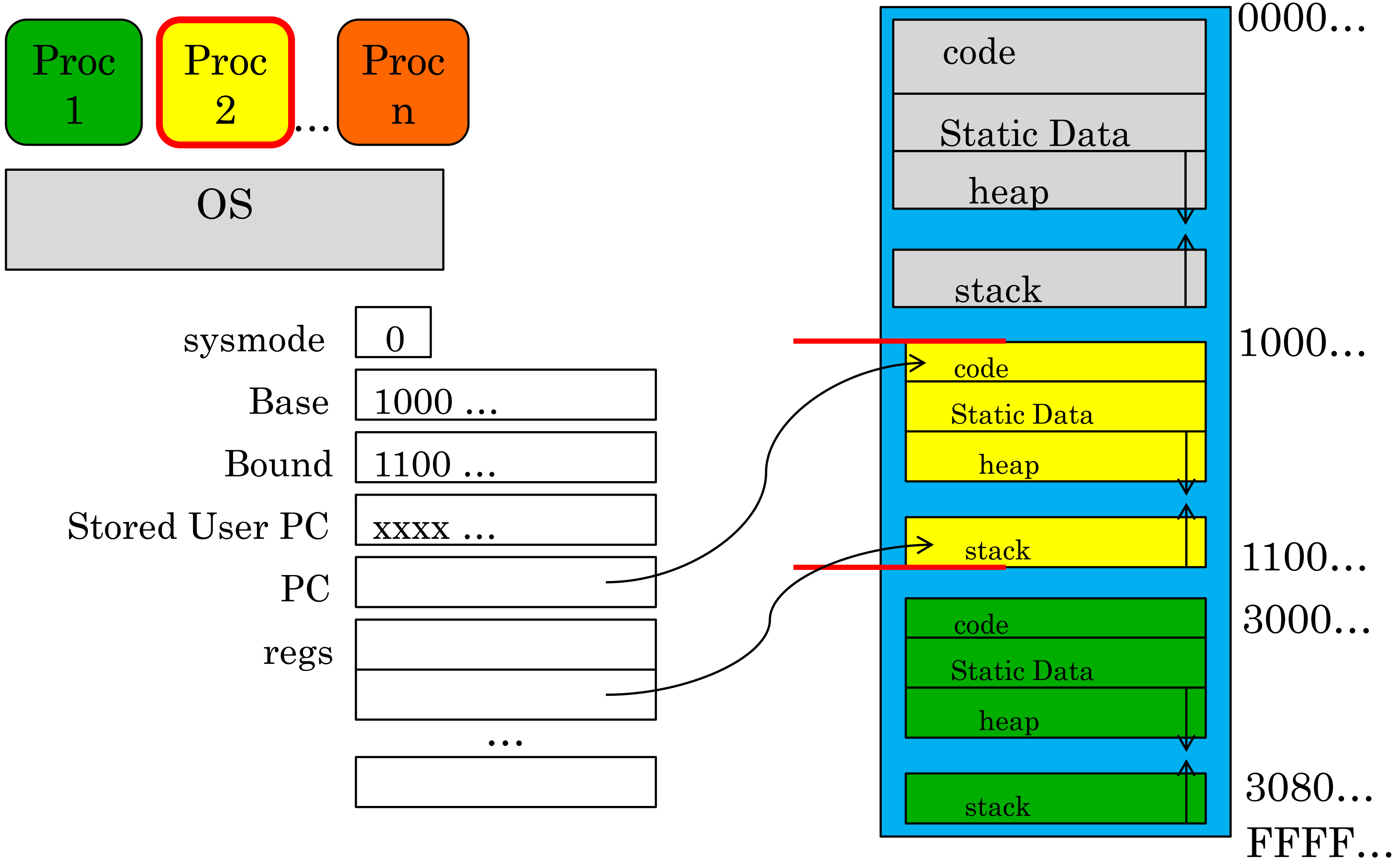
Base and Bound: About to Switch

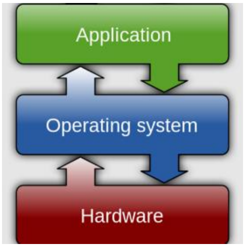


- OS runs in privileged mode, so it can set the special registers
- "Return" to user

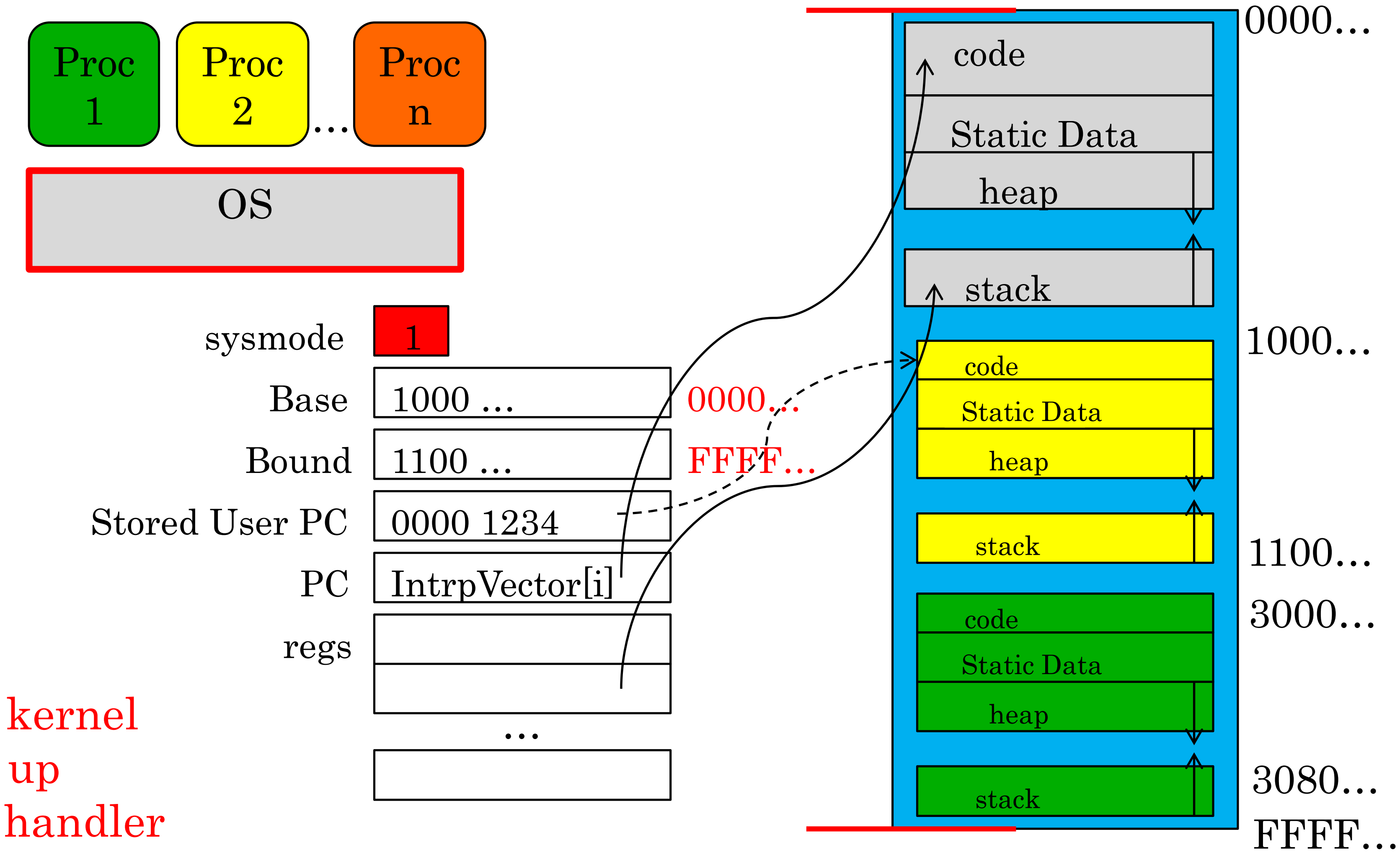


Base and Bound: User Code Running

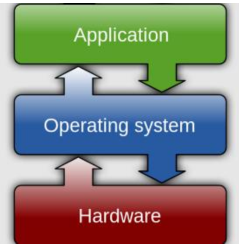




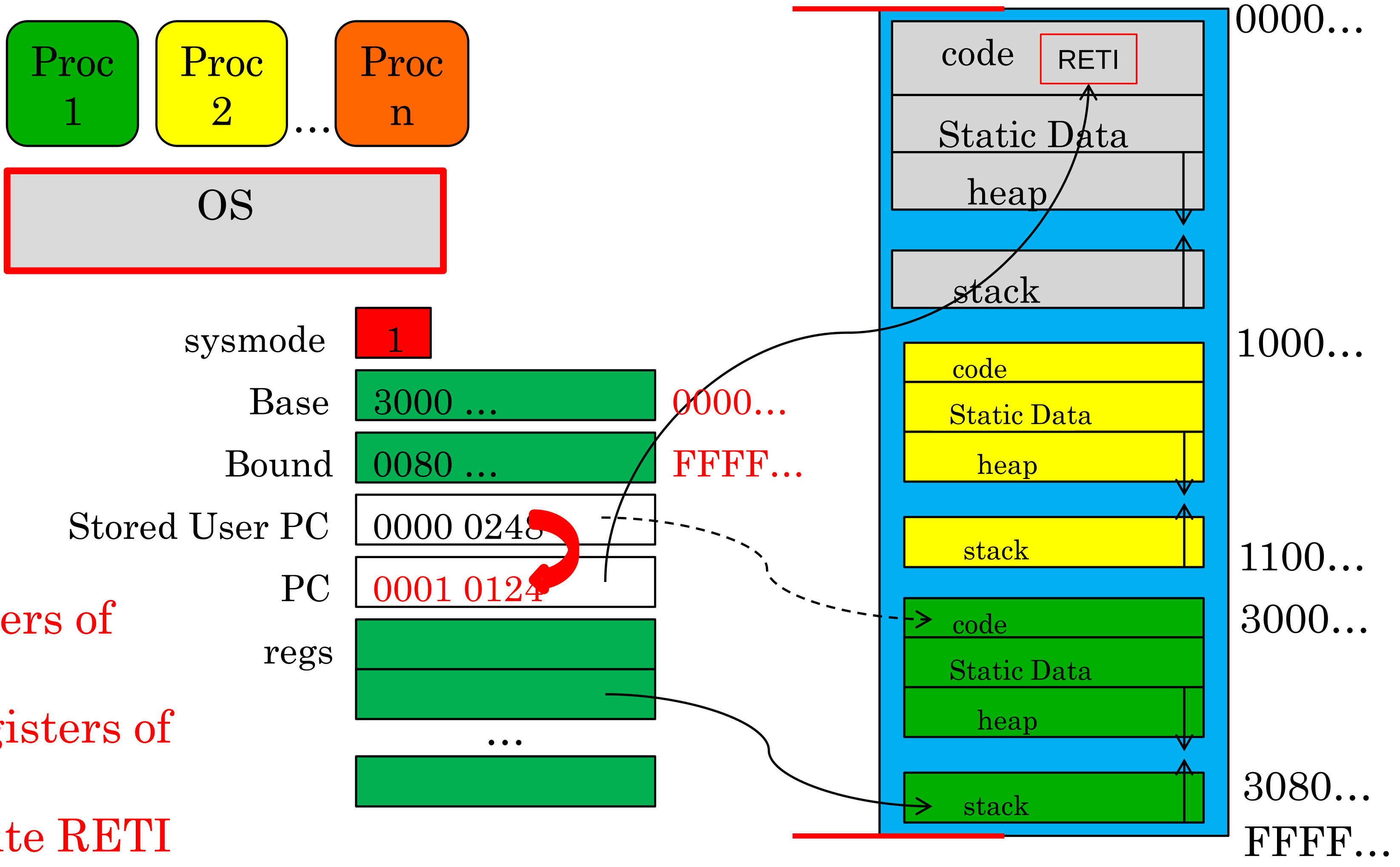
Base and Bound: Handle Interrupt



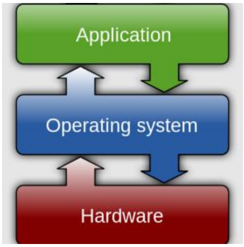
- Switch to kernel mode, set up interrupt handler



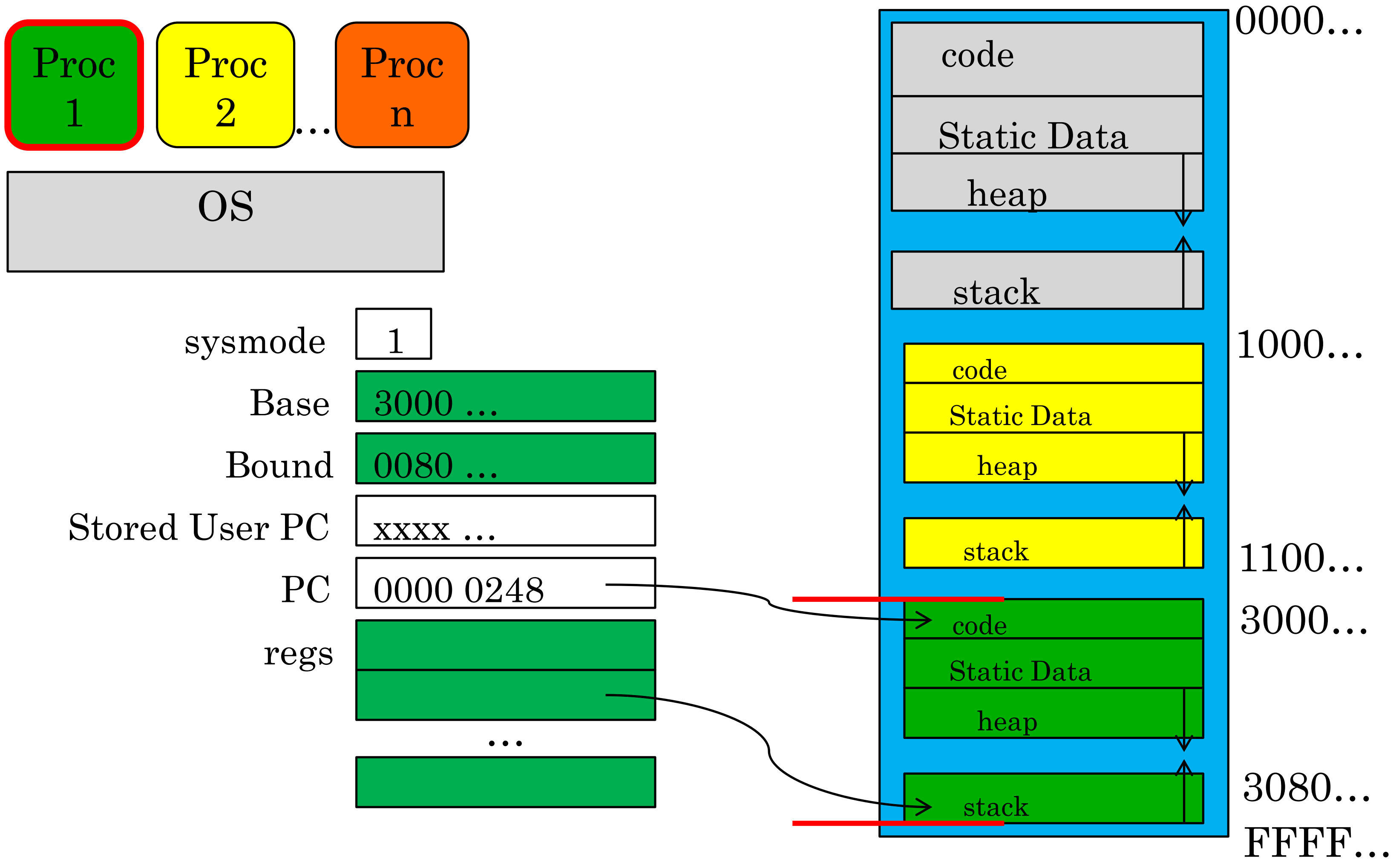
Base and Bound: Switch to Process 1

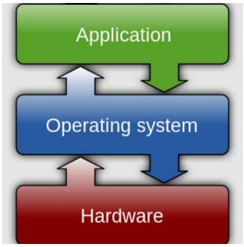


- Save registers of Process 2
- Restore registers of Process 1
- Then execute RETI

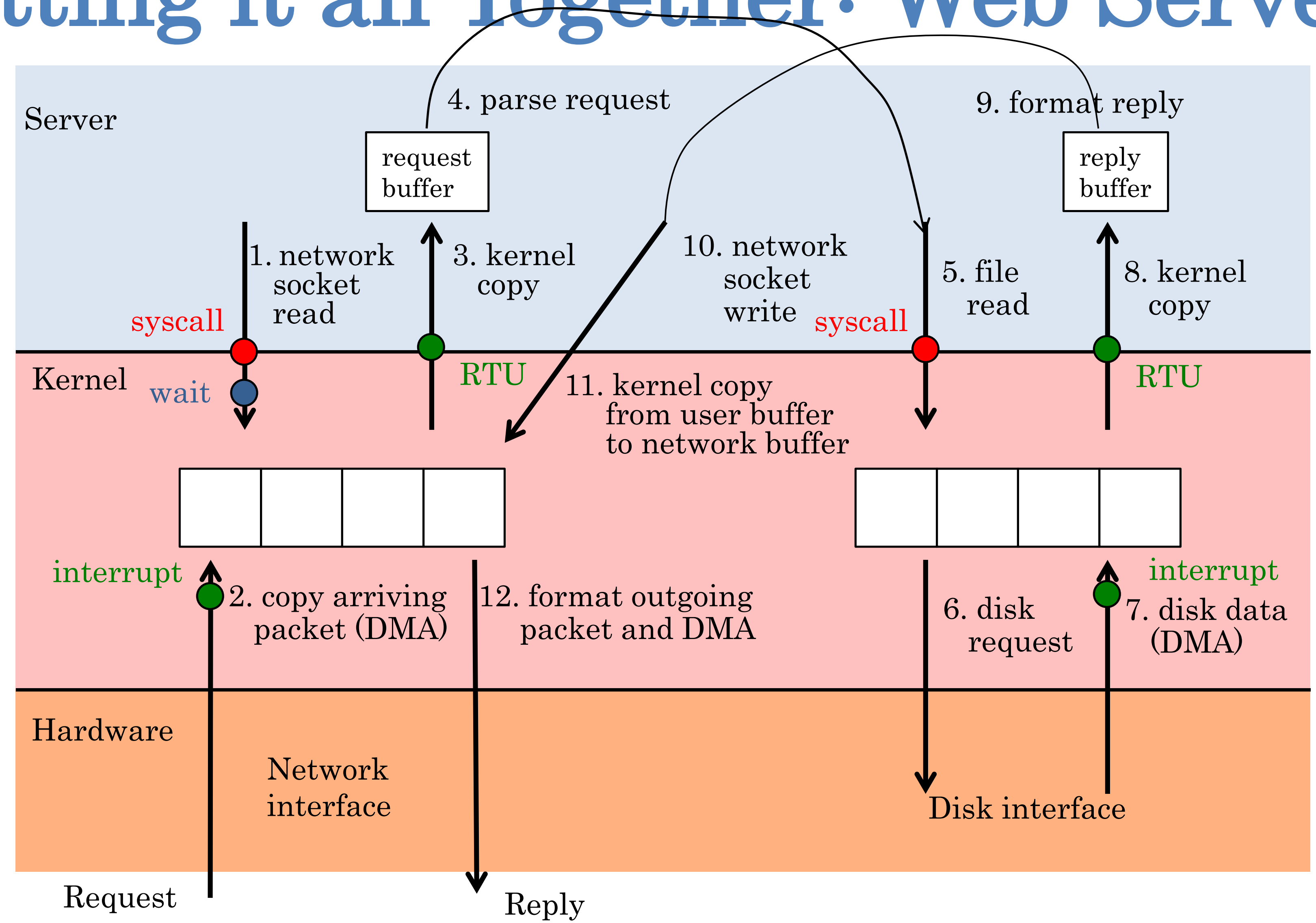


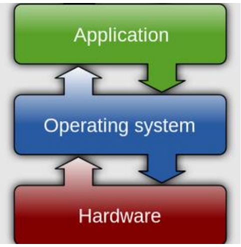
Base and Bound: Switch to Process 1





Putting it all Together: Web Server





Conclusion: Four Fundamental OS Concepts

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  - Only the "system" can access certain resources
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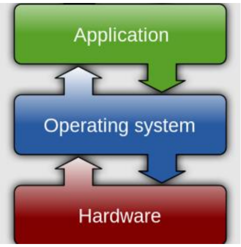

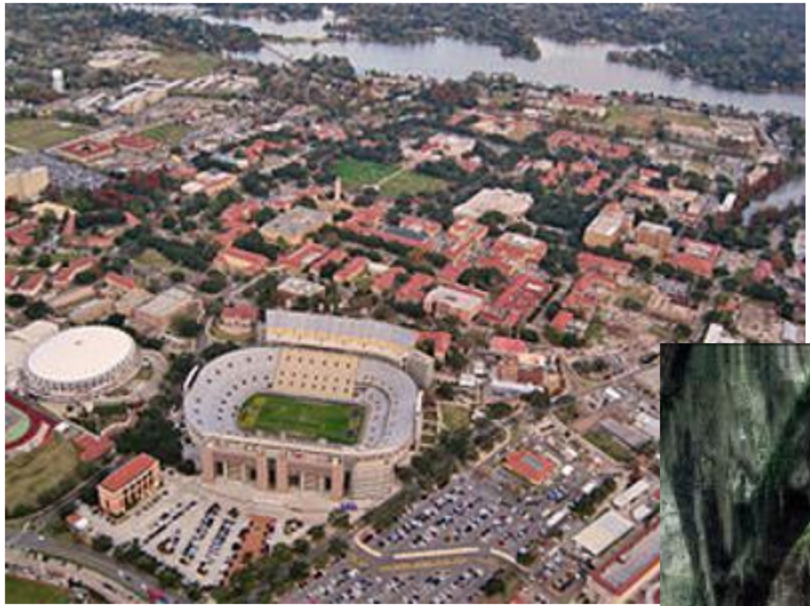

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