OS

Operating Systems

Lecture 3

Physical Memory Management

IIS & CS
Tsinghua University

Acknowledgement:
materials from Dr. Zhang Yong Guang in MSRA,
And from http://williamstallings.com/OS/OS5e.html , http://www.os-book.com

OS

Review

- Dual Mode Operation
- What is an Interrupt/Exception/System Call?
- The difference of Interrupt/Exception/System Call
- X86 related
  - How to build IDT
  - The hardware processing when INT happens
  - The software processing when INT happens
  - The system call processing (non-privilege(user) mode /privilege(supervisor) mode)
  - The different stacks in different privilege mode

Review: Dual-mode operation

- Why do we have "user mode" and "kernel mode"?
- Problem: Would you trust any users to … read and write memory, manage resource, access I/O, …?
- Solution: dual mode operation
  - ◆ CPU has a "mode" when it is executing an instruction
  - ◆ "User Mode": can only perform a restricted set of operation (applications)
  - ◆ "Kernel Mode": can do anything (OS kernel)

From “User Mode” to “Kernel Mode”

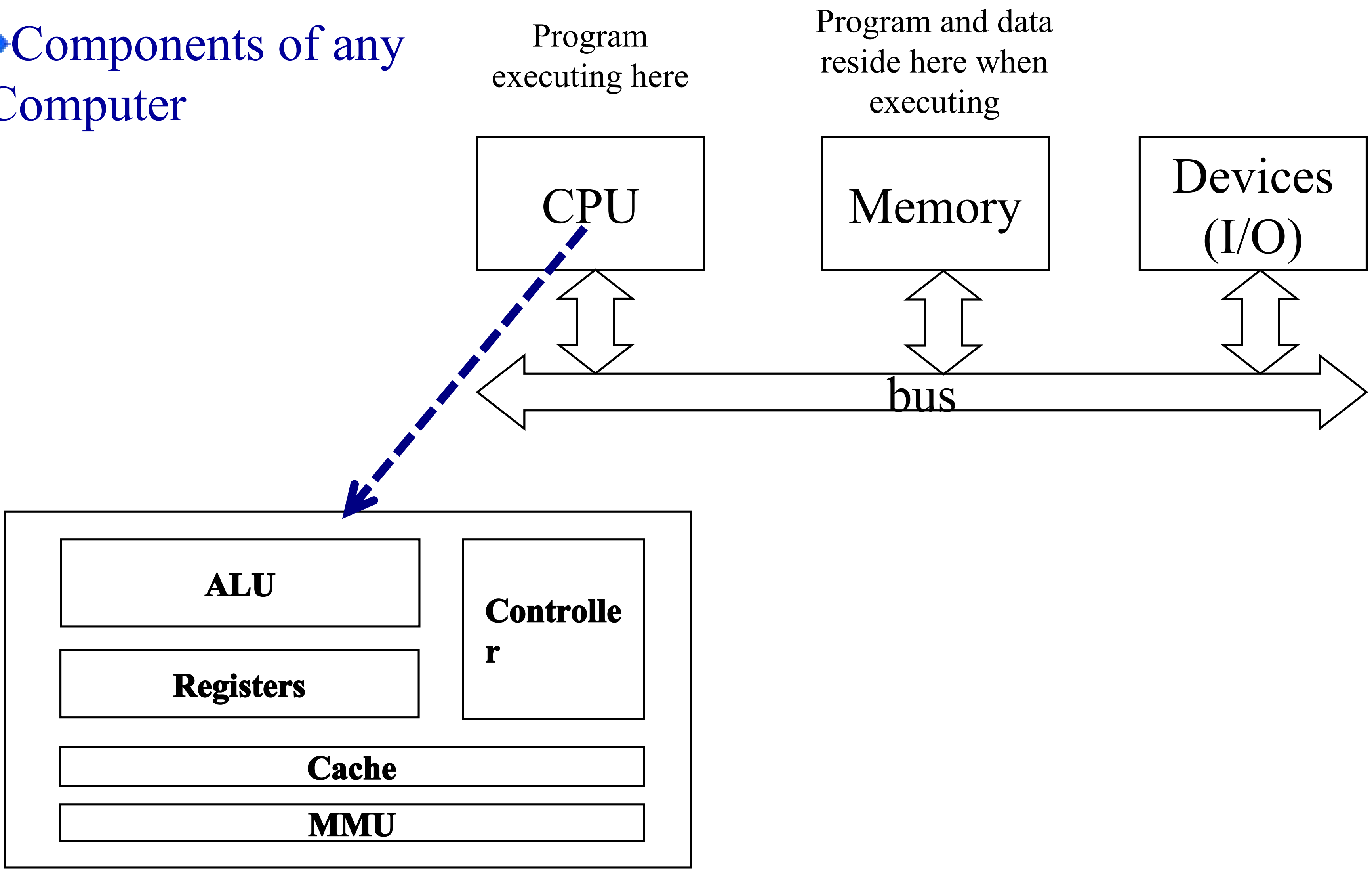
- Interrupt: hardware device requests OS service
  - CPU interrupts current execution and jumps to interrupt handler, and returns when done
  - None of this is visible to user program
- Exceptions: user program acts illegally
  - CPU executes exception handlers
  - May cause abnormal execution flow (such as terminated)
- System calls: user program requests OS service
  - User program execute a trap instruction
  - OS identifies the type of service and parameters, and executes the requested service
  - OS returns to user program when done
  - This appears as a function call to the user program

Outline

- Computer Arch/Memory Hierarchy
- Address Space & Address Generation
- Contiguous Memory Allocation
  - Dynamic Allocation of Partitions
- Non-Contiguous Memory Allocation
  - Segmentation
  - Paging
  - Page Table
    - Translation Look-aside Buffer (TLB)
    - Multi-Level Page Table
    - Inverted Page Table
  - Paged Segmentation Model

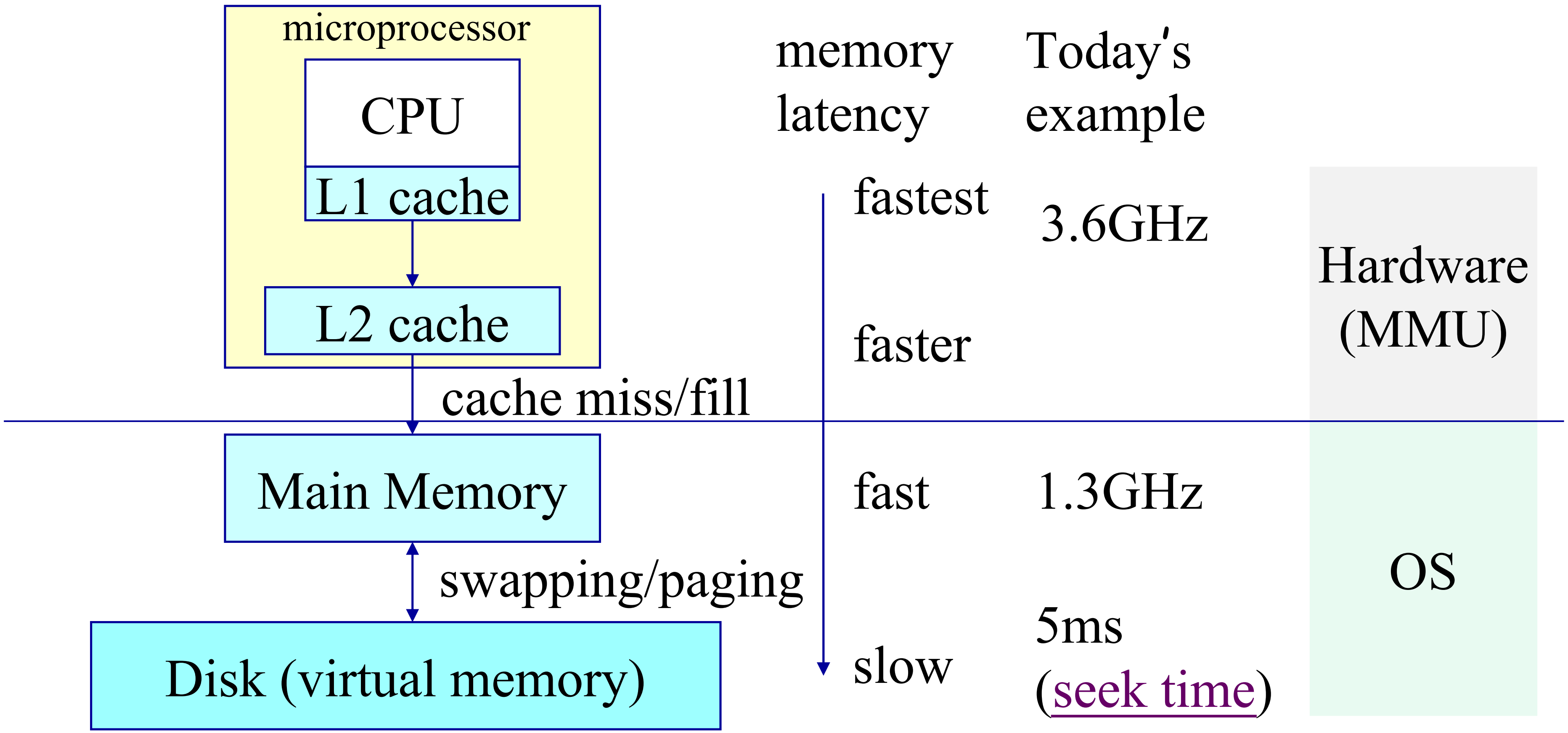
Brief Introduction to Computer Architecture

- Components of any Computer

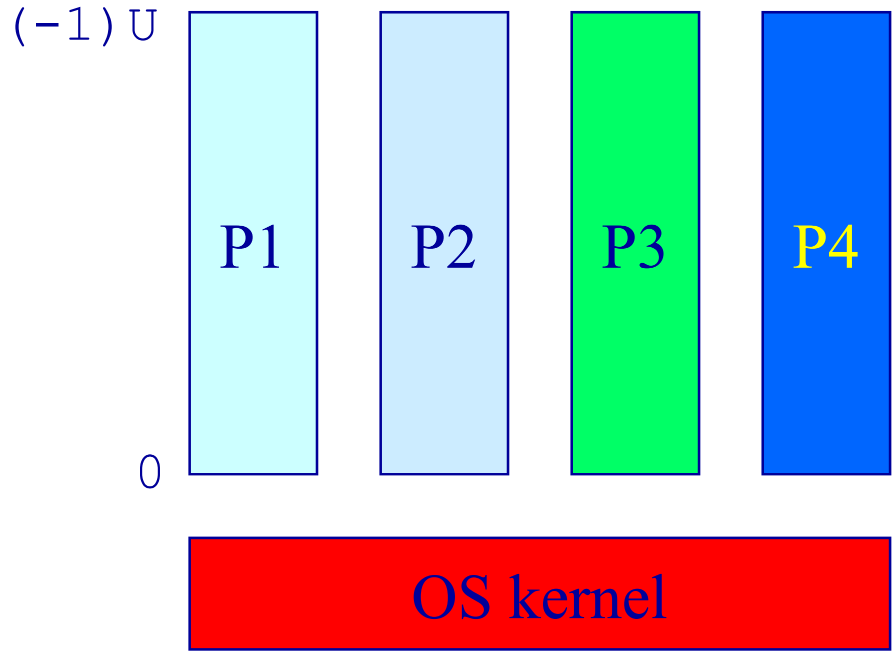


Intel® 64 and IA-32 Architectures Software Developer Manuals

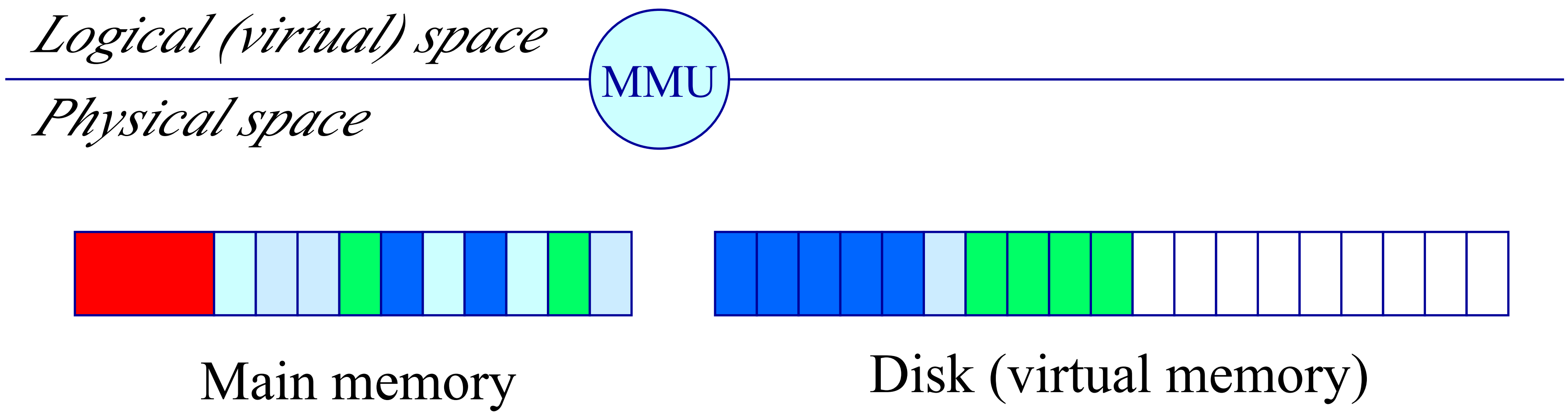
Memory Hierarchy



Modern Memory Management Paradigm



- Abstraction
  - Logical address space
- Protection
  - Isolation
- Programming models
  - Shared memory



OS Memory Models

- Different ways to manage memory in an OS
  - Program relocation
  - Segmentation
  - Paging
  - Virtual memory
  - Mostly (e.g., Linux): demand paging virtual memory

- Implementation highly hardware dependent
  - Must know memory architecture
  - MMU (Memory Management Unit): hardware components responsible for handling memory accesses requested by the CPU

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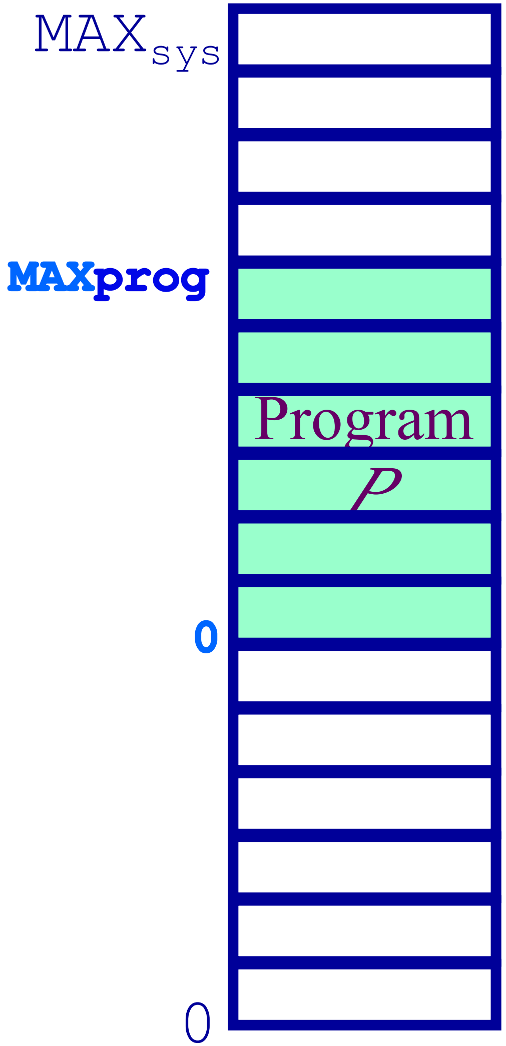
Address Space & Address Generation

address space

- *Physical address space* — The address space supported by the hardware
    - Starting at address `0`, going to address $\mathbf{MAX}_{sys}$

- *Logical address space* — A process's view of its own memory
    - Starting at address `0`, going to address $\mathbf{MAX}_{prog}$



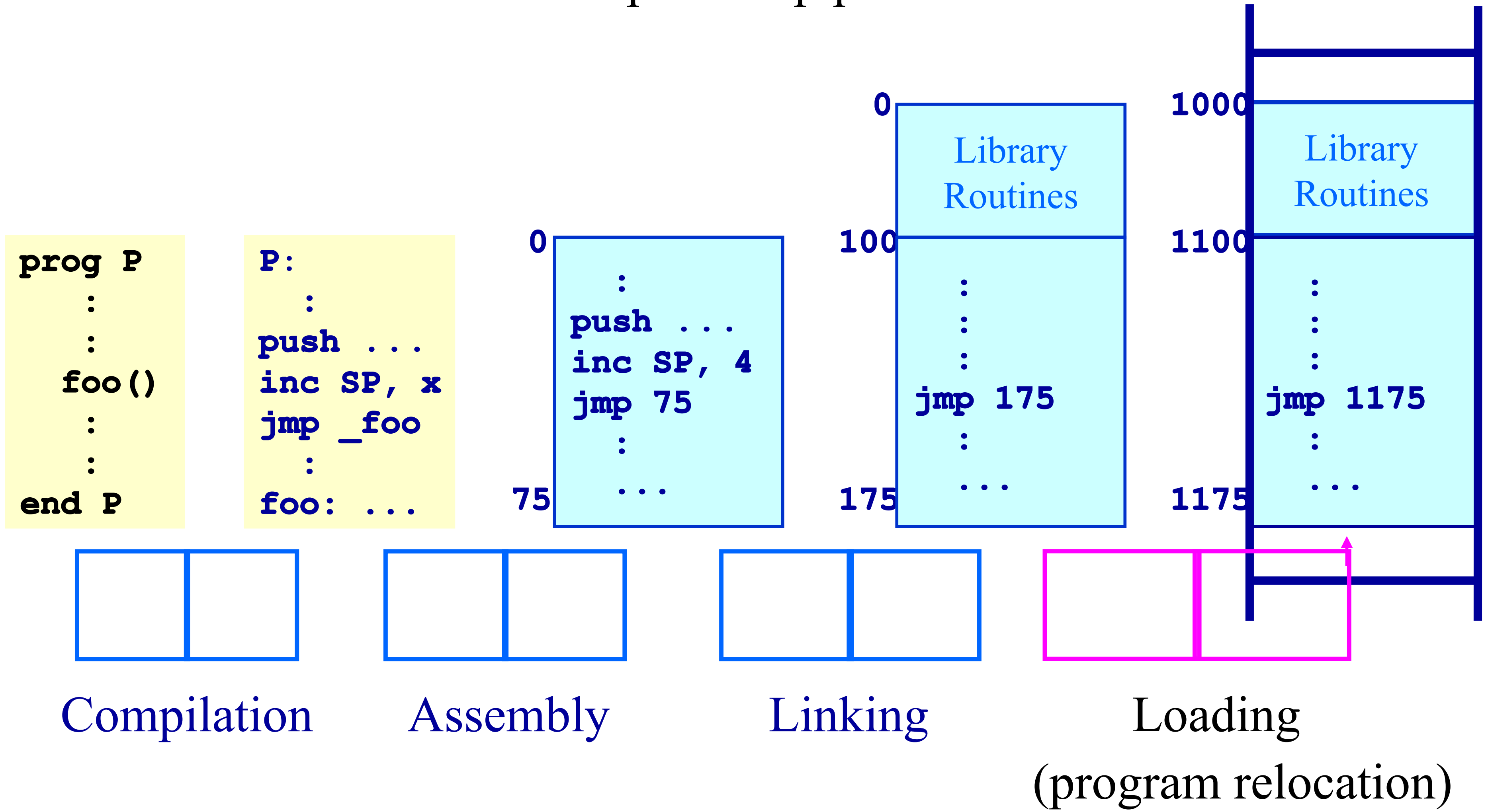
But where do addresses come from?

```
movl %eax, $0xfffa620e
```

Address Space & Address Generation

Address Generation

- The compilation pipeline



Address Space & Address Generation

Address Generation Time

- Compile time
  - If memory location known a priori
  - Must recompile code if starting location changes
- Load time
  - Compiler must generate *relocatable* code if memory location is not known at compile time
  - Absolute addresses generated at load time
- Execution time
  - The process can be moved during its execution
  - Need hardware support for address translation

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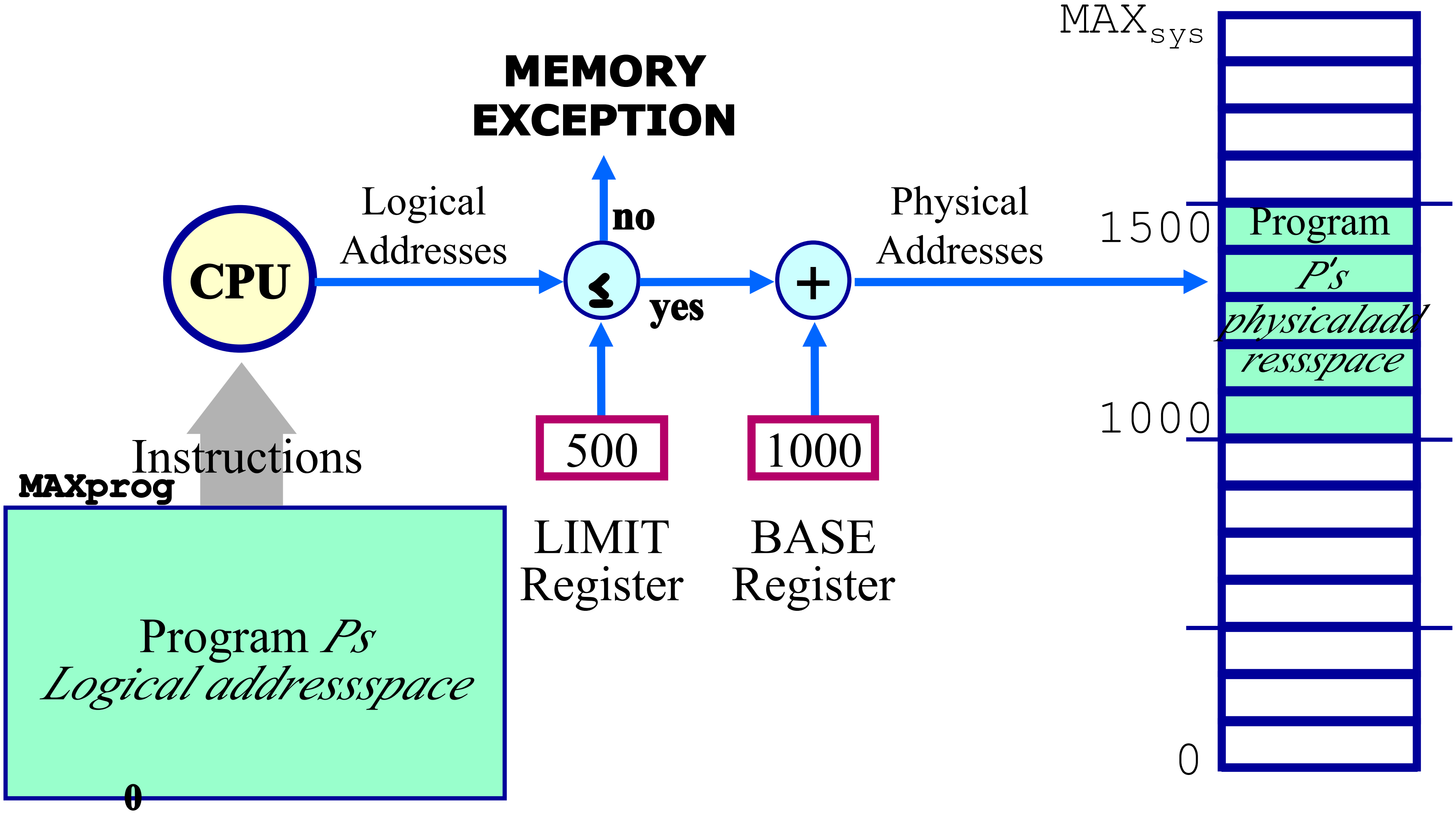
Address Space & Address Generation

Program Relocation

- Relocate logical addresses to physical at run time
  - While we are relocating, also bounds check addresses for safety.
- Require hardware support (MMU)
- Basic component
  - Address translation with two registers: BASE and LIMIT

Contiguous Memory Allocation

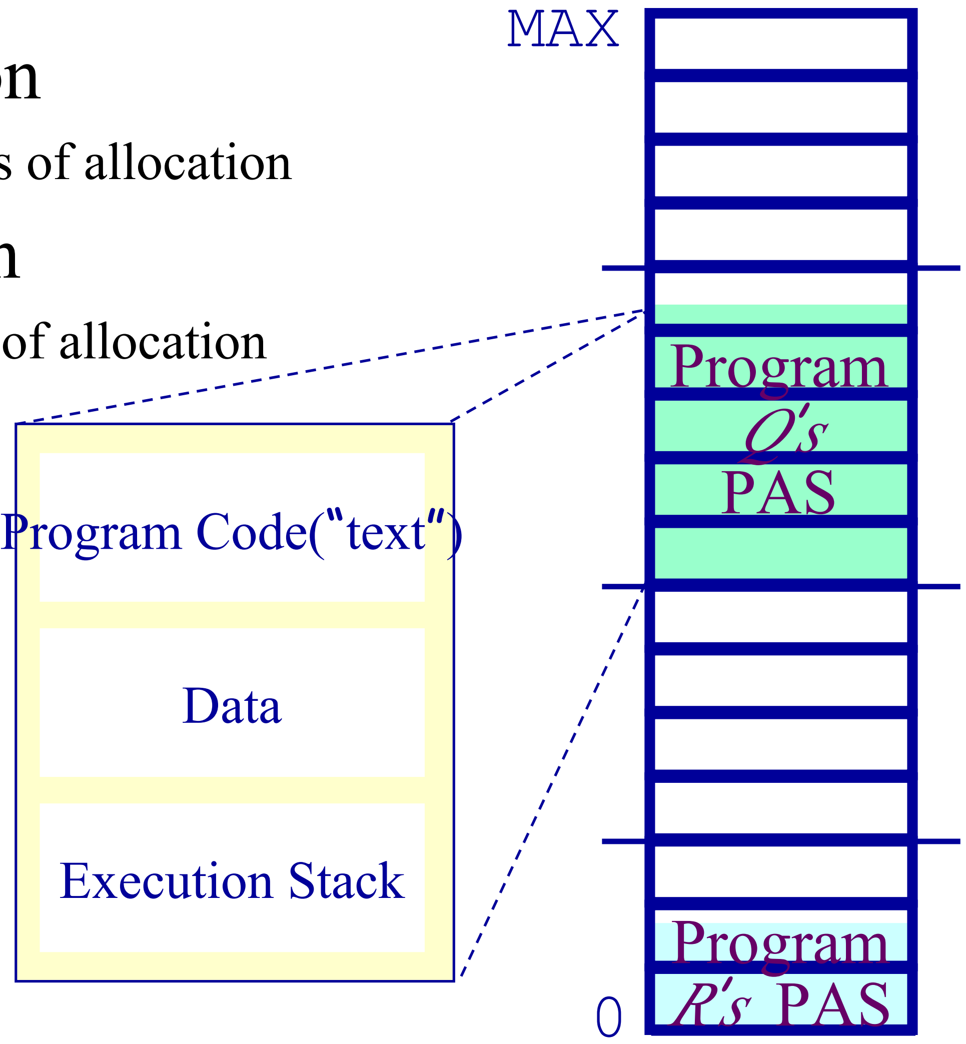
Address Translation



Contiguous Memory Allocation

The Fragmentation Problem

- Free memory cannot be utilized
- External fragmentation
  - Unused memory between units of allocation
- Internal fragmentation
  - Unused memory within a unit of allocation

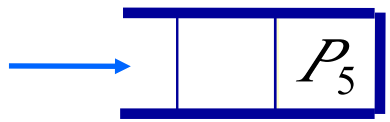


Contiguous Memory Allocation

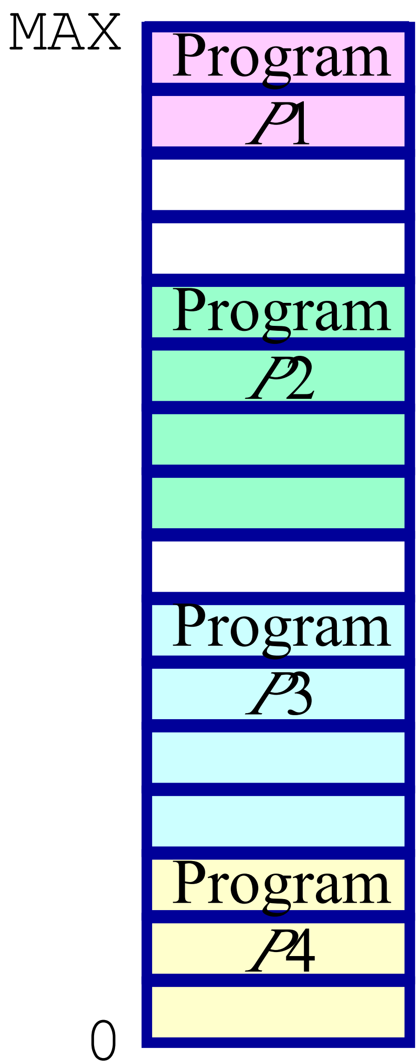
Dynamic Allocation of Partitions

- Simple memory management approach:
  - Allocate a partition when a process is admitted into the system
  - Allocate a contiguous memory partition to the process

OS keeps track of...
Full-blocks
Empty-blocks ("holes")



Allocation strategies
First-fit
Best-fit
Worst-fit

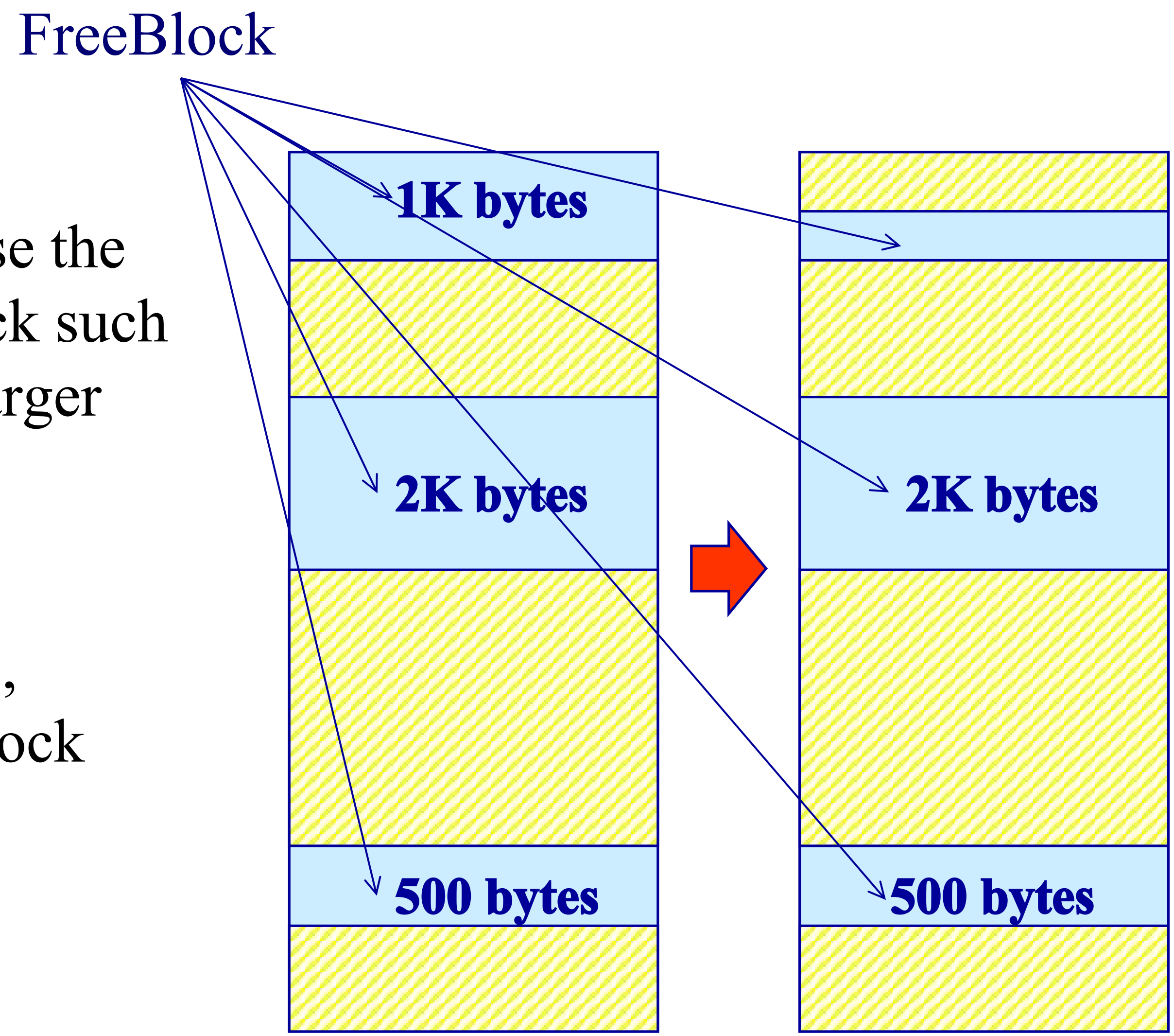


Contiguous Memory Allocation

First Fit Allocation

To allocate *n* bytes, use the *first* available free block such that the block size is larger than *n*.

To allocate 400 bytes, we use the 1st free block available



OS

Contiguous Memory Allocation

Rationale & Implementation

- Simplicity of implementation
- Requires:
  - Free block list sorted by address
  - Allocation requires a search for a suitable partition
  - De-allocation requires a check to see if the freed partition could be merged with adjacent free partitions (if any)

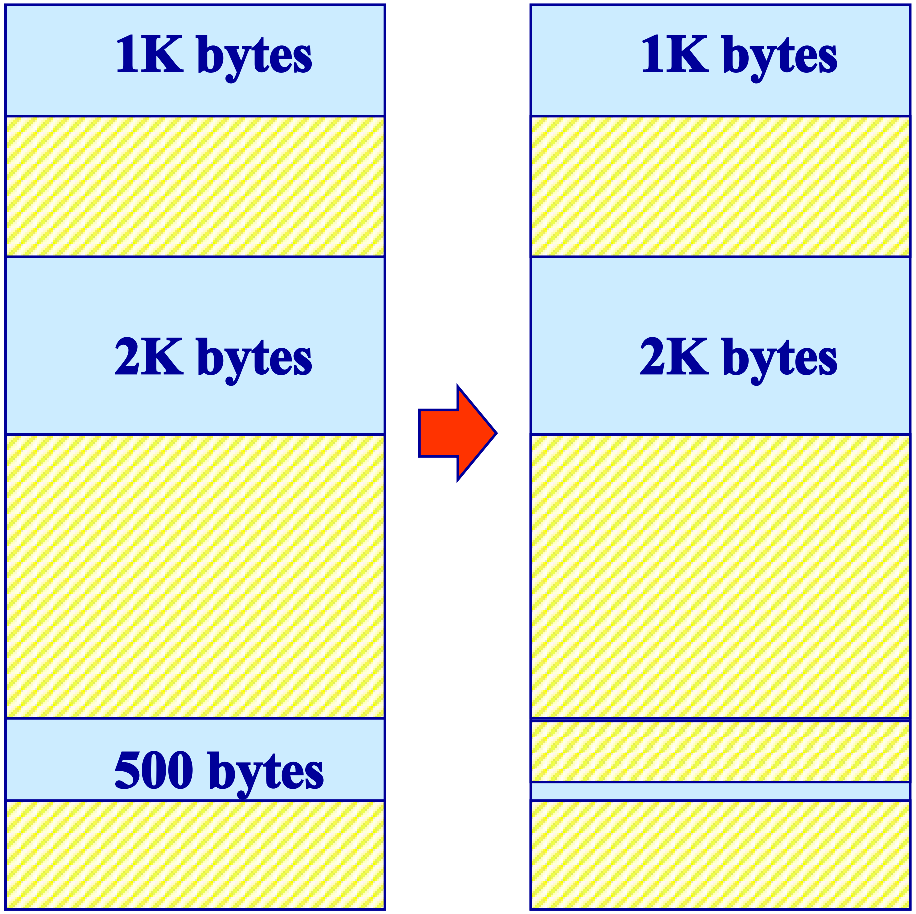
Advantages	Disadvantages
Simple	External fragmentation
Tends to produce larger free blocks toward the end of the address space	Uncertainty

Contiguous Memory Allocation

Best Fit Allocation

To allocate *n* bytes, use the *smallest* available free block such that the block size is larger than *n*.

To allocate 400 bytes, we use the 3rd free block available (smallest)



Contiguous Memory Allocation

Rationale & Implementation

- To avoid fragmenting big free blocks
- To minimize the size of external fragments produced
- Requires:
  - Free block list sorted by size
  - Allocation requires search for a suitable partition
  - De-allocation requires search + merge with adjacent free partitions, if any

Advantages

- Works well when most allocations are of small size
- Relatively simple

Disadvantages

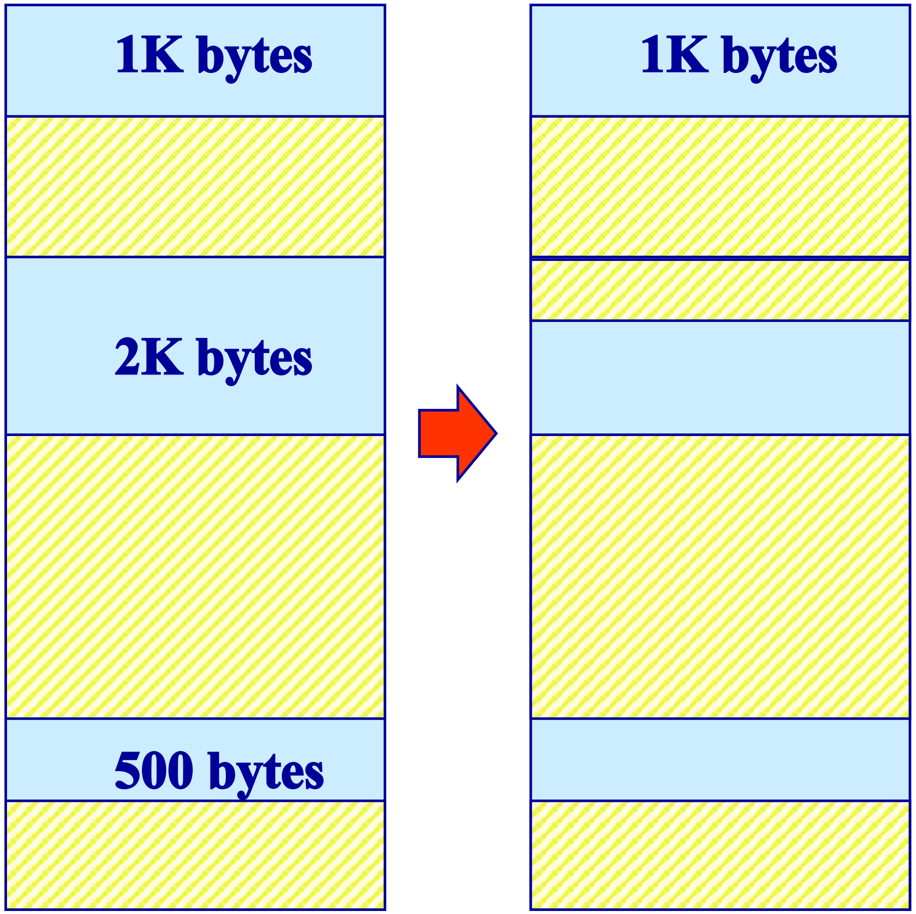
- External fragmentation
- Slow de-allocation
- Tends to produce many useless tiny fragments (not really great)

Contiguous Memory Allocation

Worst Fit Allocation

To allocate *n* bytes, use the *largest* available free block such that the block size is larger than *n.*

To allocate 400 bytes, we use the 2nd free block available (largest)



Contiguous Memory Allocation

Rationale & Implementation

- To avoid having too many tiny fragments
- Requires:
  - Free block list sorted by size
  - Allocation is fast (get the largest partition)
  - De-allocation requires merge with adjacent free partitions, if any, and then adjusting the free block list

Advantages

- Works best if allocations are of medium sizes

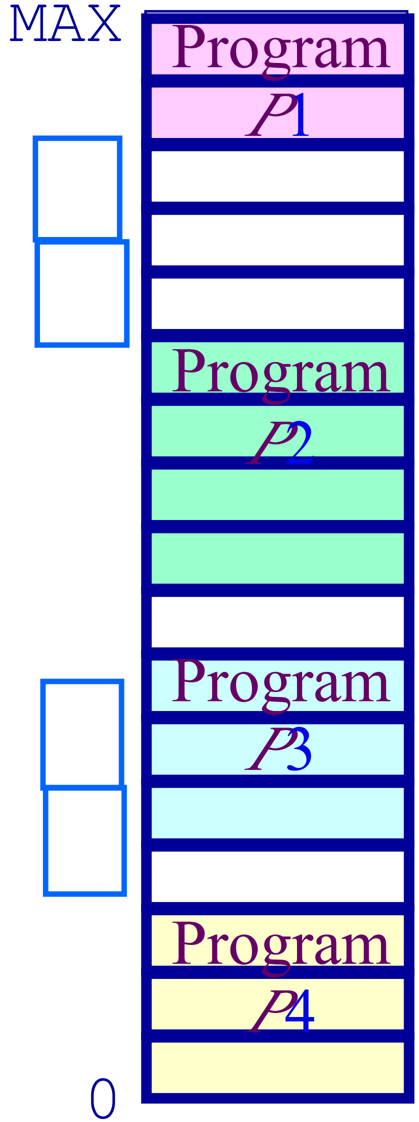
Disadvantages

- Slow de-allocation
- External fragmentation
- Tends to break large free blocks such that large partitions cannot be allocated

Contiguous Memory Allocation

De-fragmentation by Compaction

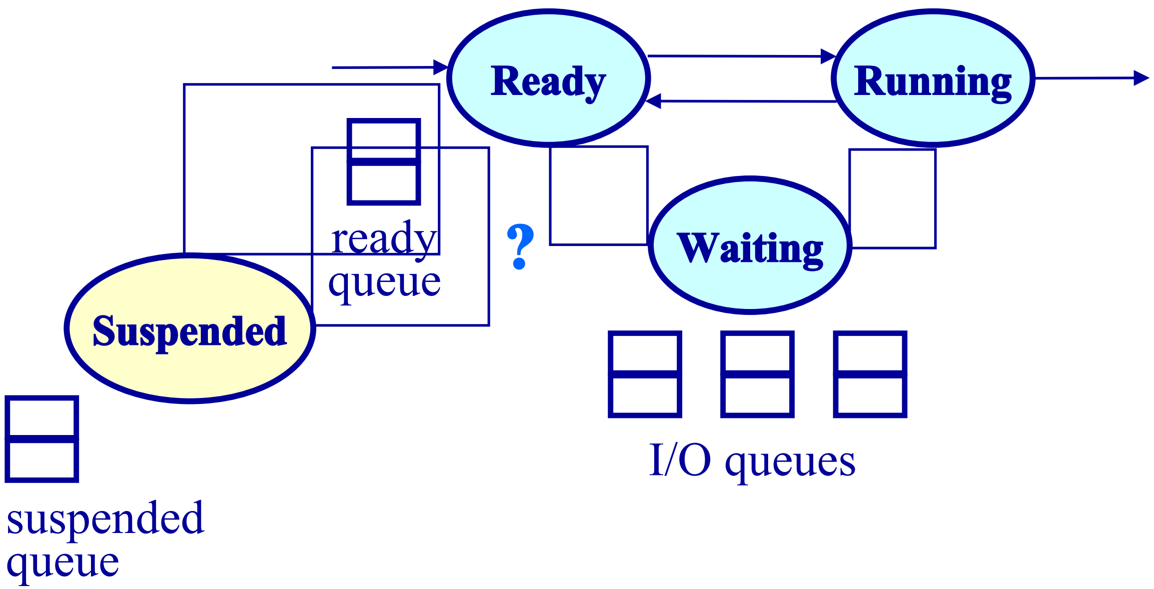
- Relocate programs to coalesce holes
- Require all programs to be dynamically relocatable
- Issues
  - When to relocate?
  - Overhead



Contiguous Memory Allocation

De-fragmentation by Swapping

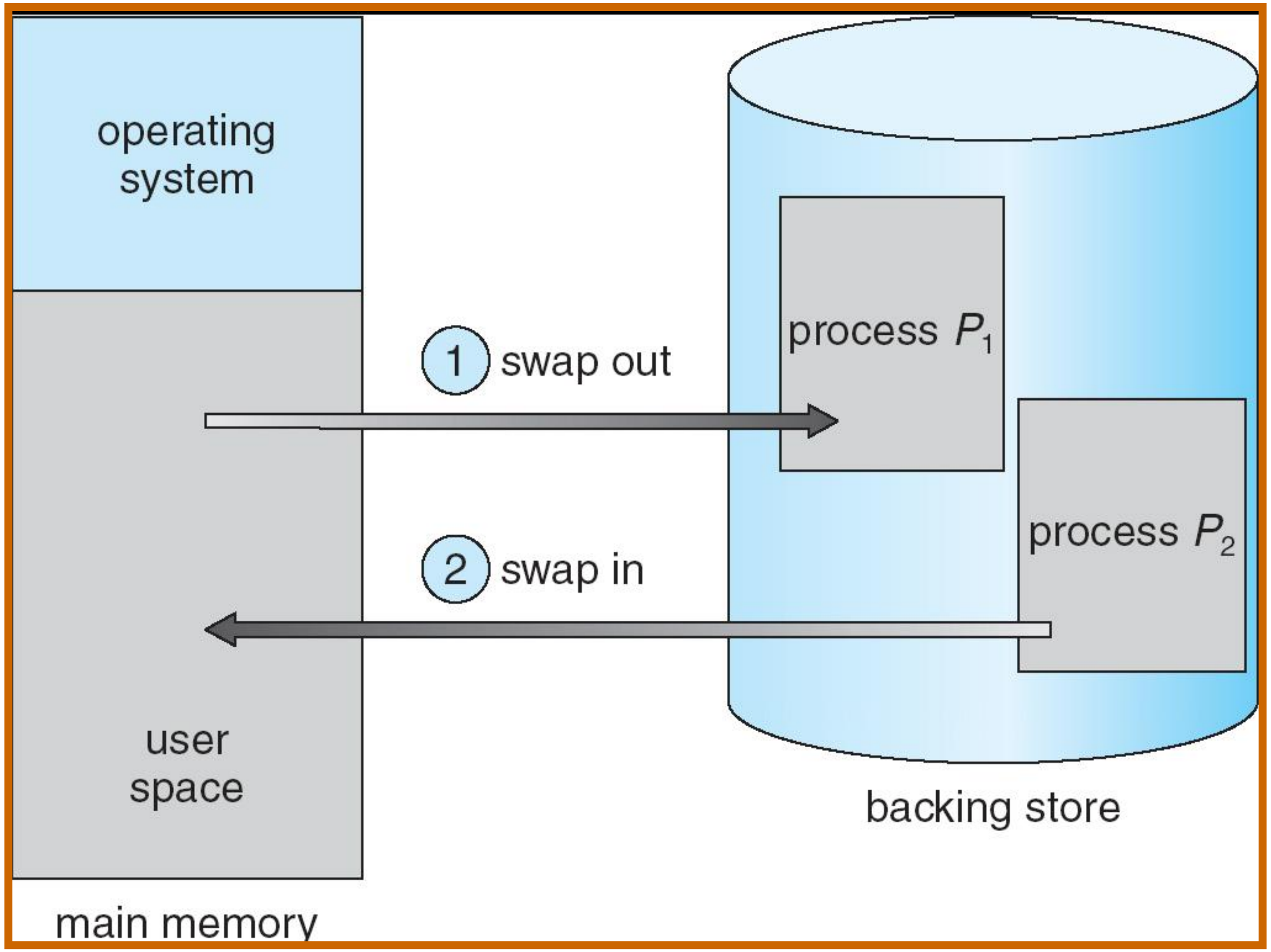
- Preempt processes & reclaim their memory



- Issue: which process(es) to swap?

Contiguous Memory Allocation

Schematic View of Swapping



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OS

Non-contiguous Allocation : Segmentation

- Previously,
  - Physical memory allocated to a process is contiguous
  - Poor memory utilization
  - Suffers from external fragmentation
- Noncontiguous allocation
  - Physical address space of a process is noncontiguous
  - Better memory utilization and management
  - Allow sharing of common blocks (code, data, library, etc.)
  - Support dynamic loading and dynamic linking
- Two schemes: segmentation and paging

Non-contiguous Allocation : Segmentation

Dynamic Loading

- Routine is not loaded until it is called
- Better memory-space utilization; unused routine is never loaded
- Useful when large amounts of code are needed to handle infrequently occurring cases
- Most OS allows user programs to do dynamic loading of components (relocatable object code)
- Some OS supports loadable kernel modules

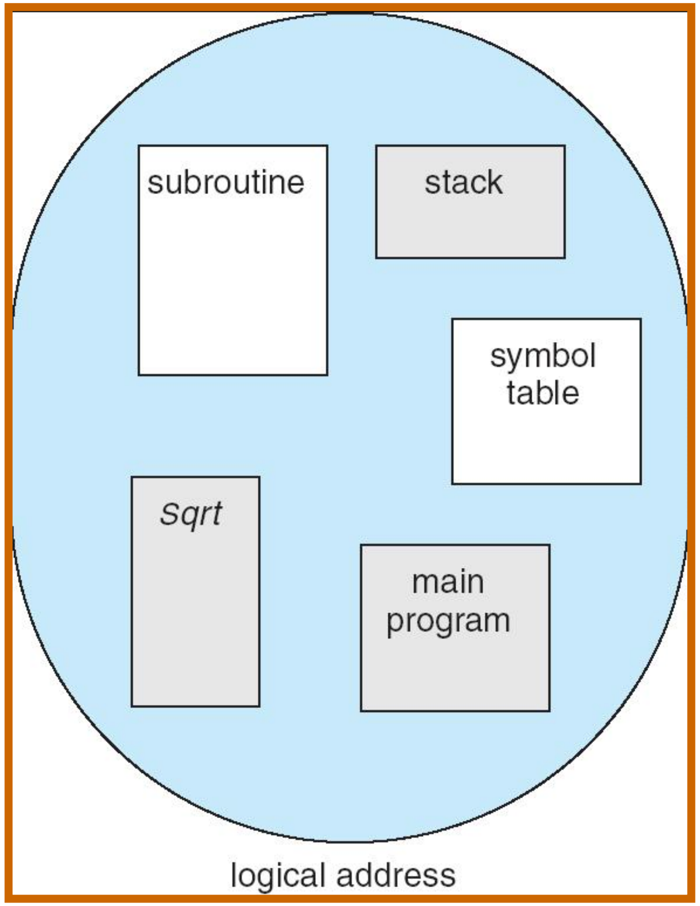
Non-contiguous Allocation : Segmentation

Dynamic Linking

- Linking postponed until execution time
  - Small piece of code, *stub*, used to locate the appropriate memory-resident library routine
  - Stub replaces itself with the address of the routine, and executes the routine
  - Operating system needed to check if routine is in processes' memory address
- Dynamic linking is particularly useful for libraries
  - Better known as *shared libraries*
- Dynamic linking in ucore

Non-contiguous Allocation : Segmentation

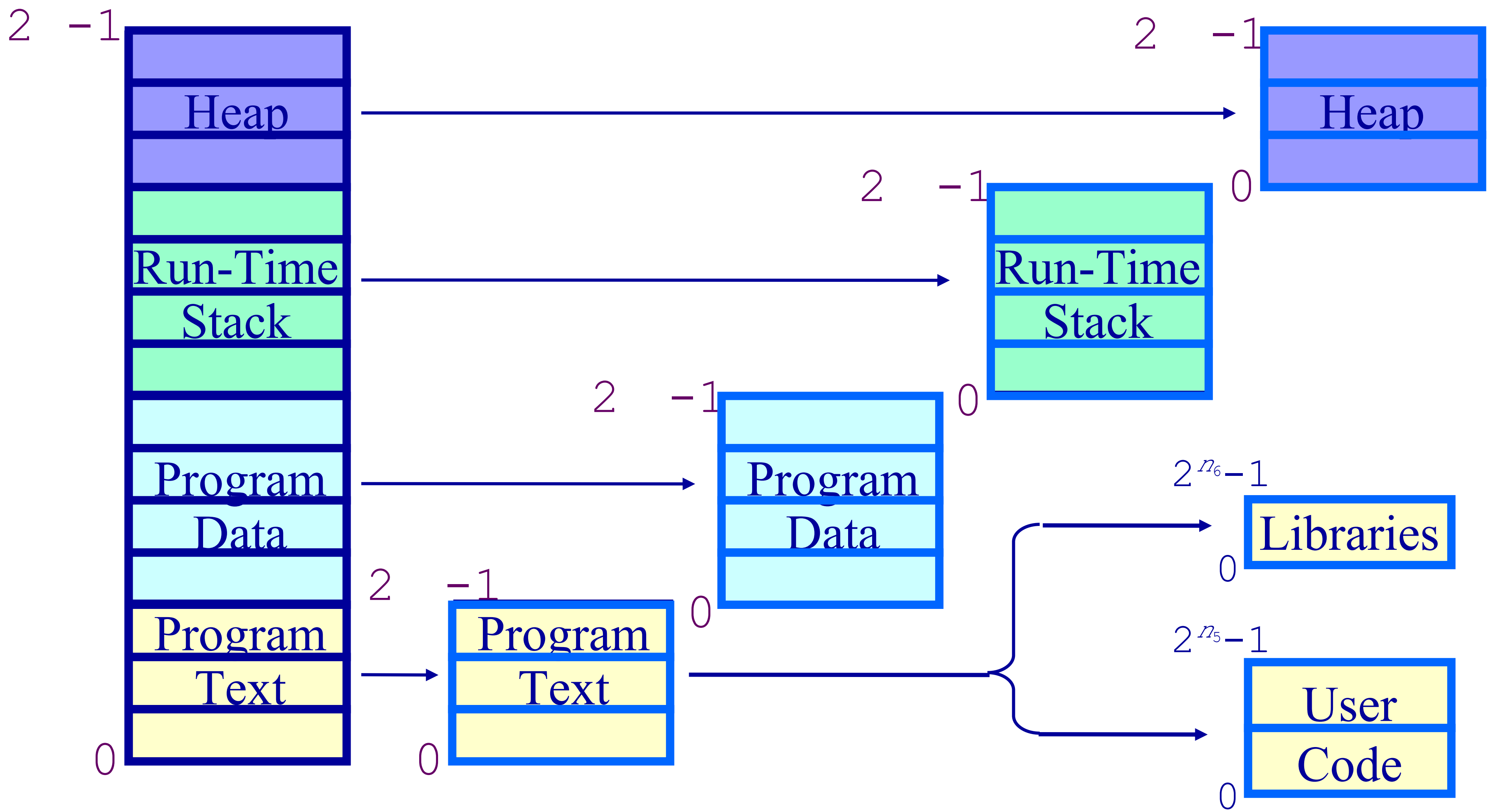
Segmentation



- A program is a collection of segments, such as
  - Main program
  - Subroutines
  - Stack
  - Symbols
  - Data
  - Common libraries
  - Common blocks
- Purpose: enable finer grain isolation and sharing

Non-contiguous Allocation : Segmentation

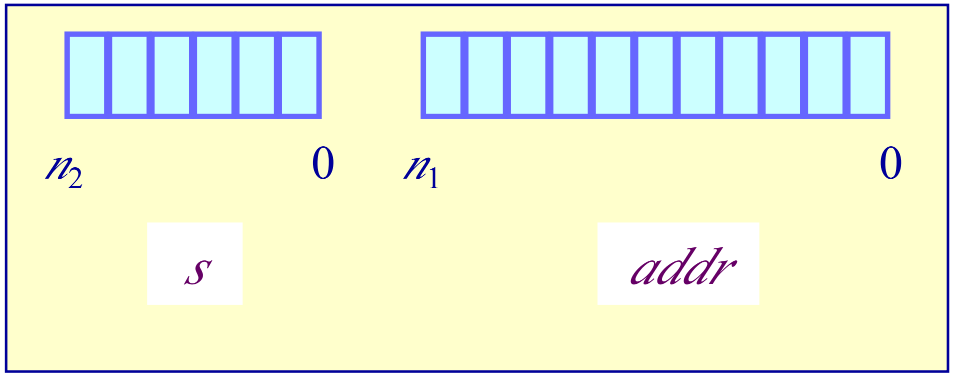
Separating into Multiple Address Spaces



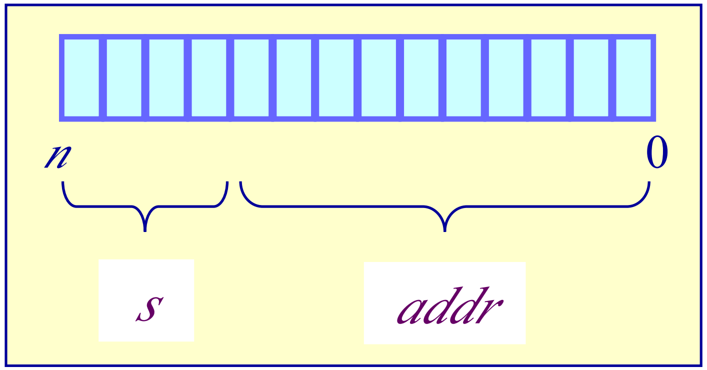
Non-contiguous Allocation : Segmentation

Segmentation Schemes

- New concept: A segment — a memory "object"
  - A logical address space
- A process now addresses objects —a pair (s, addr)
  - s — segment number
  - addr — an offset within an object



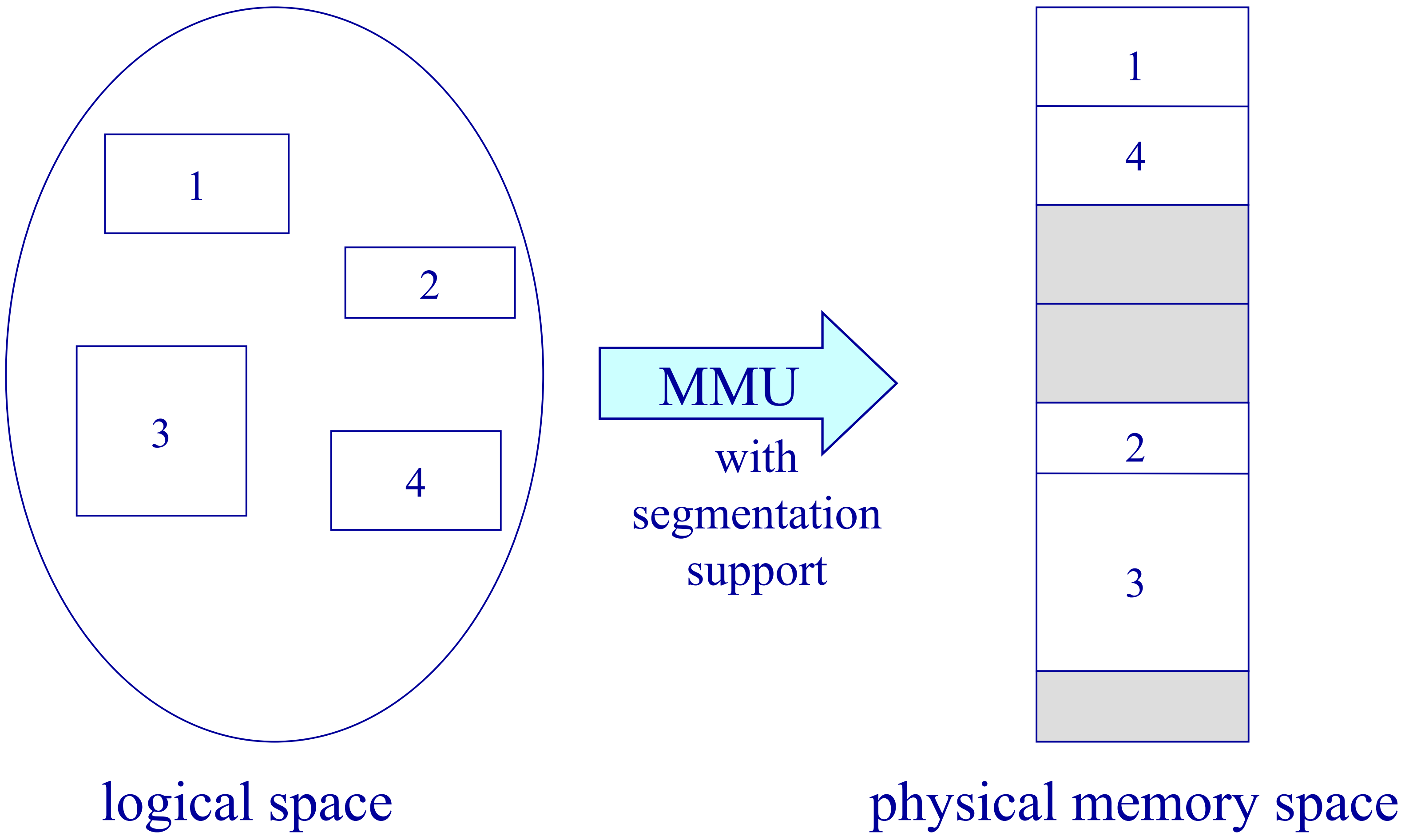
Segment + Address register scheme



Single address scheme

Non-contiguous Allocation: Segmentation

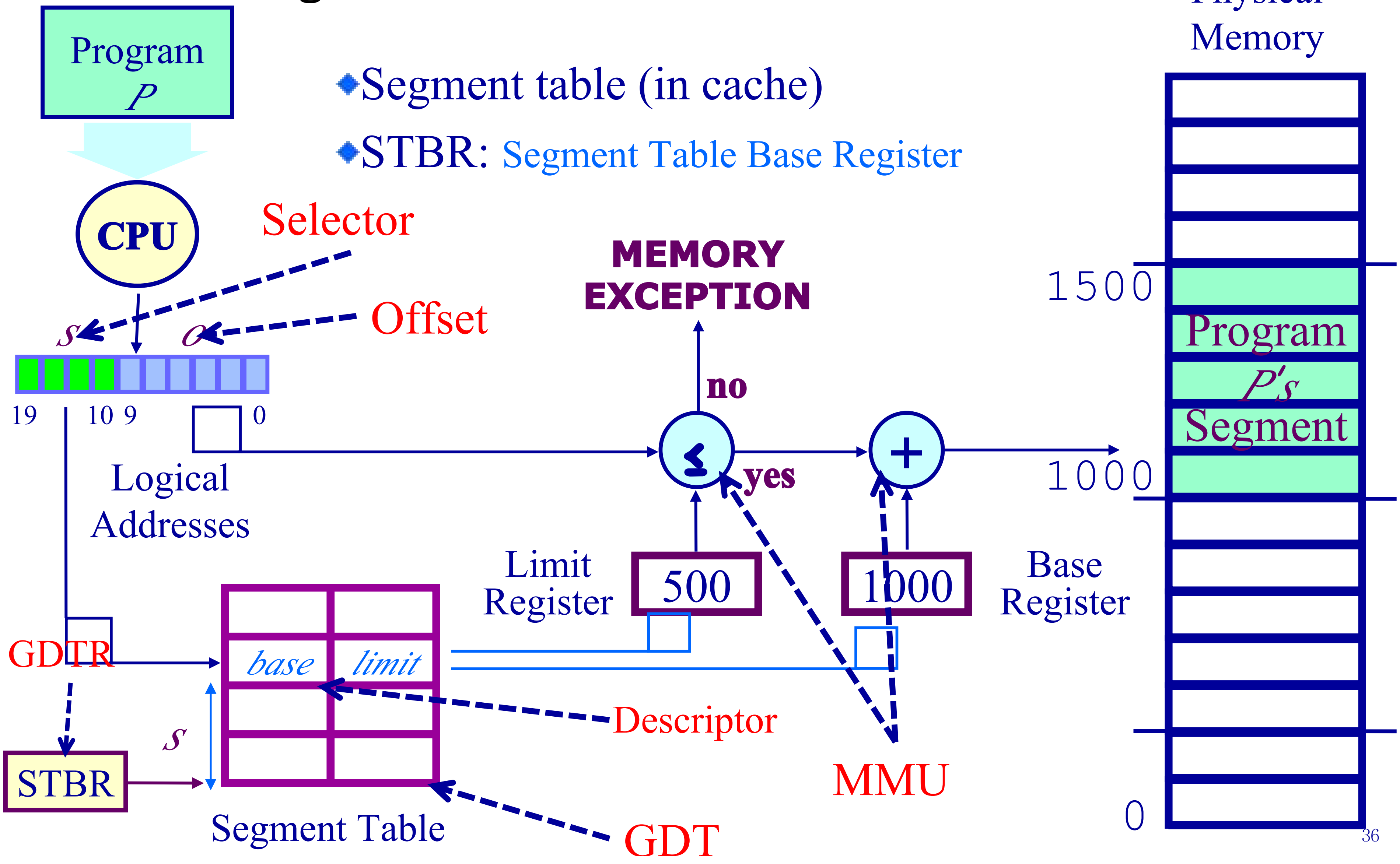
Logical View of Segmentation



Non-contiguous Allocation: Segmentation

Segmentation Hardware Architecture

- Segment table (in cache)
- STBR: Segment Table Base Register



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Non-contiguous Allocation : Paging

- Divide physical memory into fixed-sized frames
  - Size is power of 2, e.g., 512, 4096, 8192
- Divide logical address space into same size pages
- To run a program of size n pages, find n free frames and load program
- Set up a page table to translate logical to physical addresses (pages to frames)
- Frame/page: basic units of memory allocation
  - OS keep track of all free frames
  - Same-sized frame eliminates external fragmentation

Non-contiguous Allocation : Paging

Frames

- Physical memory partitioned into equal sized *frames*

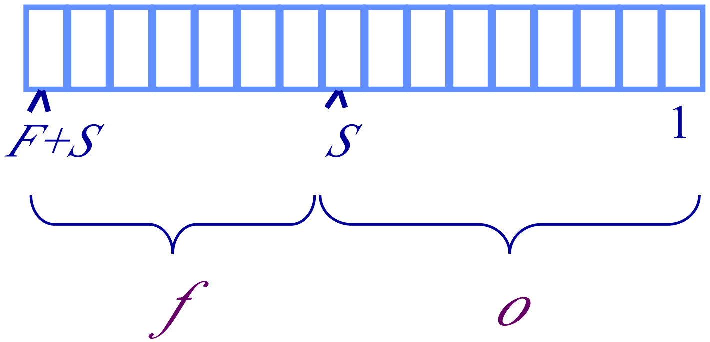
A memory address is a pair (f, o)

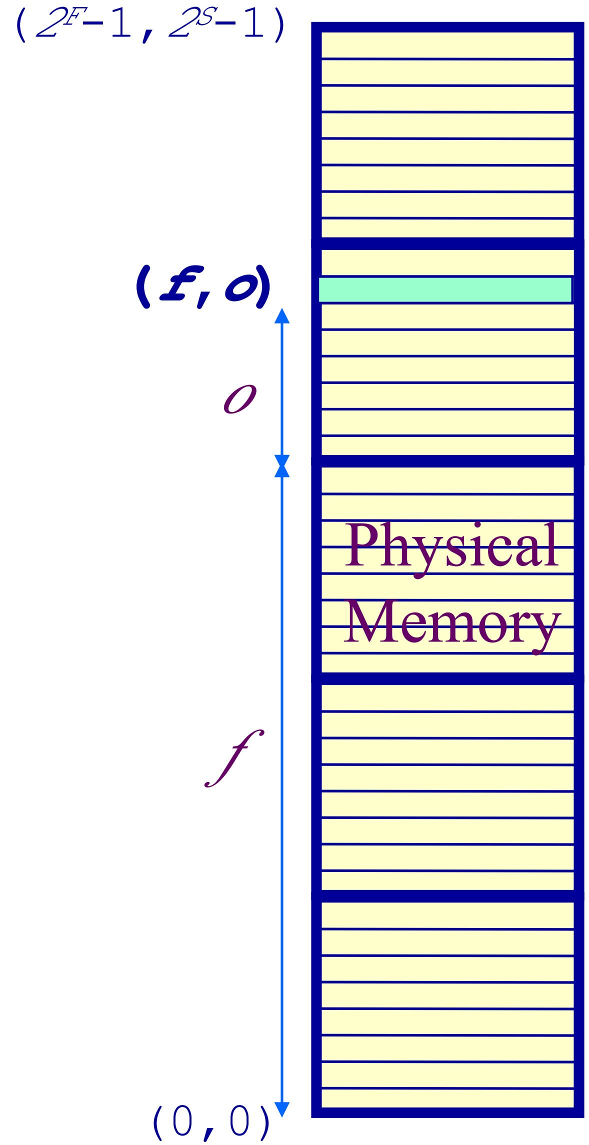
f — frame number (total 2^F frames)

o — frame offset (2^S bytes/frames)

Physical address = $2^S\ f + o$

addr:





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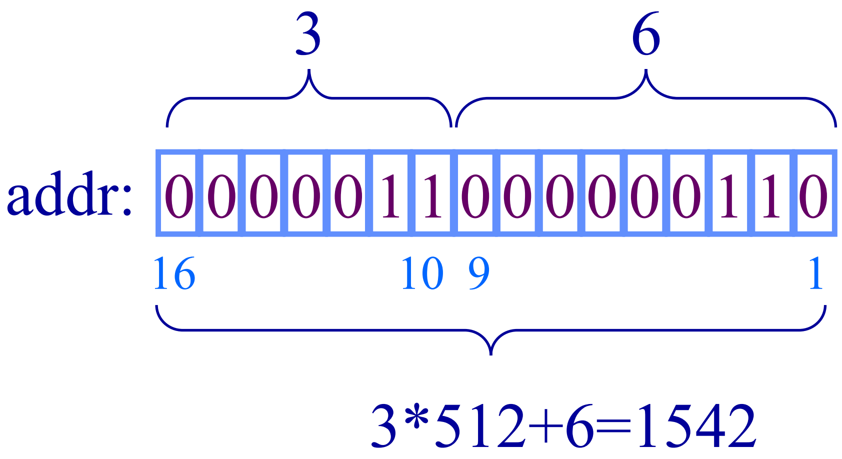
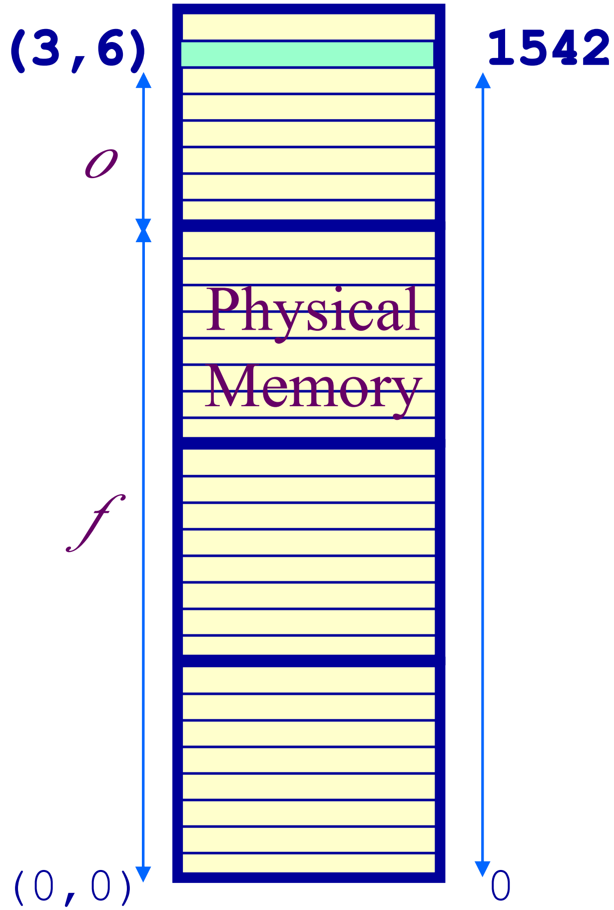
Non-contiguous Allocation : Paging

Frame Example

- Example: A 16-bit address space with 9-bit (512 byte) page frames
  - Addressing location (3, 6) = 1542





Non-contiguous Allocation : Paging

Pages

- A process's logical address space is partitioned into equal sized *pages*
  - |*page*| = |*frame*|

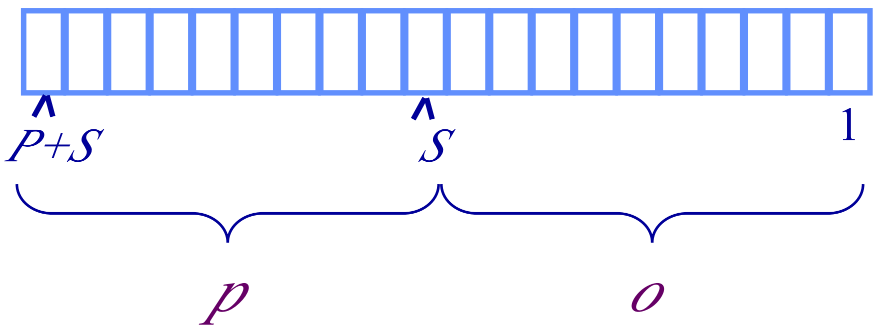
A logical address is a pair (p, o)

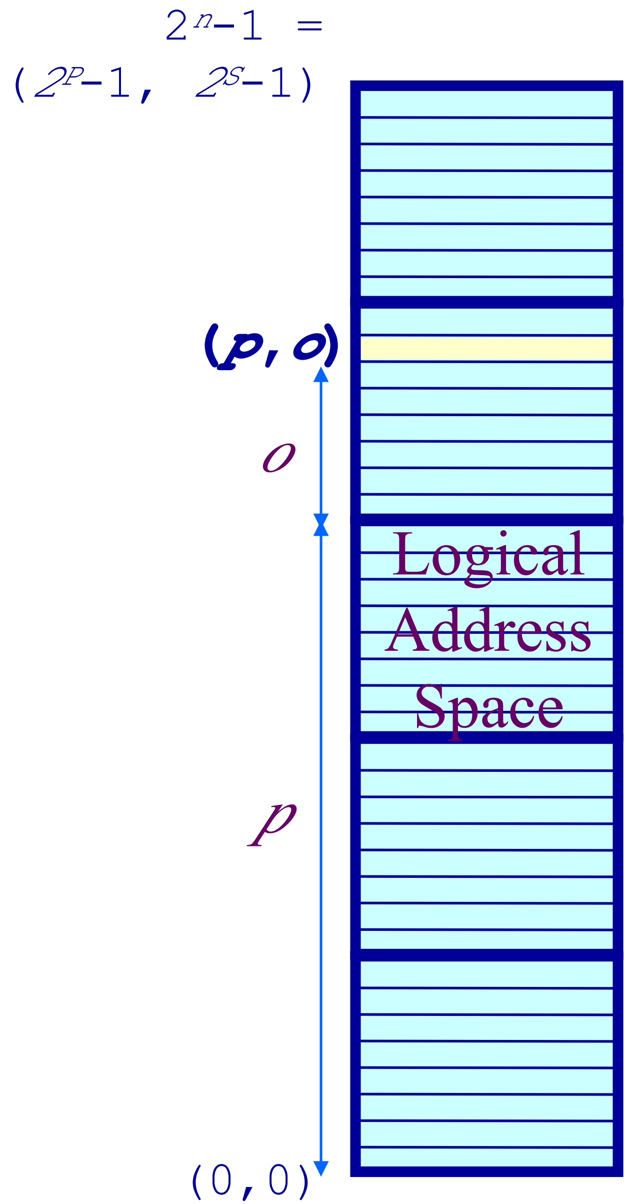
p — page number (2^P pages)

o — page offset (2^S bytes/pages)

Virtual address = $2^S\ p + o$

addr:

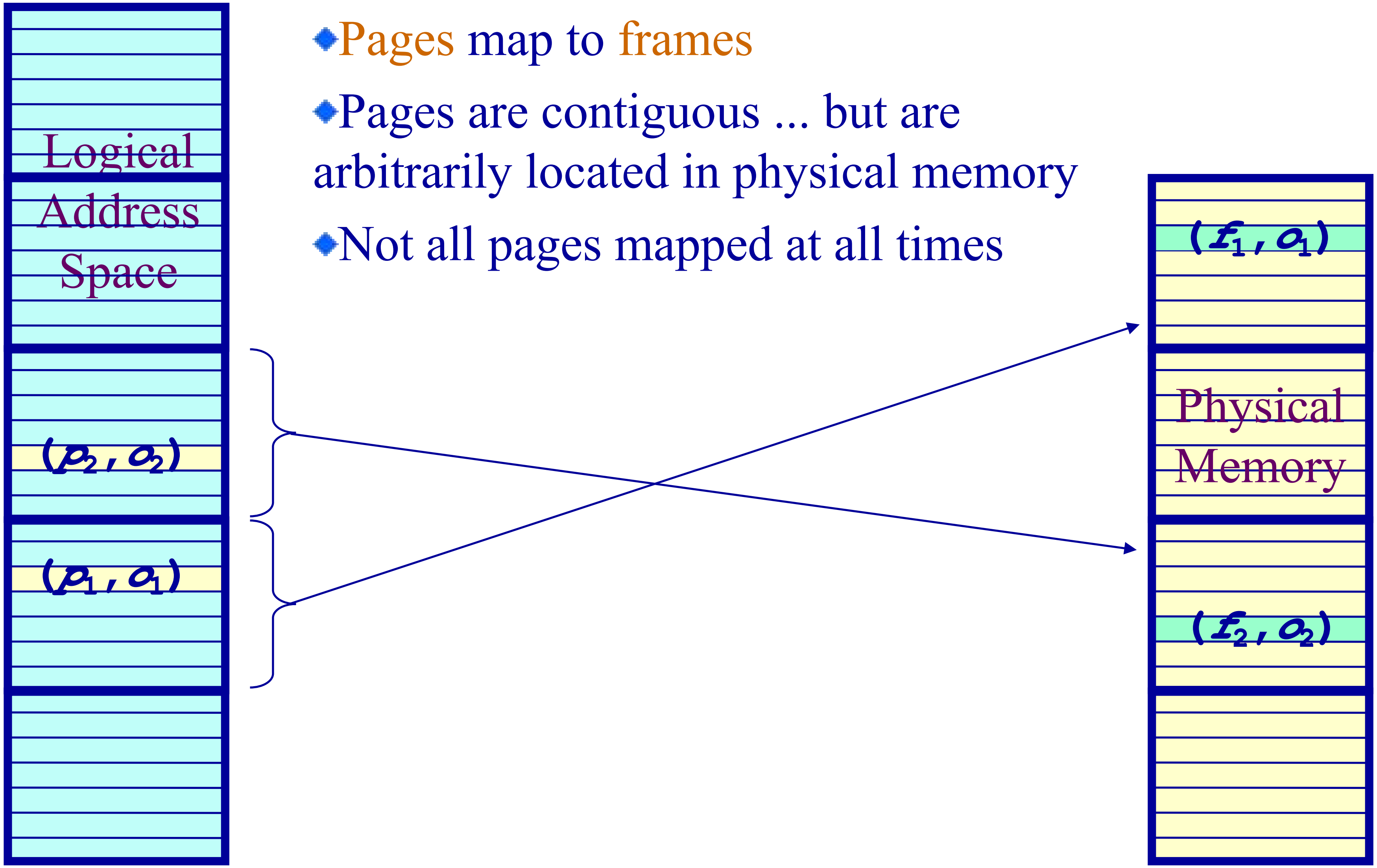




Non-contiguous Allocation : Paging

Paging Model

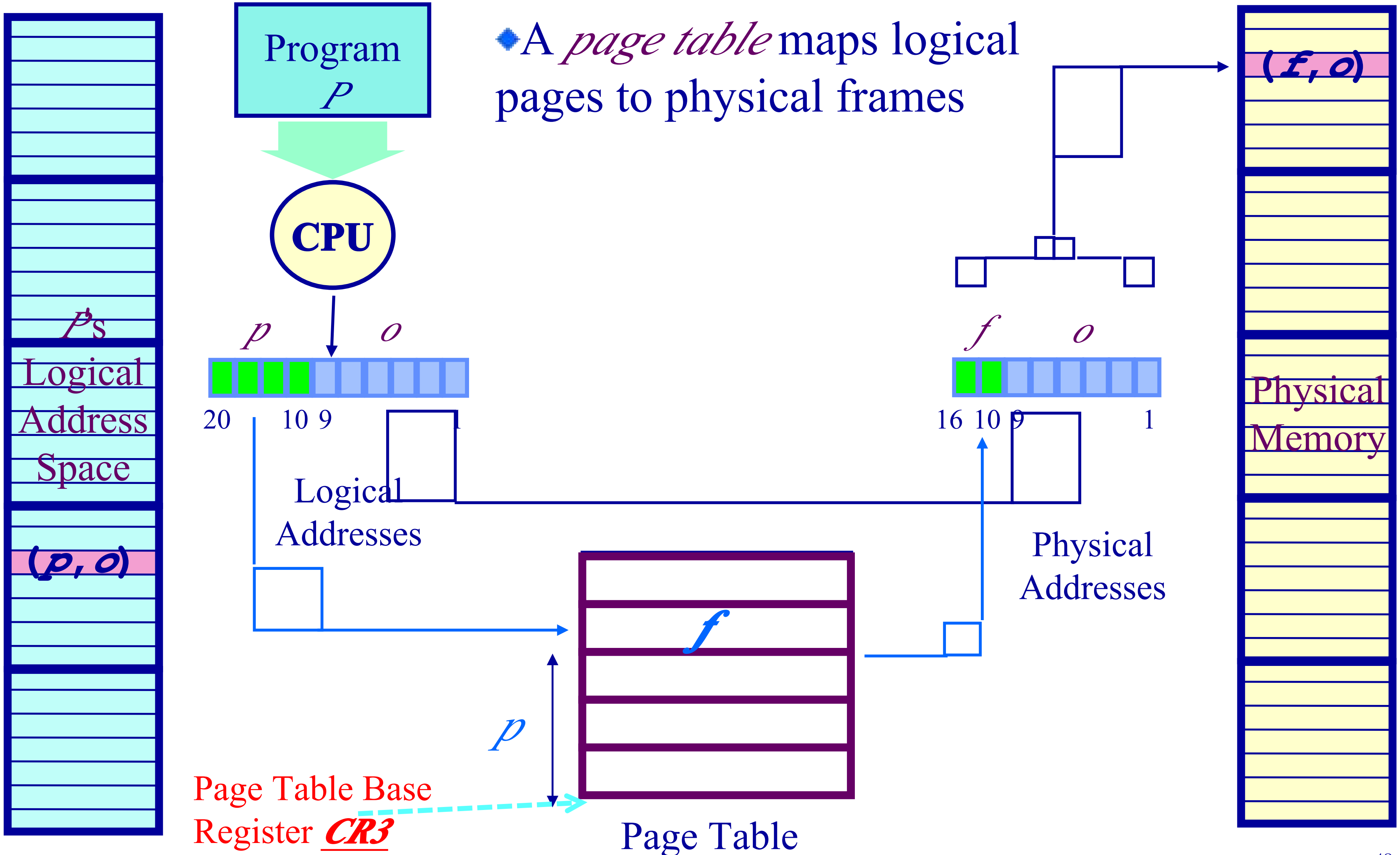
- Pages map to frames
- Pages are contiguous ... but are arbitrarily located in physical memory
- Not all pages mapped at all times



Non-contiguous Allocation : Paging

Paging Hardware Architecture

- A *page table* maps logical pages to physical frames



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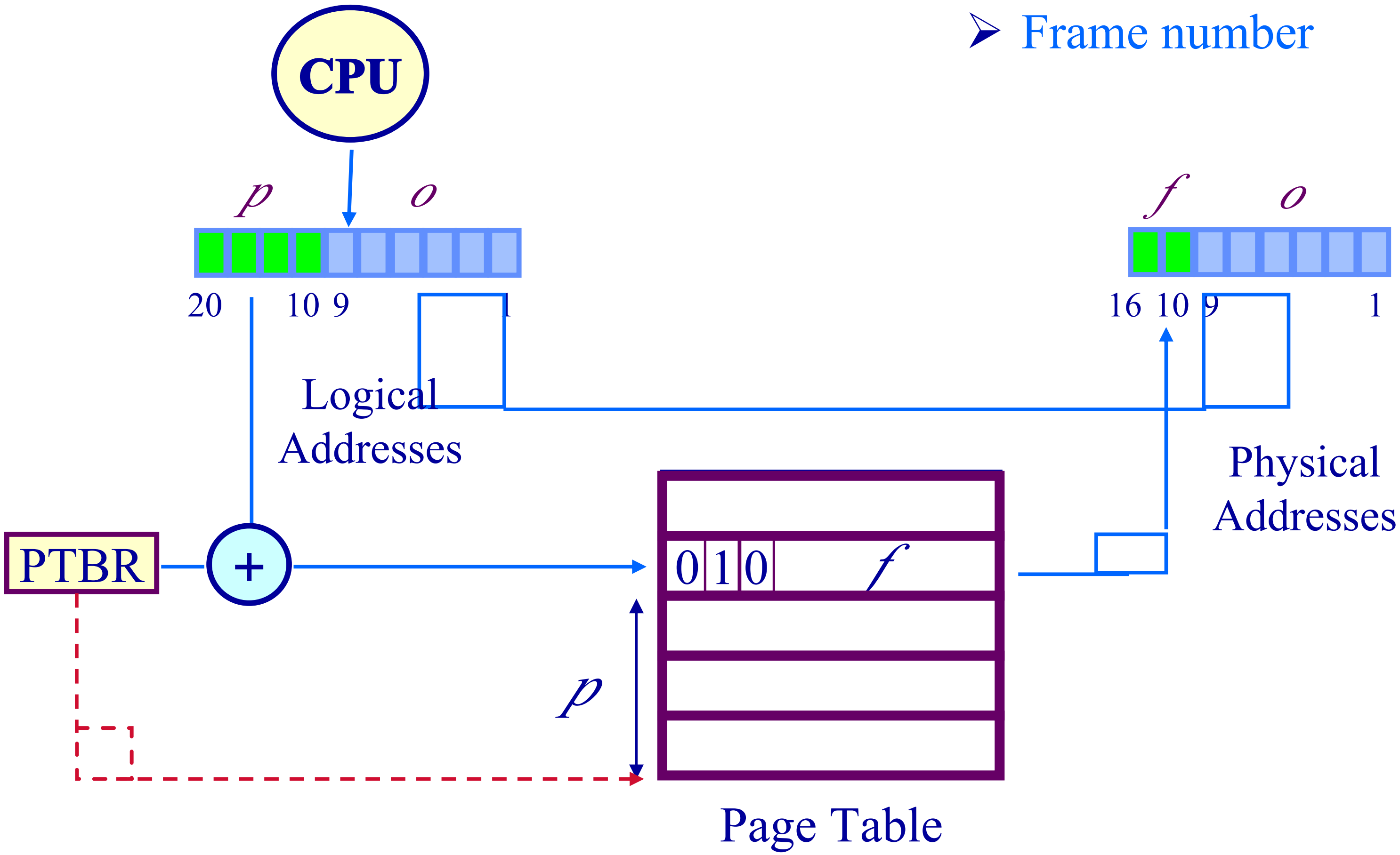
Non-contiguous Allocation : Page Table

Page Table Structure

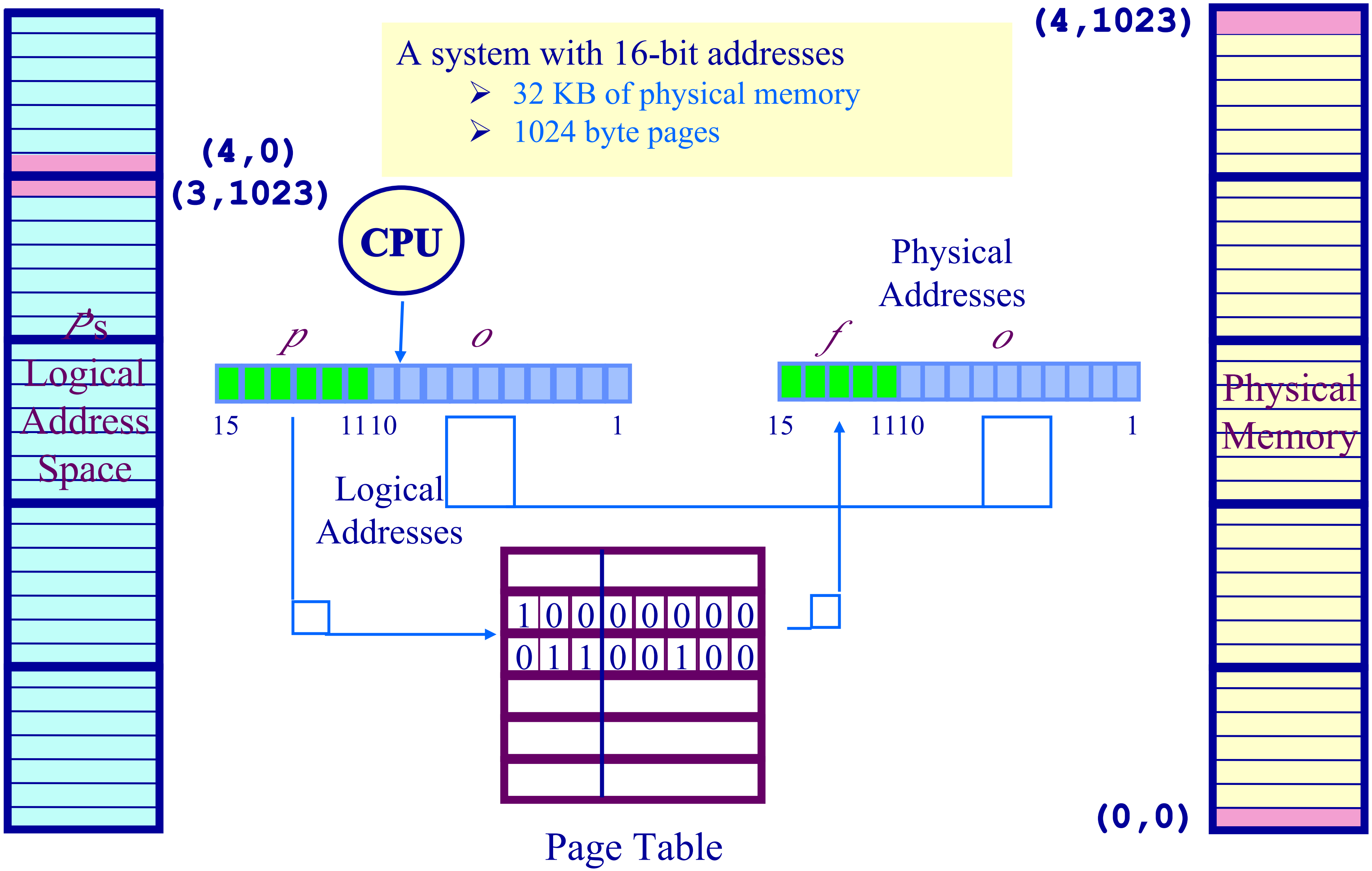
- One table per process
  - Part of process's state
  - PTBR: Page Table Base Register
- Contents:
  - Flags — dirty bit, resident bit, clock/reference bit
  - Frame number



Non-contiguous Allocation : Page Table

Example Address Translation

A system with 16-bit addresses
- 32 KB of physical memory
- 1024 byte pages



Non-contiguous Allocation : Page Table

Paging Performance Issue

- Problem — Requires 2 memory references!
  - One access to get the page table entry
  - One access to get the data
- Page table can be very large
  - For a machine with 64-bit addresses and 1024 byte pages, what is the size of a page table?
- What to do? Hint: most computing problems are solved by some form of…
  - Caching
  - Indirection

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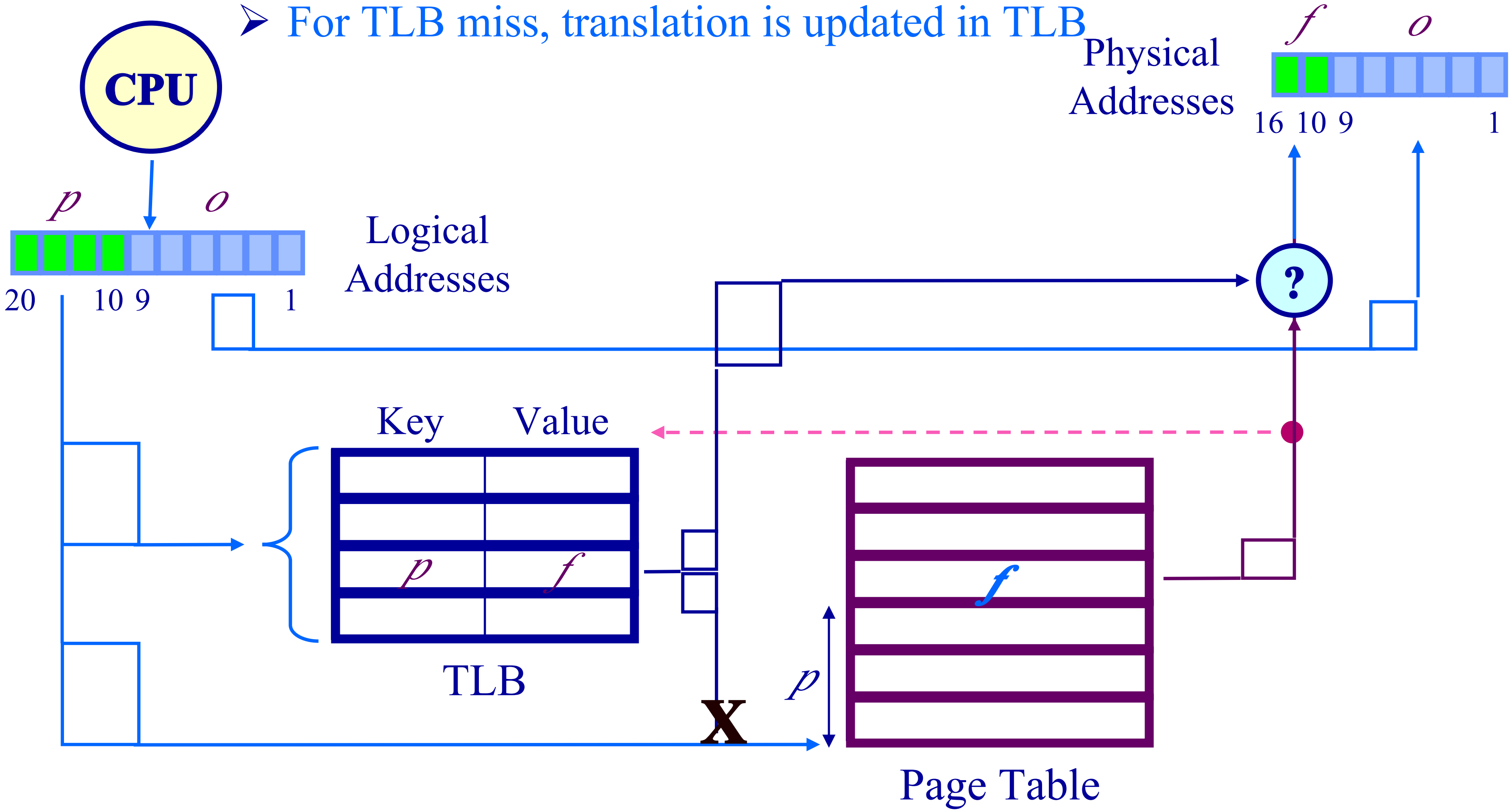
Non-contiguous Allocation : Page Table

Translation Look-aside Buffer (TLB)

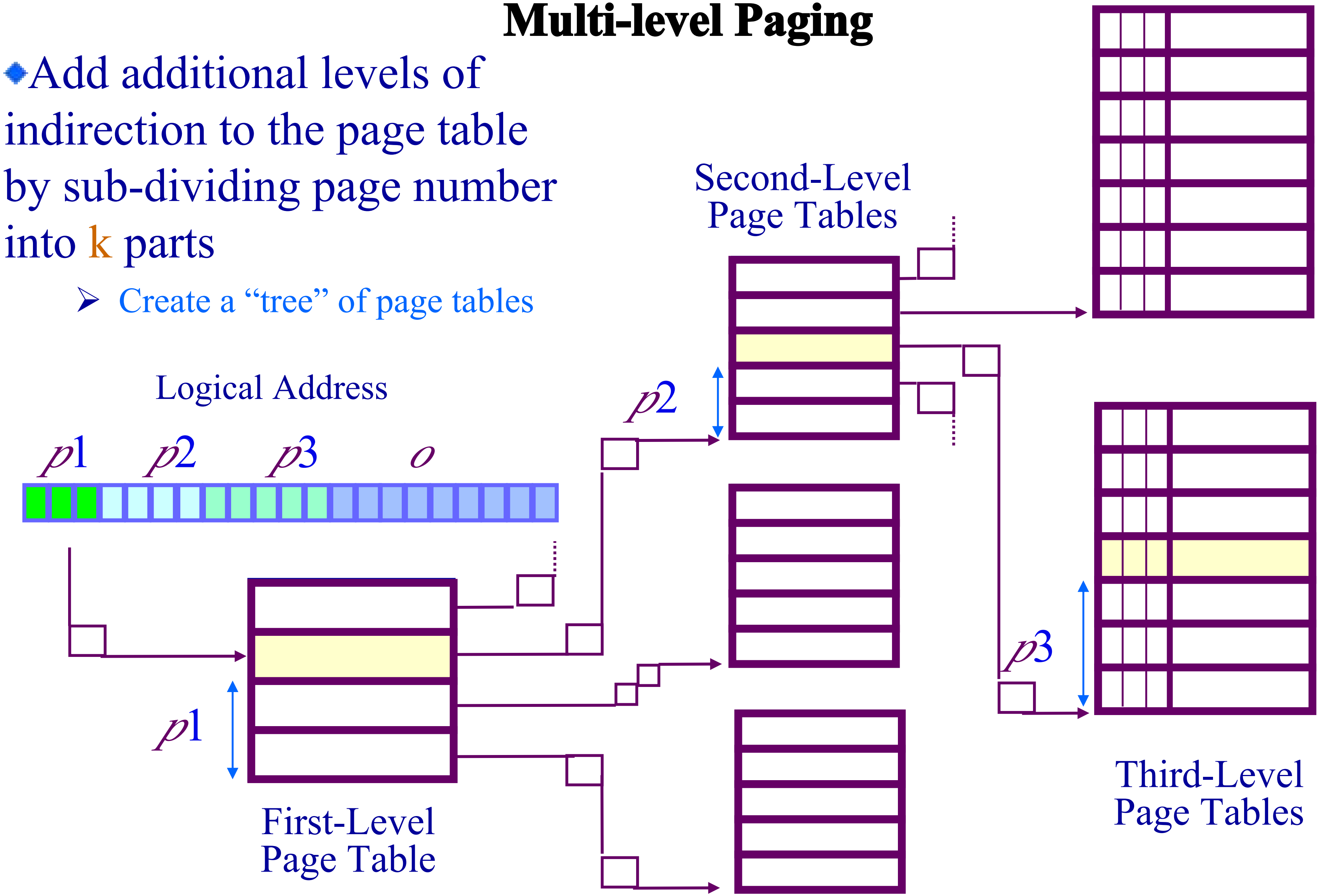
- Cache recently accessed page-to-frame translations
  - TLB implemented in associative memory for fast access
  - For TLB hit, physical page number obtained in 1 cycle
  - For TLB miss, translation is updated in TLB



Non-contiguous Allocation : Page Table

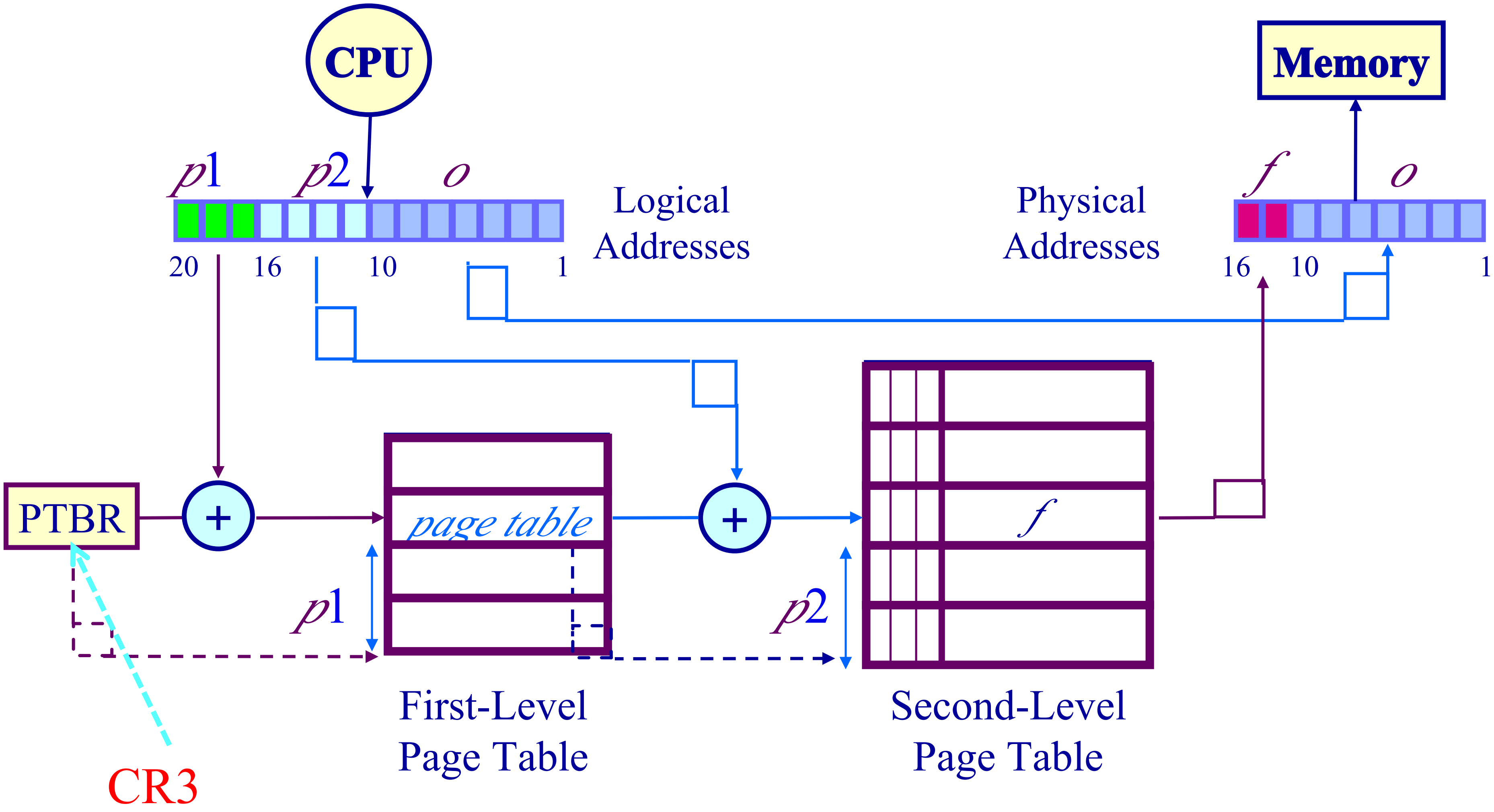
Multi-level Paging

- Add additional levels of indirection to the page table by sub-dividing page number into k parts
  - Create a "tree" of page tables



Non-contiguous Allocation : Page Table

Example: Two-level Paging



Non-contiguous Allocation : Page Table

The Problem of Large Address Spaces

- With large address spaces (64-bits) forward mapped page tables become cumbersome.
  - E.g. 5 levels of tables.
- Instead of making tables proportional to size of logical address space, make them proportional to the size of physical address space.
  - Logical (virtual) address space is growing faster than physical.

Non-contiguous Allocation : Page Table

Using Page Registers (aka Inverted Page Tables)

- Each frame is associated with a register containing
  - Residence bit: whether or not the frame is occupied
  - Occupier: page number of the page occupying frame
  - Protection bits

- Page registers: an example
  - Physical memory size: 16 MB
  - Page size: 4096 bytes
  - Number of frames: 4096
  - Space used for page registers (assuming 8 bytes/register): 32 Kbytes
  - Percentage overhead introduced by page registers: 0.2%
  - Size of virtual memory: irrelevant

Non-contiguous Allocation : Page Table

Page Registers Tradeoffs

- Advantages:
  - Size of translation table occupies a very small fraction of physical memory
  - Size of translation table is independent of logical address space size
- Disadvantages:
  - We have reverse of the information that we need….
  - How do we perform translation ?
  - Search the translation table for the desired page number

Searching for a Page in Inverted Page Tables

- If the number of frames is small, the page registers can be placed in an associative memory
- Logical page number looked up in associative memory
  - Hit: frame number is extracted
  - Miss: results in page fault
- Limitations:
  - Large associative memories are expensive
    - Difficult to make large and accessible in a single cycle.
    - They consume a lot of power

Non-contiguous Allocation : Page Table

Hashing Large Inverted Page Tables

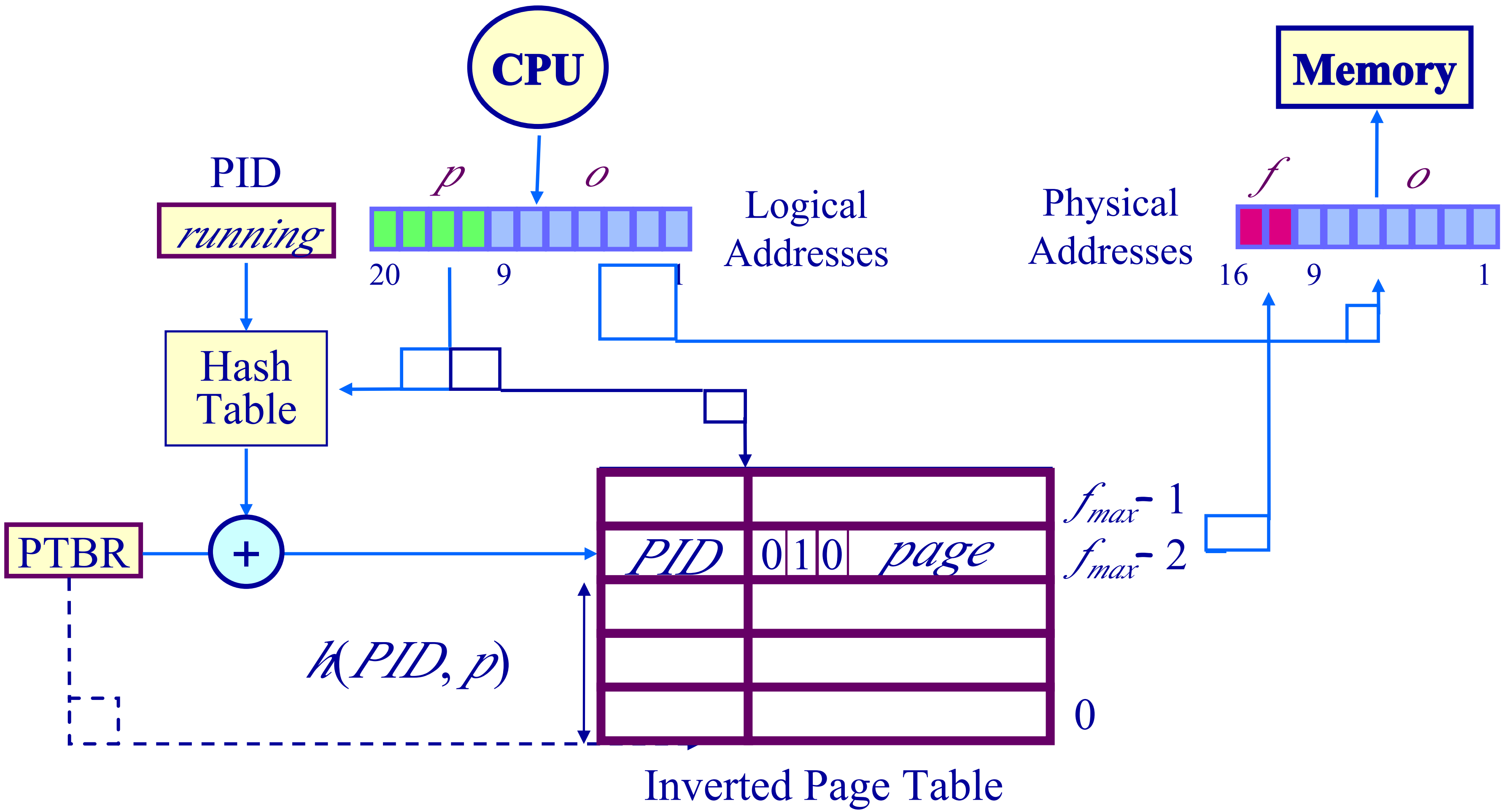
- Hash page numbers to find corresponding frame numbers in a "frame" table with one entry per frame

- Page i is placed in slot f(i) where f is an agreed-upon hash function

- To lookup page i, perform the following:
  - Compute f(i) and use it as an index into the table of page registers
  - Extract the corresponding page register
  - Check if the register tag contains i, if so, we have a hit
  - Otherwise, we have a miss

Non-contiguous Allocation : Page Table

Hashed Inverted Page Table Architecture



OS Outline

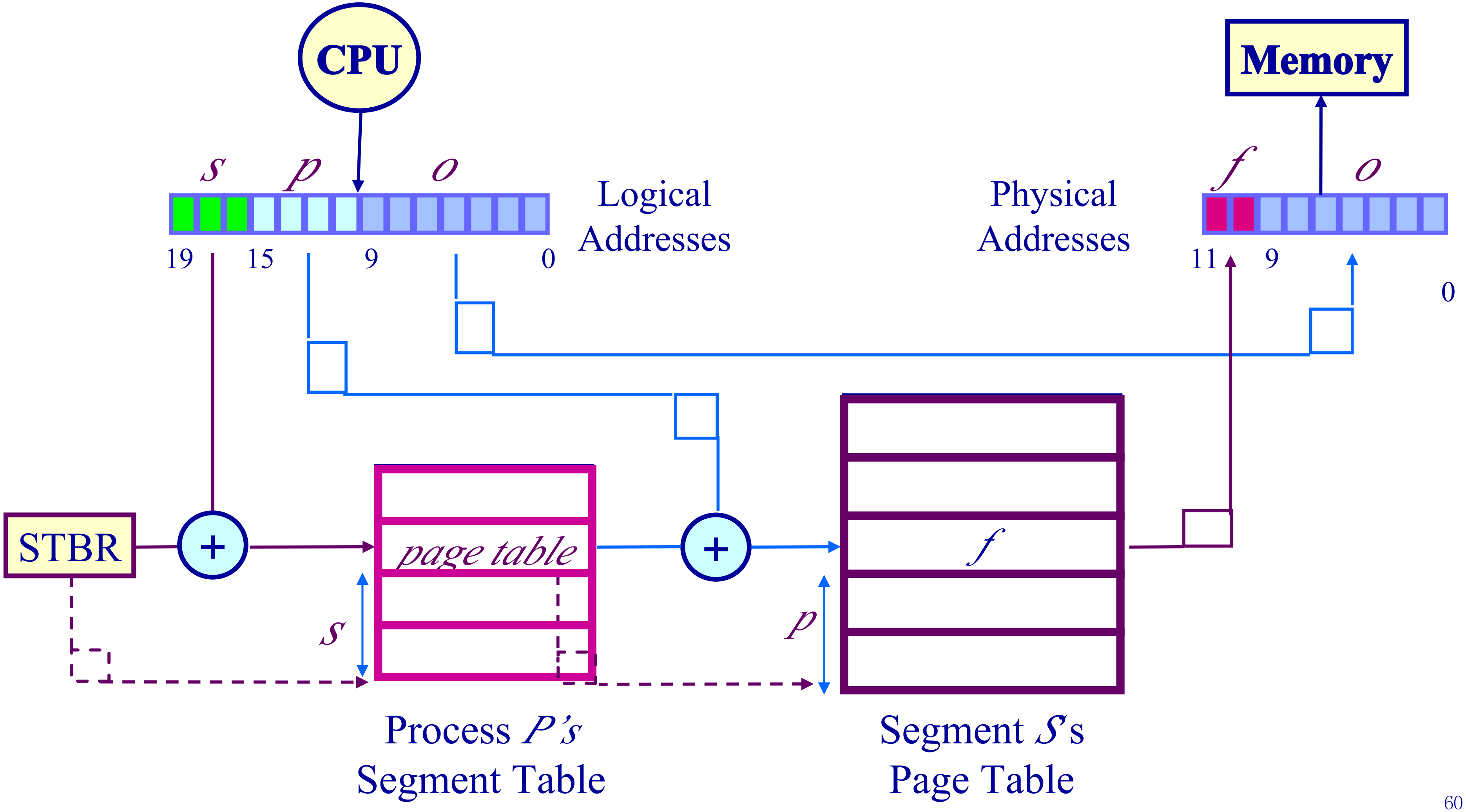
- Computer Arch/Memory Hierarchy
- Address Space & Address Generation
- Contiguous Memory Allocation
  - Dynamic Allocation of Partitions
- Non-Contiguous Memory Allocation
  - Segmentation
  - Paging
  - Page Table
    - Translation Look-aside Buffer (TLB)
    - Multi-Level Page Table
    - Inverted Page Table
  - Paged Segmentation Model

Paged Segmentation Model

- Segmentation has advantages for protection, paging has advantages for memory utilization and optimizing transfer to backing store.
- Can we combine segmentation and paging?

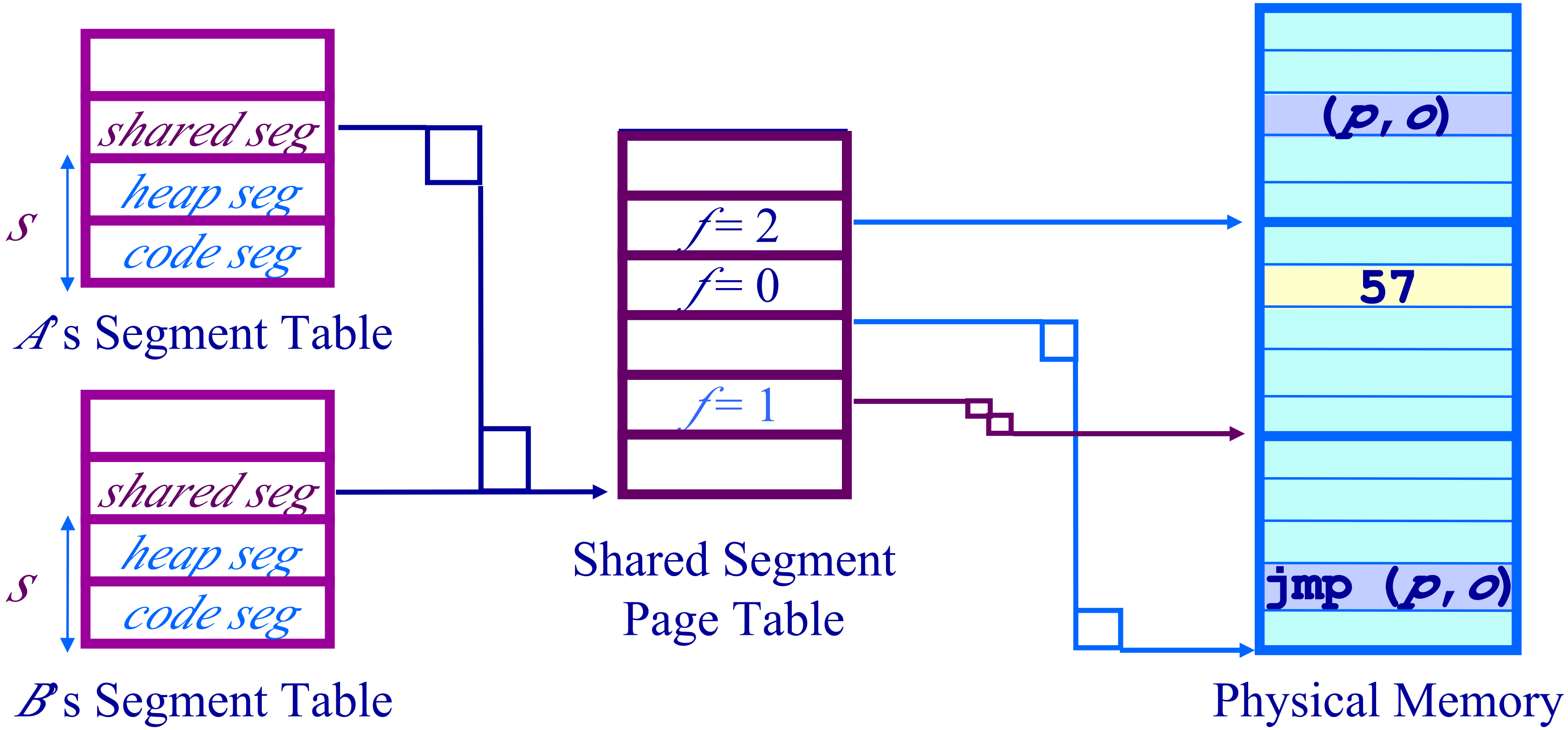
Paged Segmentation Hardware Architecture

- Add an additional level of indirection to page table



Sharing in Paged-Segmented Systems

- If segments are paged then page tables are automatically shared
  - Processes need only agree on a number for the shared segment



This week's Work

Lab1 should be finished!