Contents

Chapter 8
Memory-Management Strategies

Memory Management

- Motivation
  - Keep several processes in memory to improve a system’s performance
- Selection of different memory management methods
  - Application-dependent
  - Hardware-dependent
- Memory – A large array of words or bytes, each with its own address.
  - Memory is always too small!

Memory Management

- The Viewpoint of the Memory Unit
  - A stream of memory addresses!
- What should be done?
  - Which areas are free or used (by whom)
  - Decide which processes to get memory
  - Perform allocation and de-allocation
- Remark:
  - Interaction between CPU scheduling and memory allocation!

Background

- Address Binding – binding of instructions and data to memory addresses

Binding Time 有三種可能時間

Known at compile time, where a program will be in memory - “absolute code” MS-DOS *.COM

編譯完後的程式，每次都存在固定的位置跑

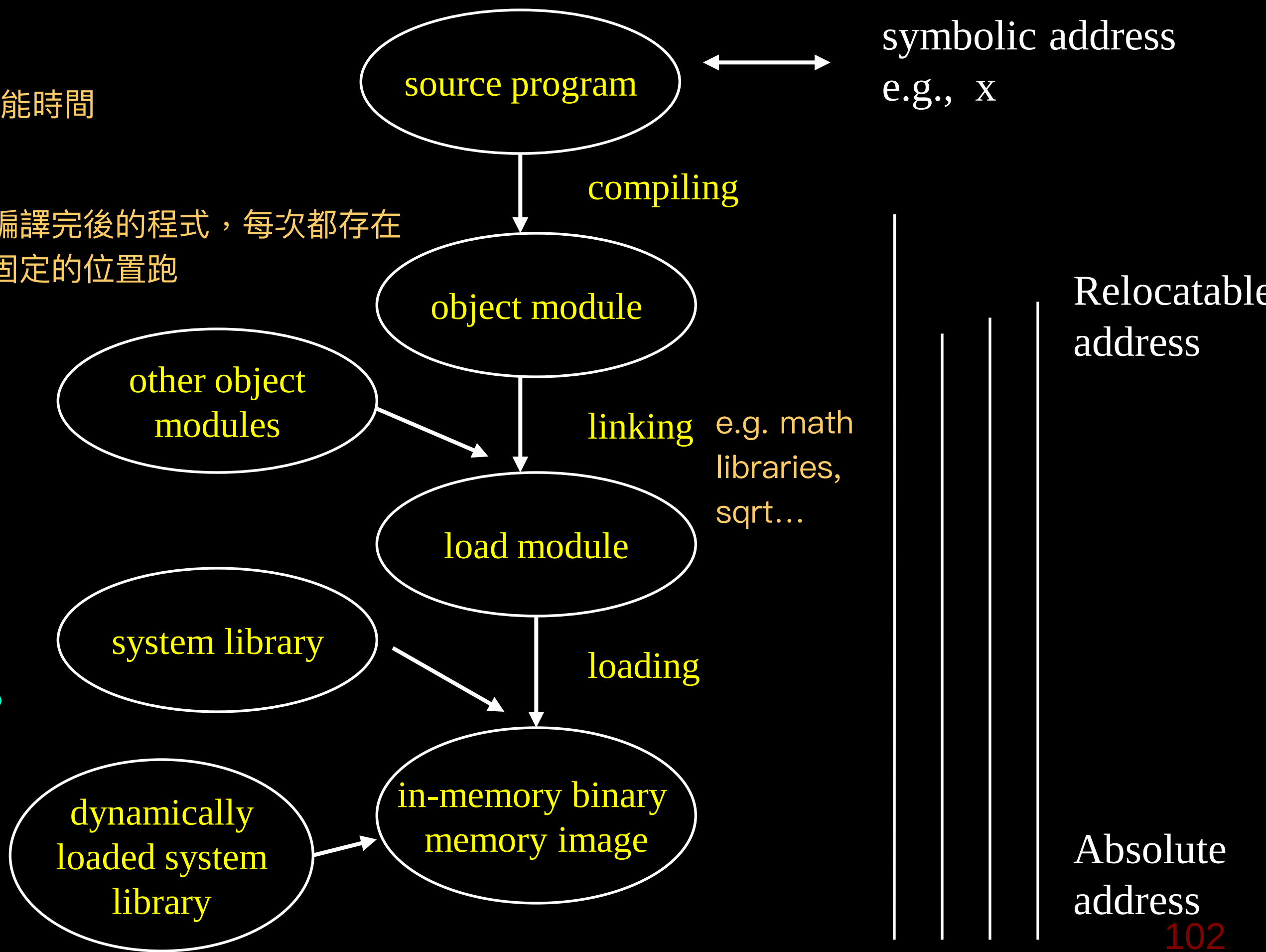
把 source code 對應到 memory

At load time:

- All memory reference by a program will be translated
- Code is relocatable
- Fixed while a program runs

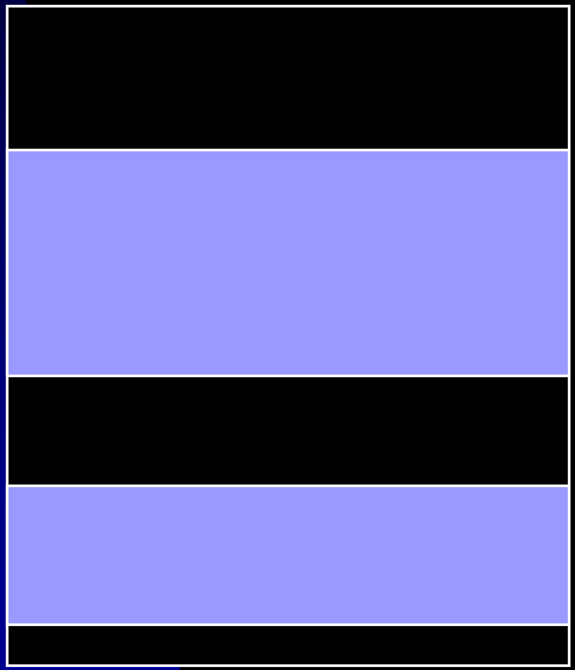
At execution time

- binding may change as a program run



Background

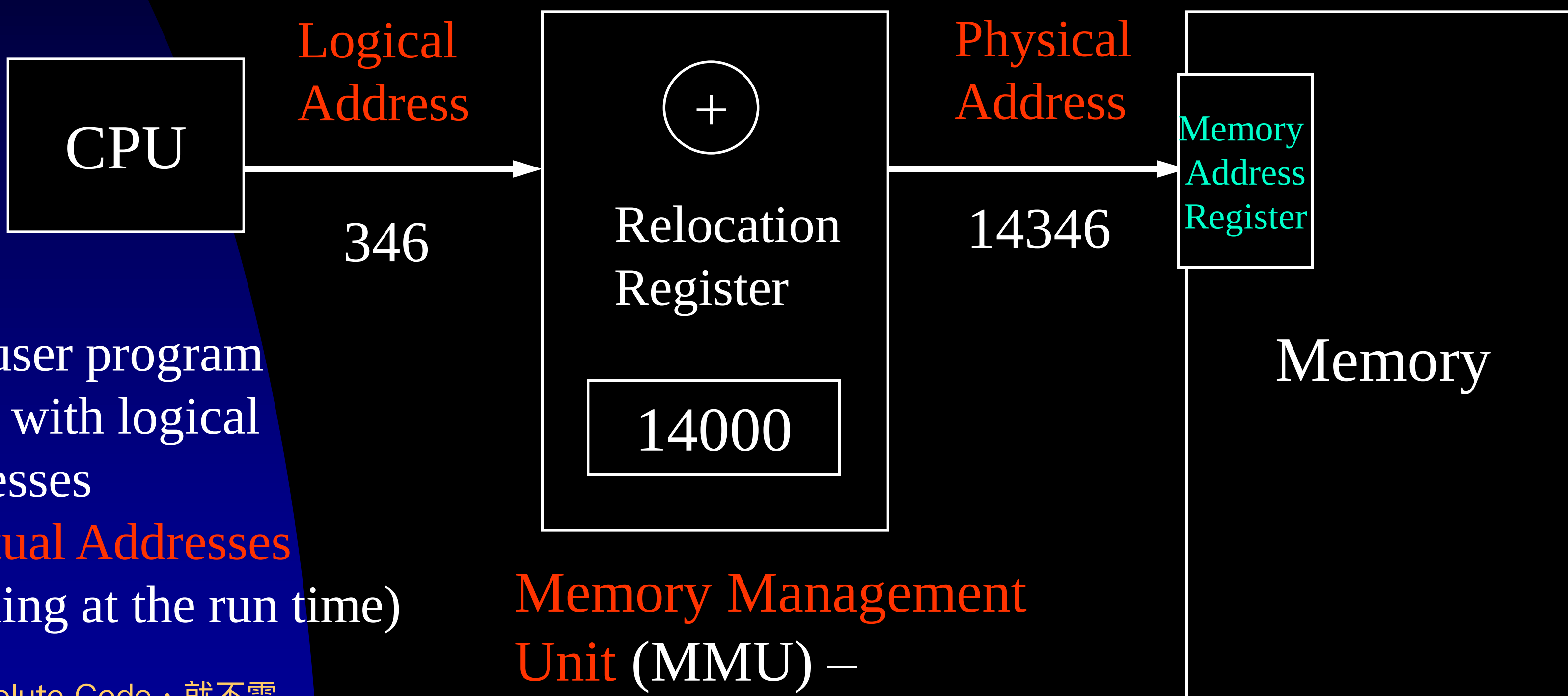
Main
Memory



- Binding at the Compiling Time
  - A process must execute at a specific memory space
- Binding at the Load Time
  - Relocatable Code
- Process may move from a memory segment to another $\rightarrow$ binding is delayed till run-time

Logical Versus Physical Address

e.g. instruction addrs, operands addrs



The user program deals with logical addresses
- Virtual Addresses
(binding at the run time)

if Absolute Code，就不需要 MMU？

Memory Management Unit (MMU) – "Hardware-Support"

不能軟體模擬

Logical Versus Physical Address

- A logical (physical) address space is the set of logical (physical) addresses generated by a process. Physical addresses of a program is transparent to any process!
- MMU maps from virtual addresses to physical addresses. Different memory mapping schemes need different MMU's that are hardware devices. (slow down)
- Compile-time & load-time binding schemes results in the collapsing of logical and physical address spaces.

Dynamic Loading

- Dynamic Loading 需要時再 load 進來
  - A routine will not be loaded until it is called. A relocatable linking loader must be called to load the desired routine and change the program's address tables.
  - Advantage
    - Memory space is better utilized.
  - Users may use OS-provided libraries to achieve dynamic loading

Dynamic Linking

- Dynamic Linking ⟷ Static Linking

⇩ ⇩

A small piece of code, called stub, is used to locate or load the appropriate routine

language library
+
program object module
↓
binary program image

Advantage

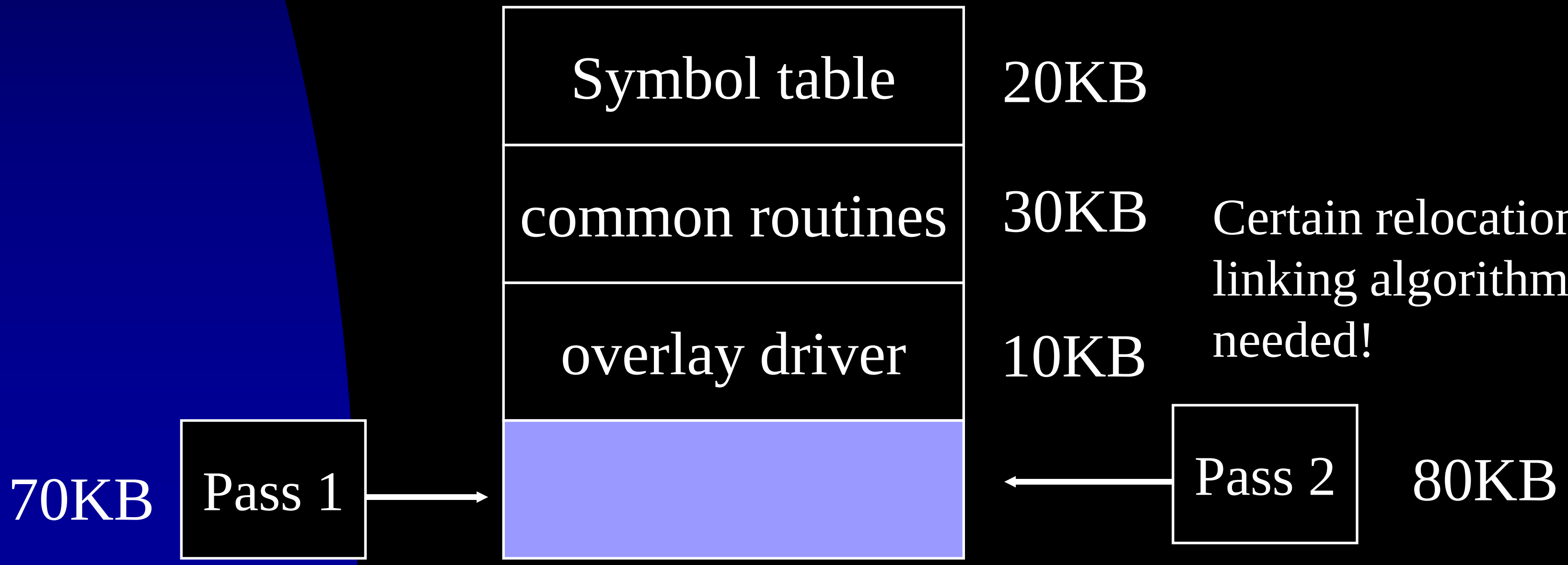
Save memory space by sharing the library code among processes → Memory Protection & Library Update!

Simple

Overlays

以前記憶體不夠時，寫 assembly code

- Motivation
  - Keep in memory only those instructions and data needed at any given time.
  - Example: Two overlays of a two-pass assembler



Certain relocation & linking algorithms are needed!

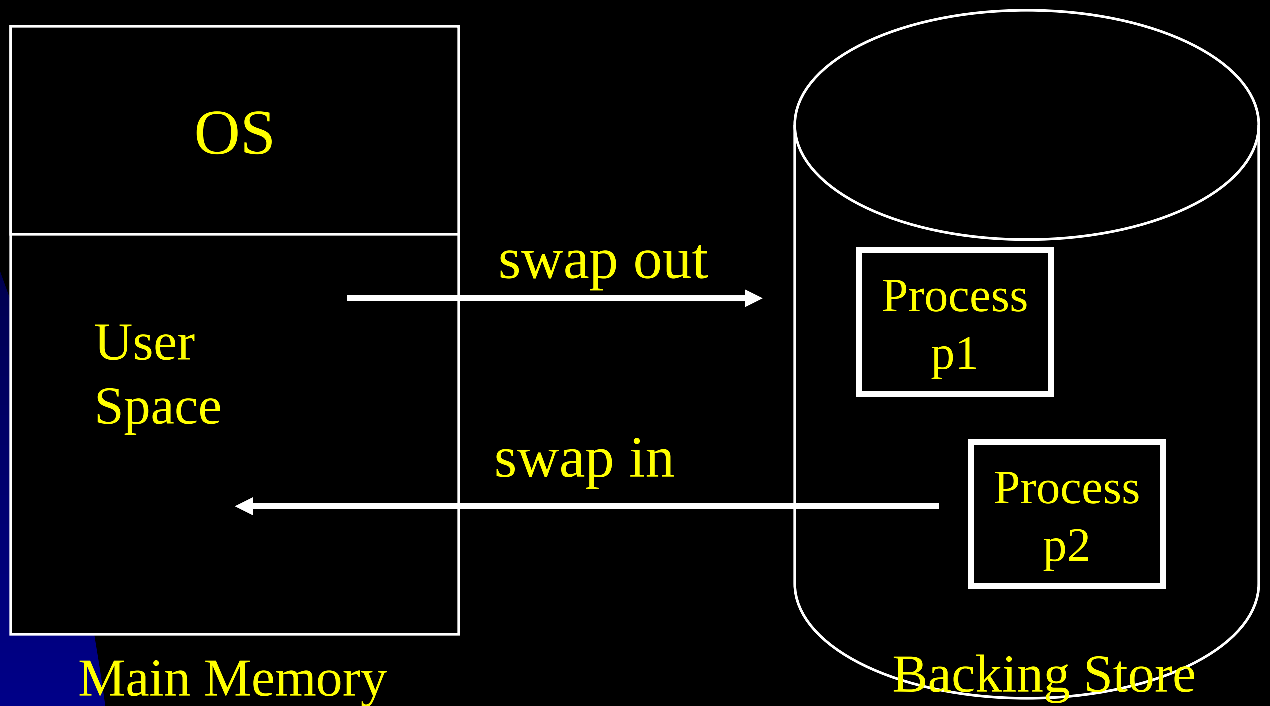
Overlays

- Memory space is saved at the cost of run-time I/O.
- Overlays can be achieved w/o OS support:

  $\Rightarrow$ "absolute-address" code
- However, it's not easy to program a overlay structure properly!

  $\Rightarrow$ Need some sort of automatic techniques that run a large program in a limited physical memory!

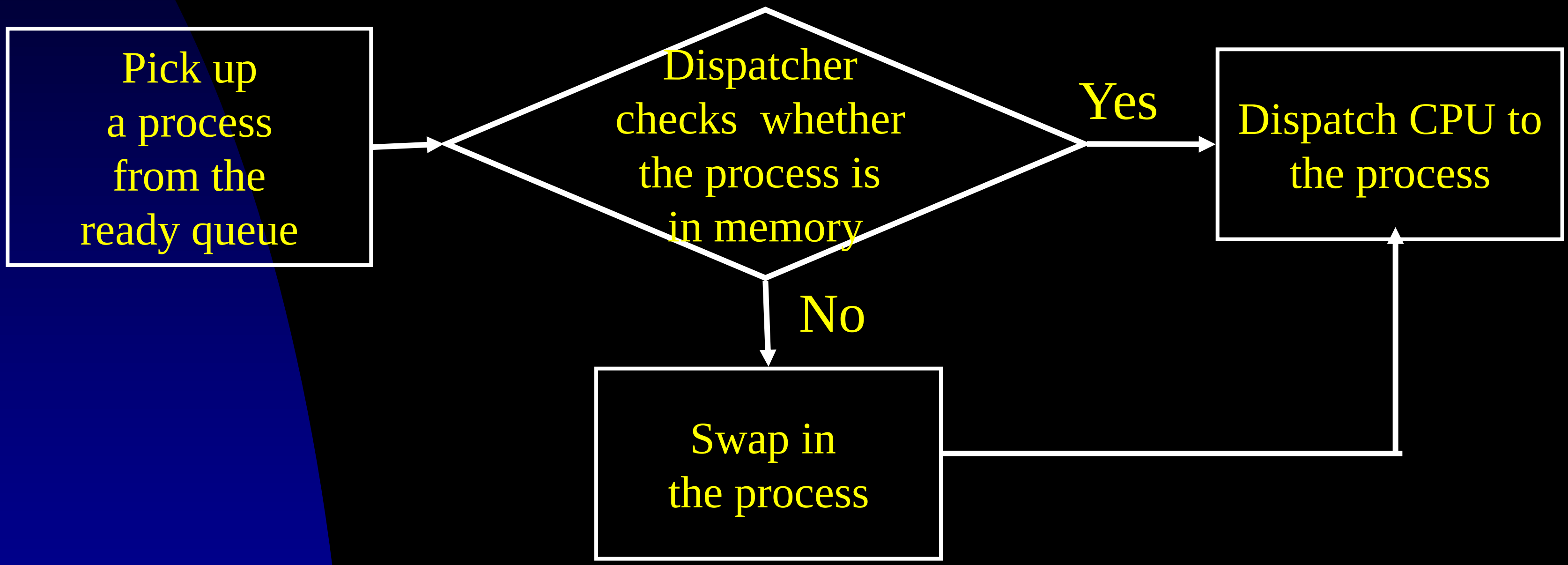
Swapping



Should a process be put back into the same memory space that it occupied previously? ↔ Binding Scheme?!

Swapping

- A Naive Way



Potentially High Context-Switch Cost:

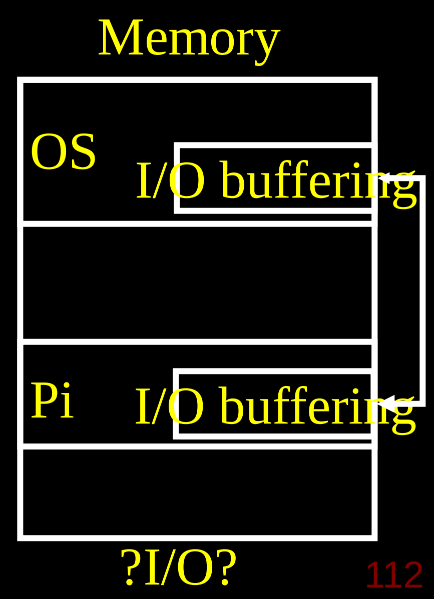
2 * (10000KB/50MBps + 8ms) = 416ms

Transfer Time Latency Delay

Swapping

- The execution time of each process should be long relative to the swapping time in this case (e.g., 416ms in the last example)!
- Only swap in what is actually used. $\Rightarrow$ Users must keep the system informed of memory usage.
- Who should be swapped out?
  - “Lower Priority” Processes?
  - Any Constraint?

    $\Rightarrow$ System Design



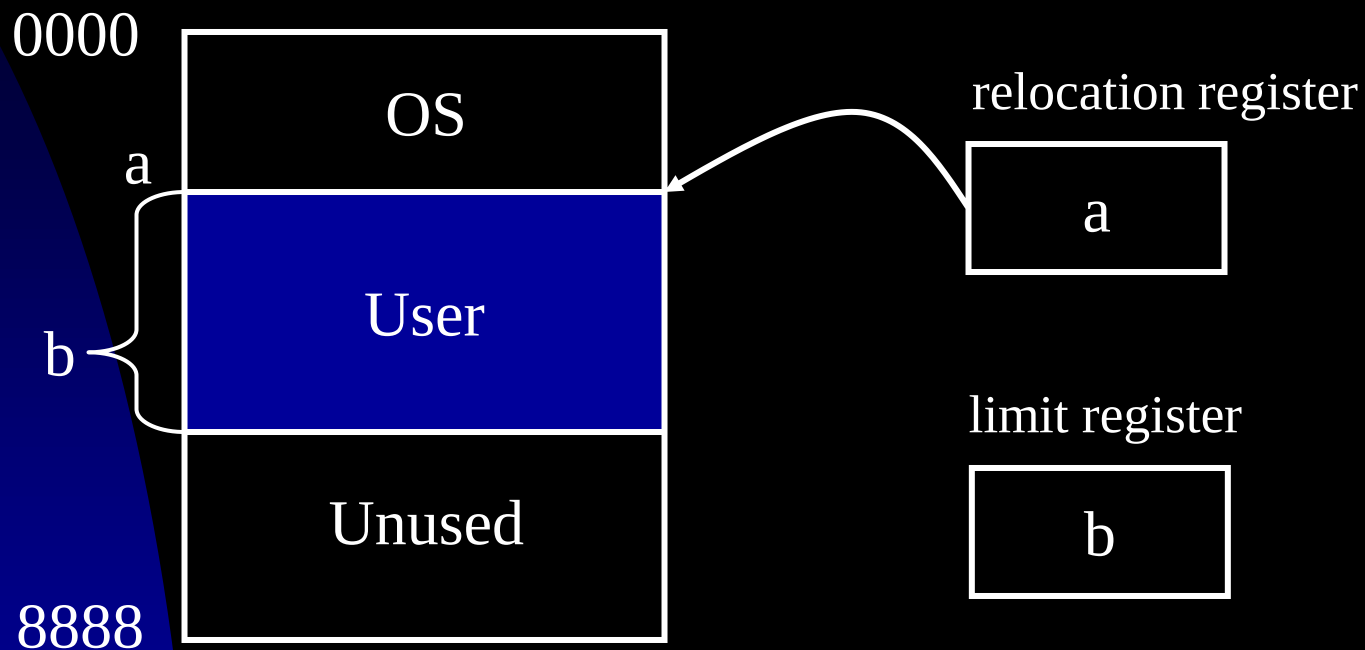
Swapping

- Separate swapping space from the file system for efficient usage
- Disable swapping whenever possible such as many versions of UNIX – Swapping is triggered only if the memory usage passes a threshold, and many processes are running!
- In Windows 3.1, a swapped-out process is not swapped in until the user selects the process to run.

Swapping

- Mobile systems do not support swapping in general but might have paging (iOS and Android)
  - Limited space for storage
  - Limited writes due to endurance constraints
- Strategies for Memory Management of Mobile Systems
  - Applications voluntarily relinquish allocated memory (iOS).
  - Terminate applications when there is no sufficient memory (application state storing?)

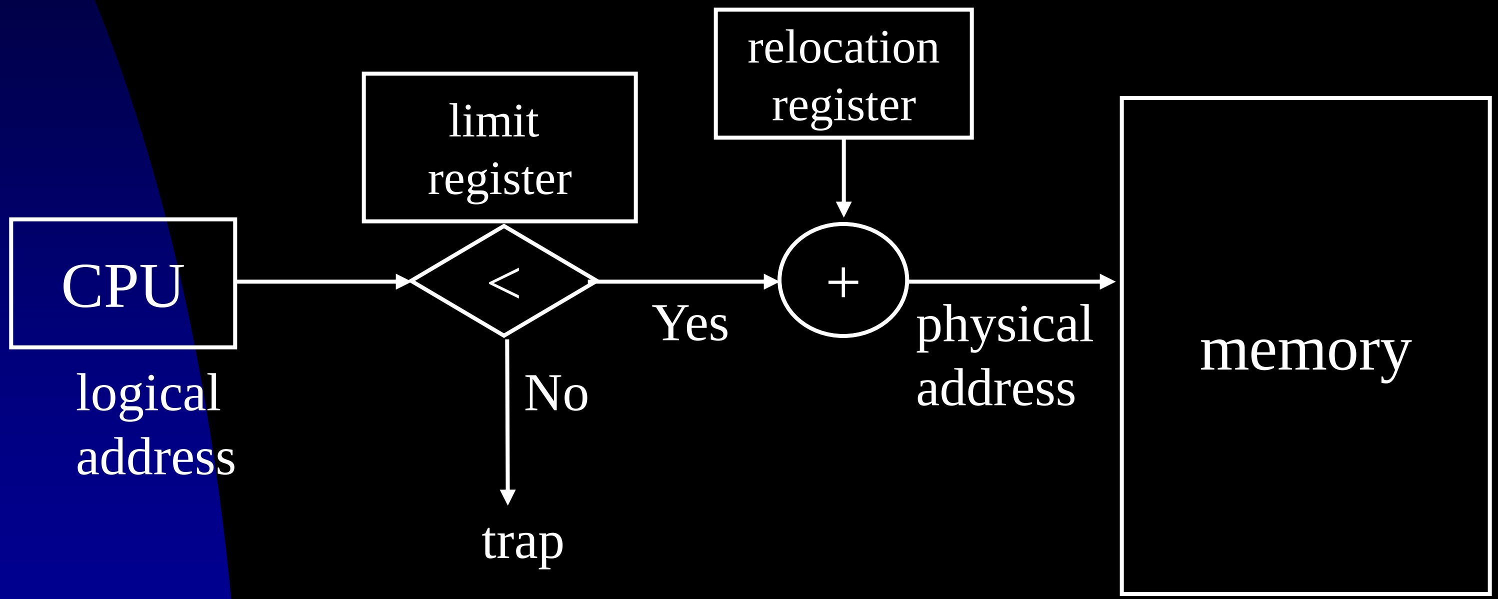
Contiguous Allocation – Single User



- A single user is allocated as much memory as needed
- Problem: Size Restriction $\rightarrow$ Overlays (MS/DOS)

Contiguous Allocation – Single User

- Hardware Support for Memory Mapping and Protection

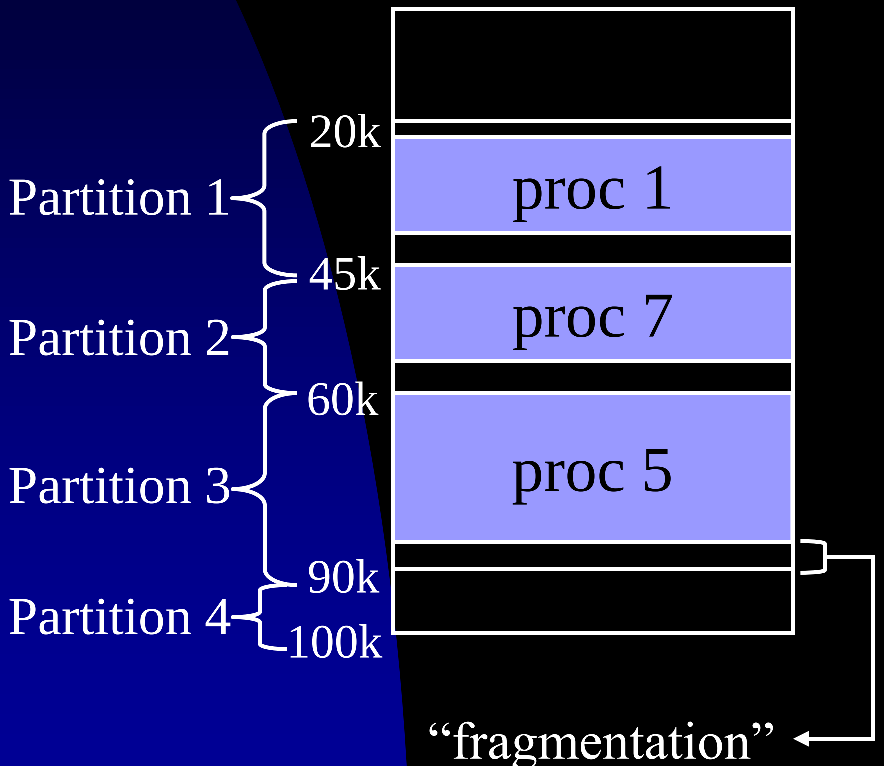


Disadvantage: Wasting of CPU and Resources

∵ No Multiprogramming Possible

Contiguous Allocation – Multiple Users

- Fixed Partitions



- Memory is divided into fixed partitions, e.g., OS/360 (or MFT)
- A process is allocated on an entire partition
- An OS Data Structure:

Partitions

#	size	location	status
1	25KB	20k	Used
2	15KB	45k	Used
3	30KB	60k	Used
4	10KB	90k	Free

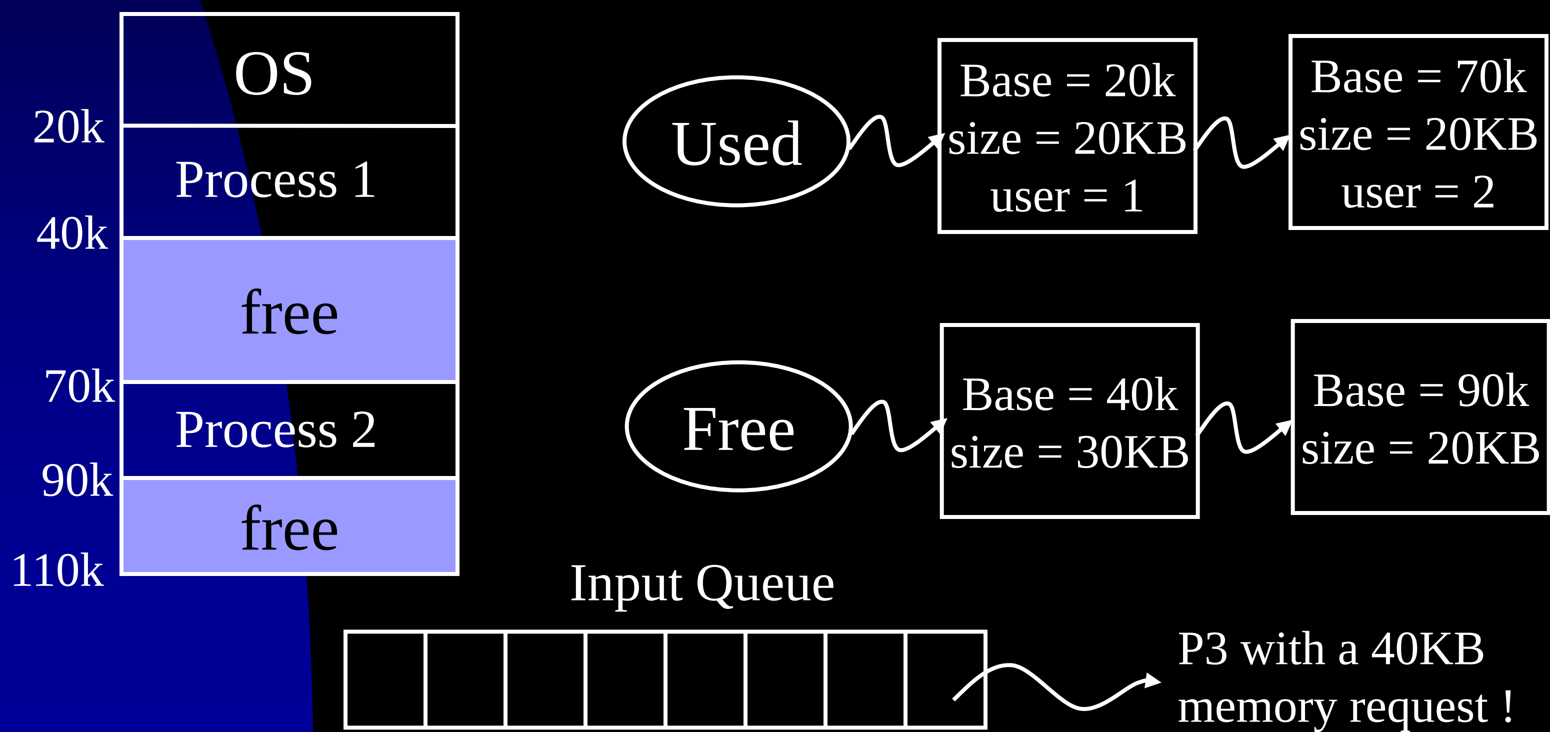
Contiguous Allocation – Multiple Users

- Hardware Supports
  - Bound registers
  - Each partition may have a protection key (corresponding to a key in the current PSW)
- Disadvantage:
  - Fragmentation gives poor memory utilization !

Contiguous Allocation – Multiple Users

- Dynamic Partitions
  - Partitions are dynamically created.
  - OS tables record free and used partitions

位置排序：good for merging、大小排序各有優缺



Contiguous Allocation – Multiple Users

By exp

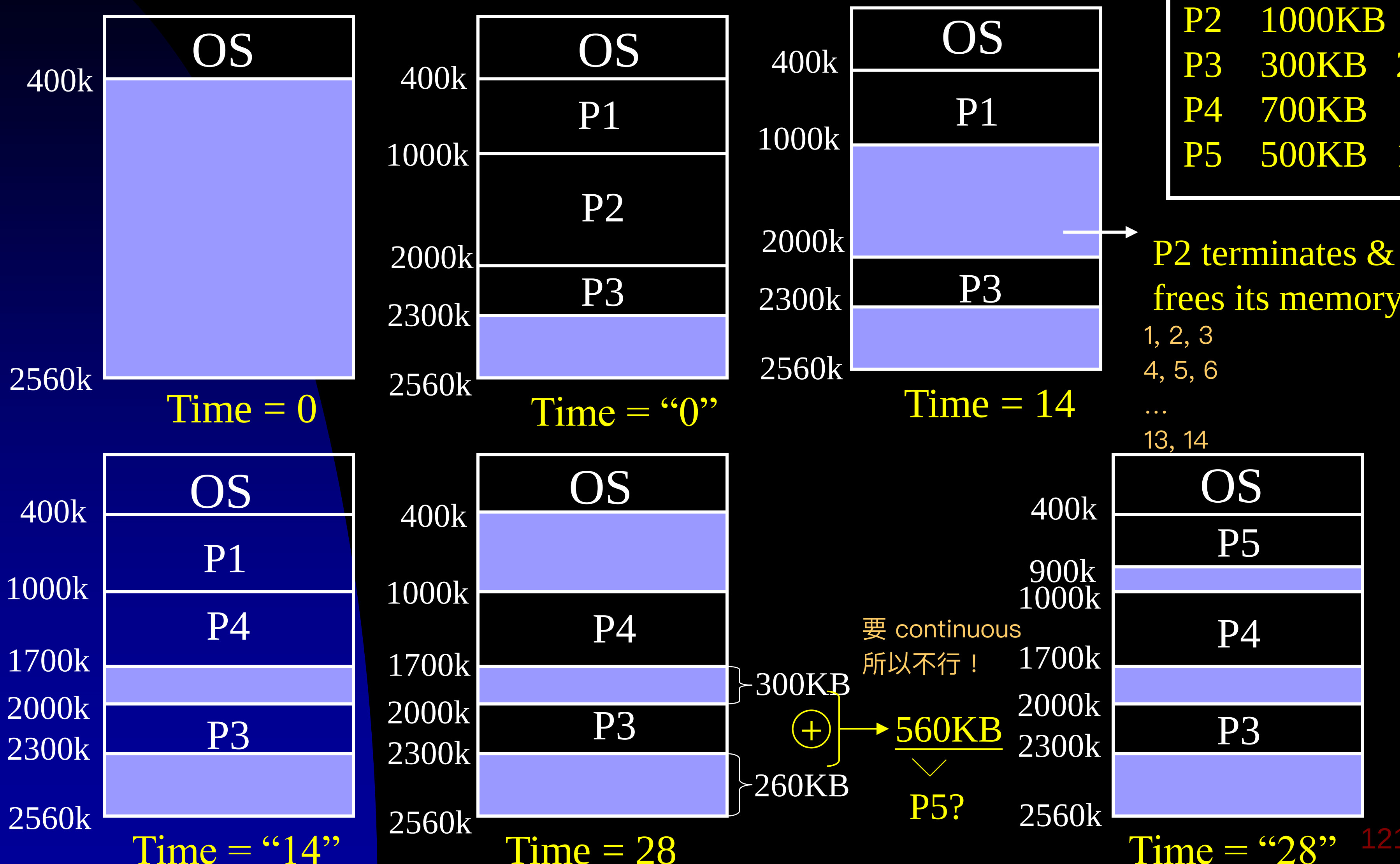
Better in Time and Storage Usage

- Solutions for dynamic storage allocation :
  - First Fit – Find a hole which is big enough
    - Advantage: Fast and likely to have large chunks of memory in high memory locations
  - Best Fit – Find the smallest hole which is big enough. $\rightarrow$ It might need a lot of search time and create lots of small fragments !
    - Advantage: Large chunks of memory available
  - Worst Fit – Find the largest hole and create a new partition out of it!
    - Advantage: Having largest leftover holes with lots of search time!

Contiguous Allocation Example – First Fit (RR Scheduler with Quantum = 1)

A job queue

Process	Memory	Time
P1	600KB	10
P2	1000KB	5
P3	300KB	20
P4	700KB	8
P5	500KB	15



Fragmentation – Dynamic Partitions

系統的

- External fragmentation occurs as small chunks of memory accumulate as a by-product of partitioning due to imperfect fits.
  - Statistical Analysis For the First-Fit Algorithm:
    - 1/3 memory is unusable – 50-percent rule

$$\frac{1/3}{2/3} = 50\%$$

  - Solutions:
    - Merge adjacent free areas.
    - Compaction
      - Compact all free areas into one contiguous region
      - Requires user processes to be relocatable

Any optimal compaction strategy???

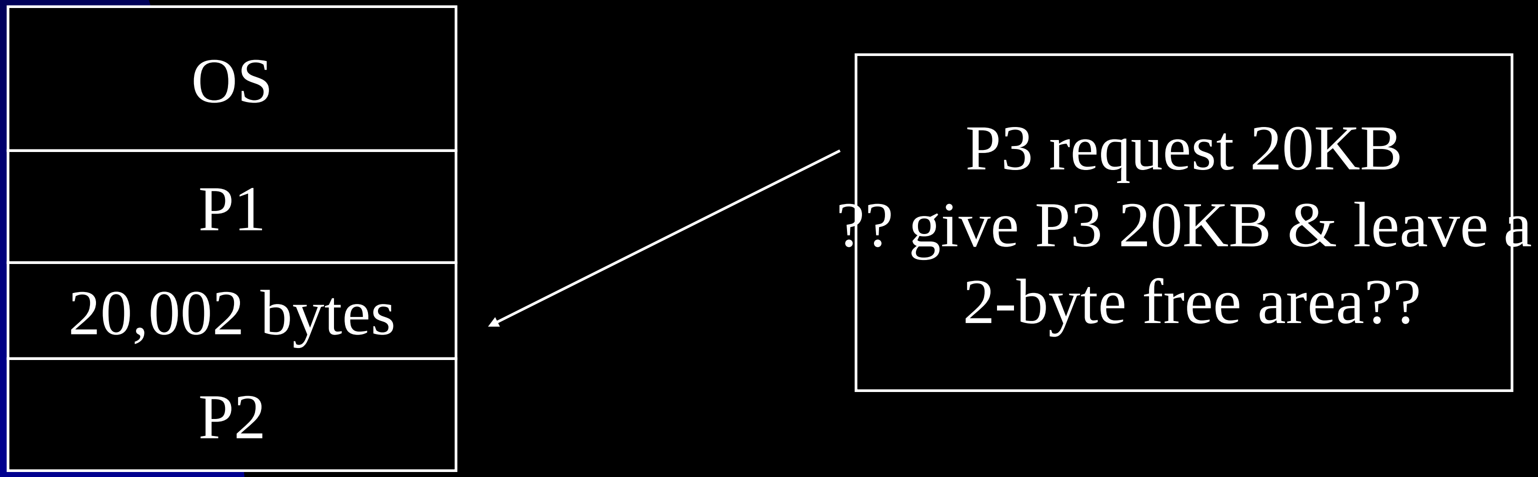
Fragmentation – Dynamic Partitions

- Cost: Time Complexity O(n!)?!! exponential
- Combination of swapping and compaction
  - Dynamic/static relocation

Fragmentation – Dynamic Partitions

- Internal fragmentation:

  A small chunk of “unused” memory internal to a partition.



Reduce free-space maintenance cost

→ Give 20,002 bytes to P3 and have 2 bytes as an internal fragmentation!

Fragmentation – Dynamic Partitions

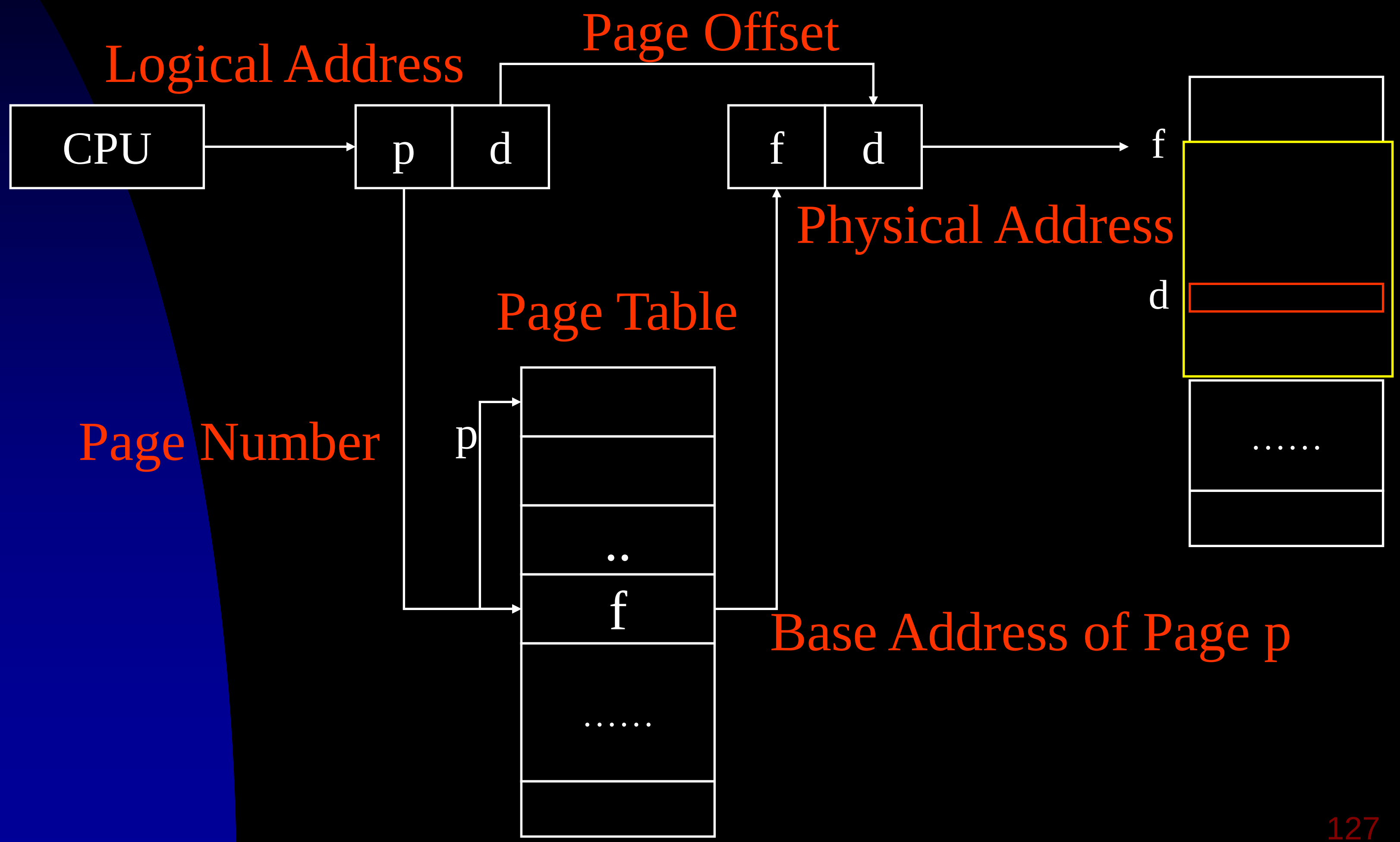
- Dynamic Partitioning:
  - Advantage:
    - ⇒ Eliminate fragmentation to some degree
    - ⇒ Can have more partitions and a higher degree of multiprogramming
  - Disadvantage:
    - Compaction vs Fragmentation
      - The amount of free memory may not be enough for a process! (contiguous allocation)
      - Memory locations may be allocated but never referenced.
    - Relocation Hardware Cost & Slow Down

⇒ Solution: Paged Memory!

Paging

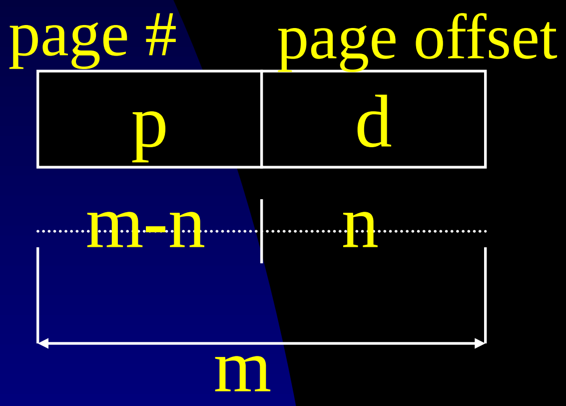
- Objective
  - Users see a logically contiguous address space although its physical addresses are throughout physical memory
- Units of Memory and Backing Store
  - Physical memory is divided into fixed-sized blocks called *frames.*
  - The logical memory space of each process is divided into blocks of the same size called *pages.*
  - The backing store is also divided into blocks of the same size if used.

Paging – Basic Method



Paging – Basic Method

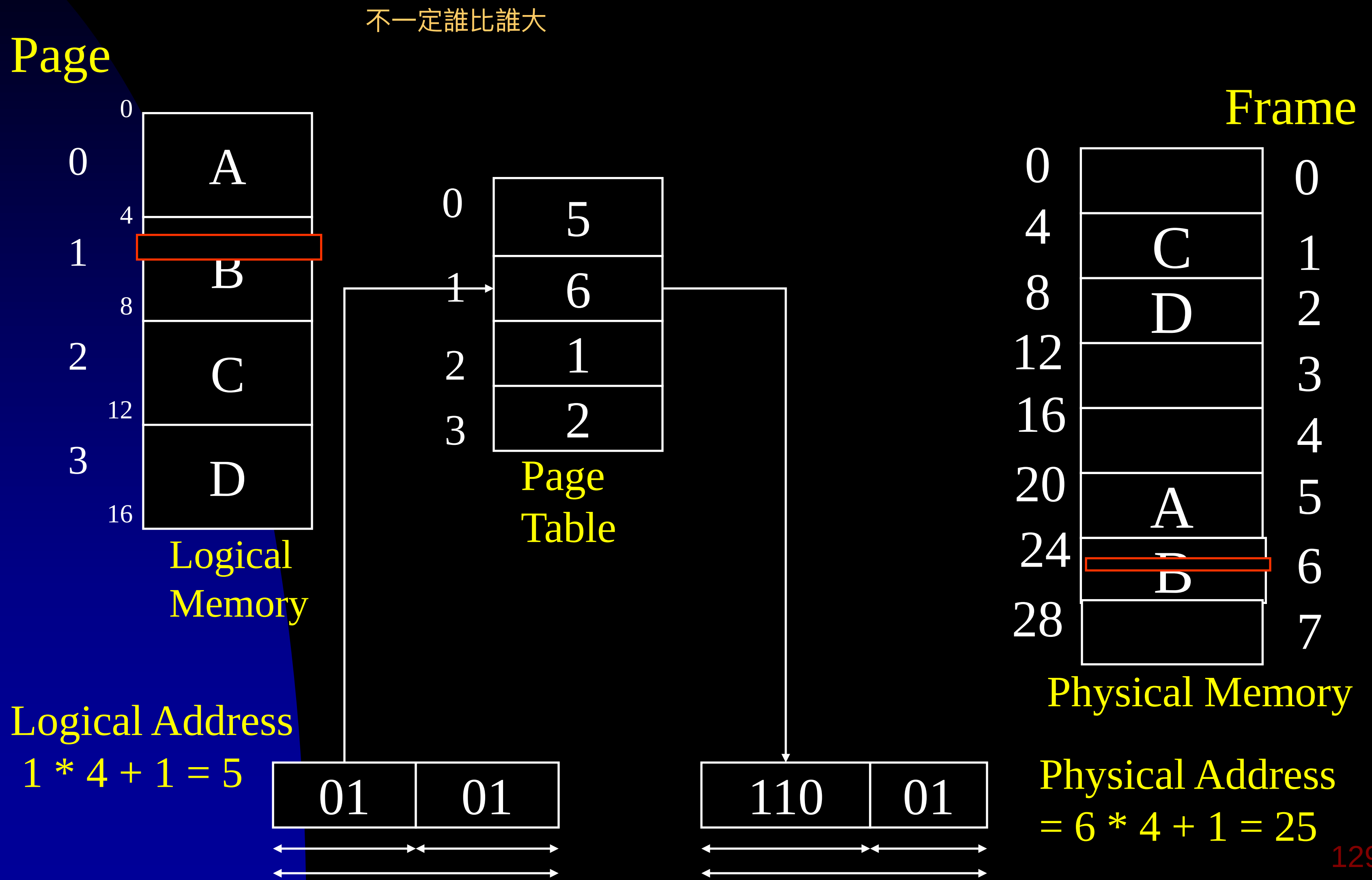
- Address Translation



max number of pages: 2^{m-n}
Logical Address Space: 2^m
Physical Address Space: ???

- A page size tends to be a power of 2 for efficient address translation.
- The actual page size depends on the computer architecture. Today, it is from 512B or 16KB.

Paging – Basic Method



Paging – Basic Method

- No External Fragmentation
  - Paging is a form of dynamic relocation.
  - The average internal fragmentation is about one-half page per process 不嚴重
- The page size generally grows over time as processes, data sets, and memory have become larger.
  - 4-byte page table entry & 4KB per page → $2^{32} * 2^{12}B = 2^{44}B$ = 16TB of physical memory

Page Size ↑	Disk I/O Efficiency ↑	Page Table Maintenance ↓	Internal Fragmentation ↑

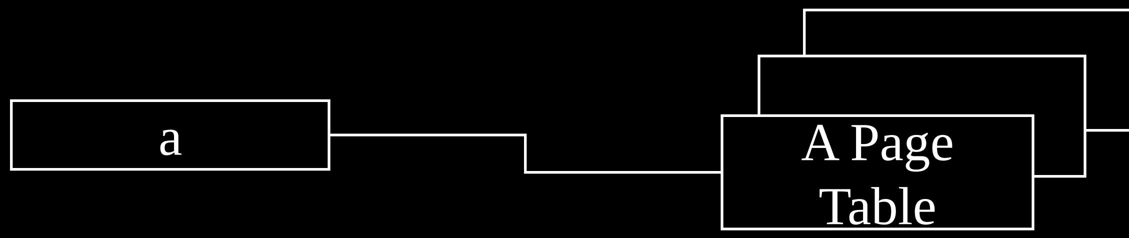
* Example: 8KB or 4MB for Solaris.

Paging – Basic Method

- Page Replacement:
  - An executing process has all of its pages in physical memory.
- Maintenance of the Frame Table
  - One entry for each physical frame
    - The status of each frame (free or allocated) and its owner
- The page table of each process must be saved when the process is preempted. → Paging increases context-switch time!

Paging – Hardware Support

- Page Tables 速度考量
  - Where: Registers or Memory
    - Efficiency is the main consideration!
  - The use of registers for page tables
    - The page table must be small!
  - The use of memory for page tables
    - Page-Table Base Register (PTBR)

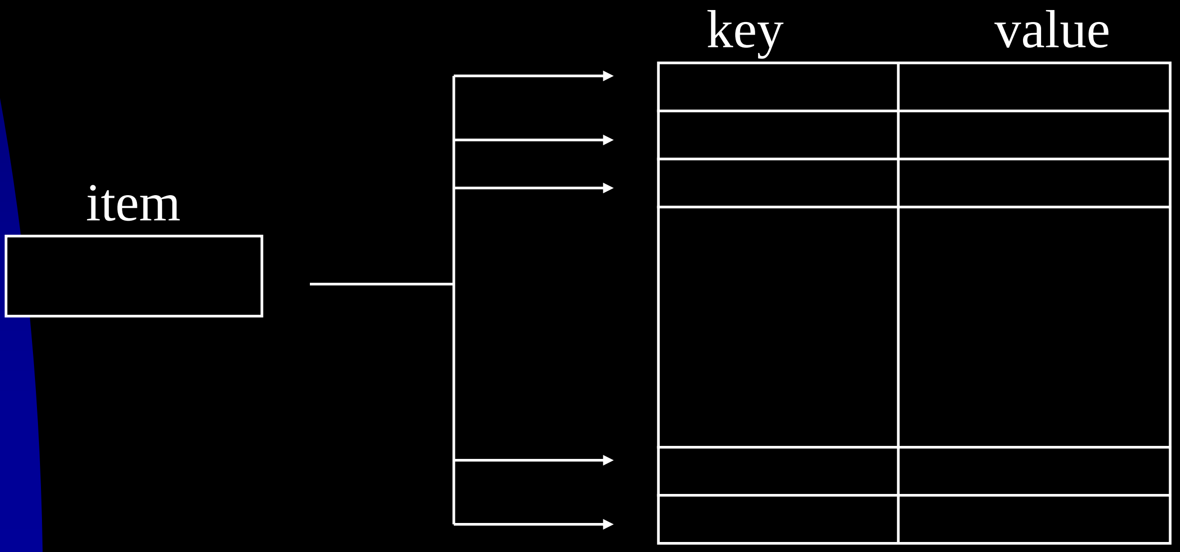


Paging – Hardware Support

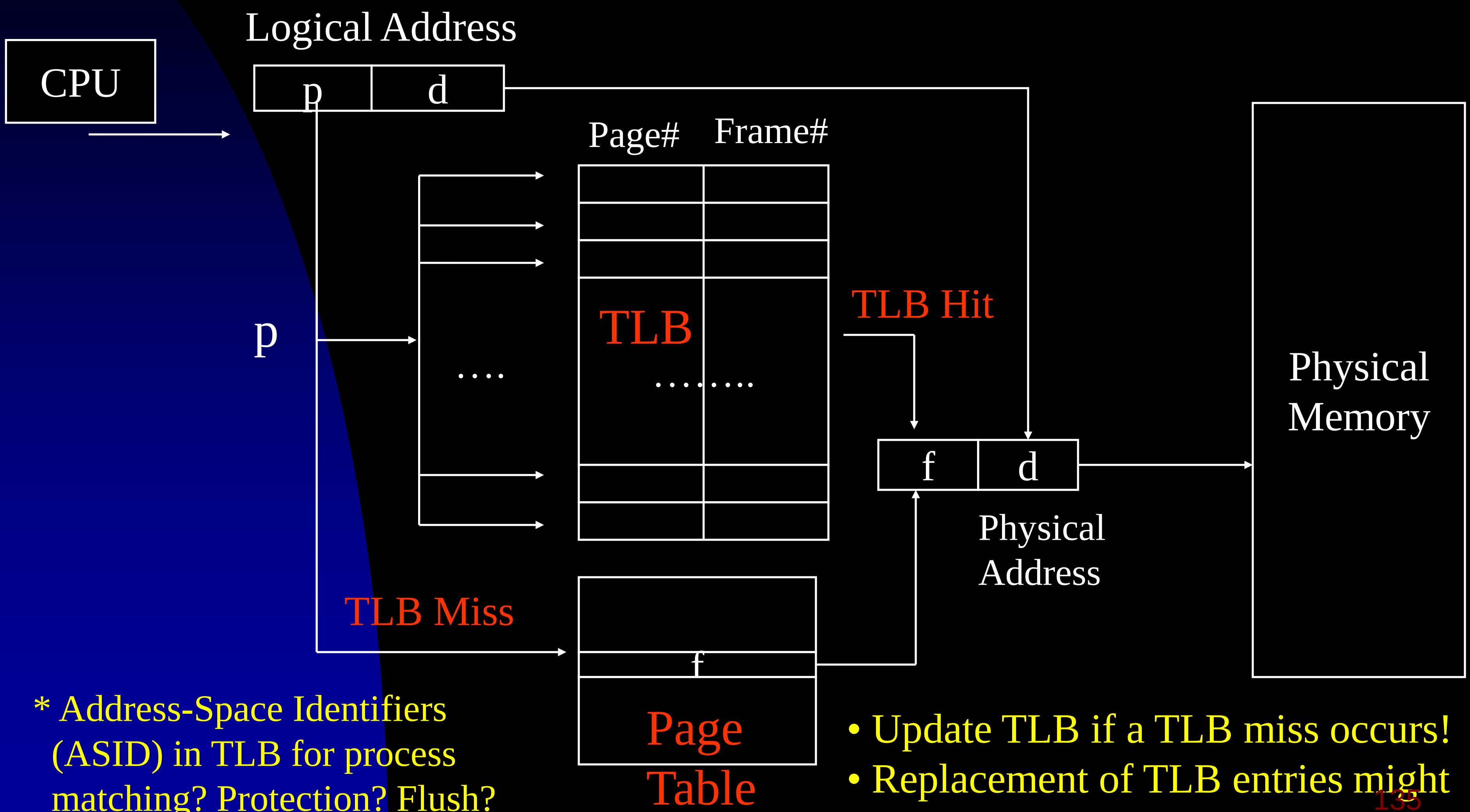
- Page Tables on Memory
  - Advantages:
    - The size of a page table is unlimited!
    - The context switch cost may be low if the CPU dispatcher merely changes PTBR, instead of reloading another page table.
  - Disadvantages:
    - Memory access is slowed by a factor of 2
      - Translation Look-aside buffers (TLB)
        - Associate, high-speed memory
        - (key/tag, value) – 16 ~ 1024 entries
        - Less than 10% memory access time

Paging – Hardware Support

- Translation Look-aside Buffers(TLB):
  - Disadvantages: Expensive Hardware and Flushing of Contents for Switching of Page Tables
  - Advantage: Fast – Constant-Search Time



Paging – Hardware Support



* Address-Space Identifiers (ASID) in TLB for process matching? Protection? Flush?

- Update TLB if a TLB miss occurs!
- Replacement of TLB entries might be needed.

Paging – Effective Memory Access Time

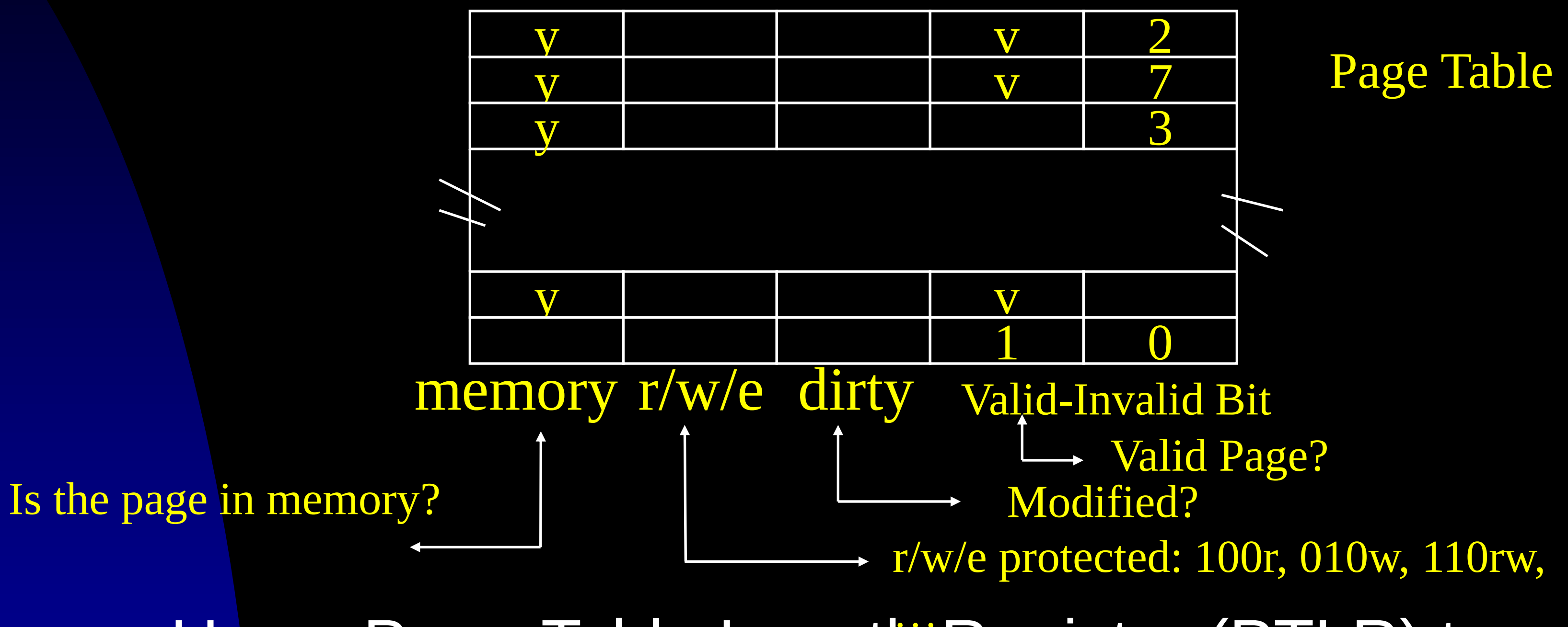
- Hit Ratio = the percentage of times that a page number is found in the TLB
  - The hit ratio of a TLB largely depends on the size and the replacement strategy of TLB entries!
- Effective Memory Access Time
  - Hit-Ratio * (TLB lookup + a mapped memory access) + (1 – Hit-Ratio) * (TLB lookup + a page table lookup + a mapped memory access)

Paging – Effective Memory Access Time

- An Example
  - 20ns per TLB lookup, 100ns per memory access
  - Effective Access Time = 0.8*120ns +0.2*220ns = 140 ns, when hit ratio = 80%
  - Effective access time = 0.98*120ns +0.02*220ns = 122 ns, when hit ratio = 98%
- Intel 486 has a 32-register TLB and claims a 98 percent hit ratio.

Paging – Protection & Sharing

- Protection



  - Use a Page-Table Length Register (PTLR) to indicate the size of the page table.
  - Unused Paged table entries might be ignored during maintenance.

Paging – Protection & Sharing

- Example: a 12287-byte Process ($16384=2^{14}$)

0	P0
2K	P1
4K	P2
6K	P3
8K	P4
10K	P5
10,468 … 12,287	

0		V	2
1		V	3
2		V	4
3		V	7
4		V	8
5		V	9
6		i	0
7		i	0

Page Table

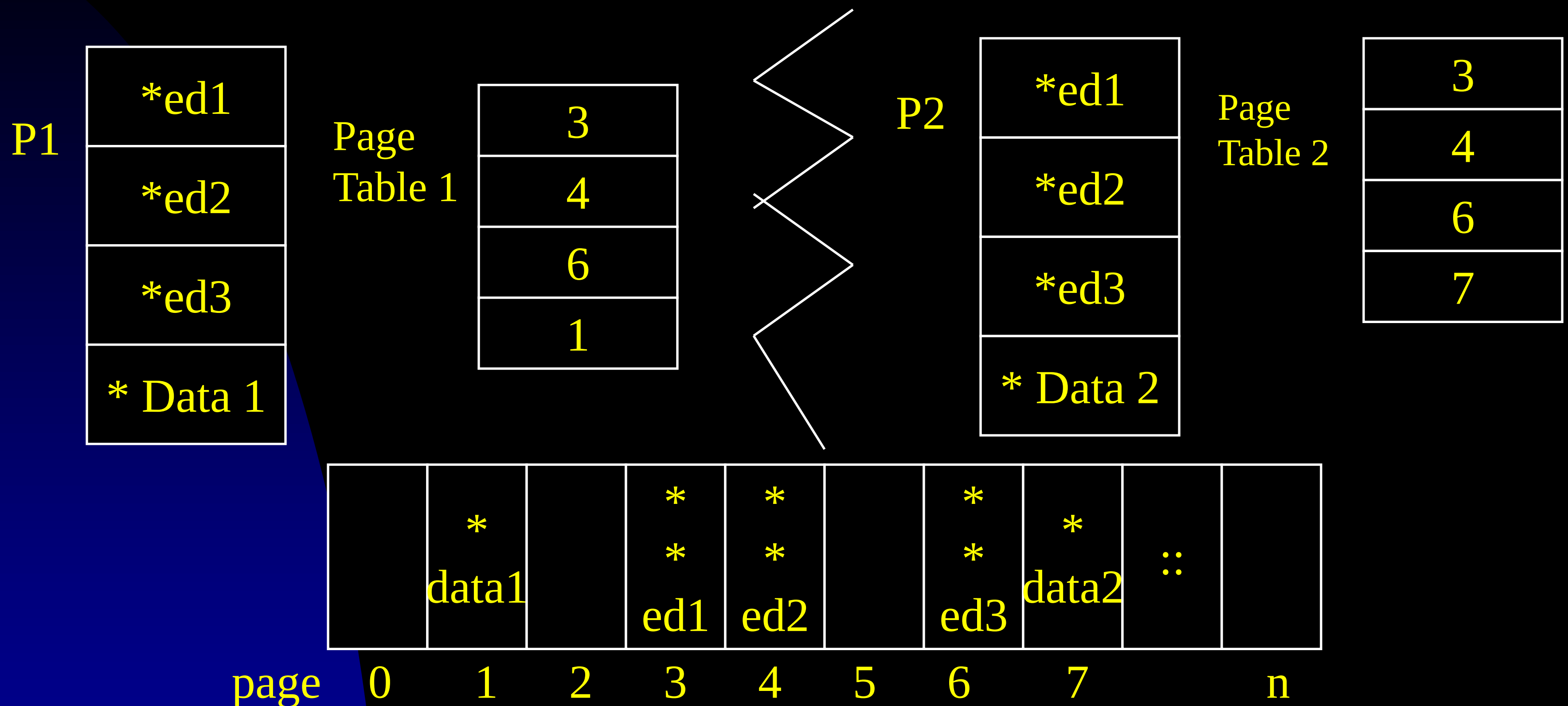
(PTLR entries?)

0	
1	
2	P0
3	P1
4	P2
5	
6	
7	P3
8	P4
9	P5

Logical address

p	d
3	11

Paging – Protection & Sharing



- Procedures which are executed often (e.g., editor) can be divided into procedure + data. Memory can be saved a lot.
- The space of reentrant procedures can be saved! The non-modified nature of shared code must be enforced
- Address referencing inside shared pages could be an issue.

Multilevel Paging

- Motivation
  - The logical address space of a process in many modern computer system is very large, e.g., 2^{32} to 2^{64} Bytes.

32-bit address → 2^{20} page entries → 4MB

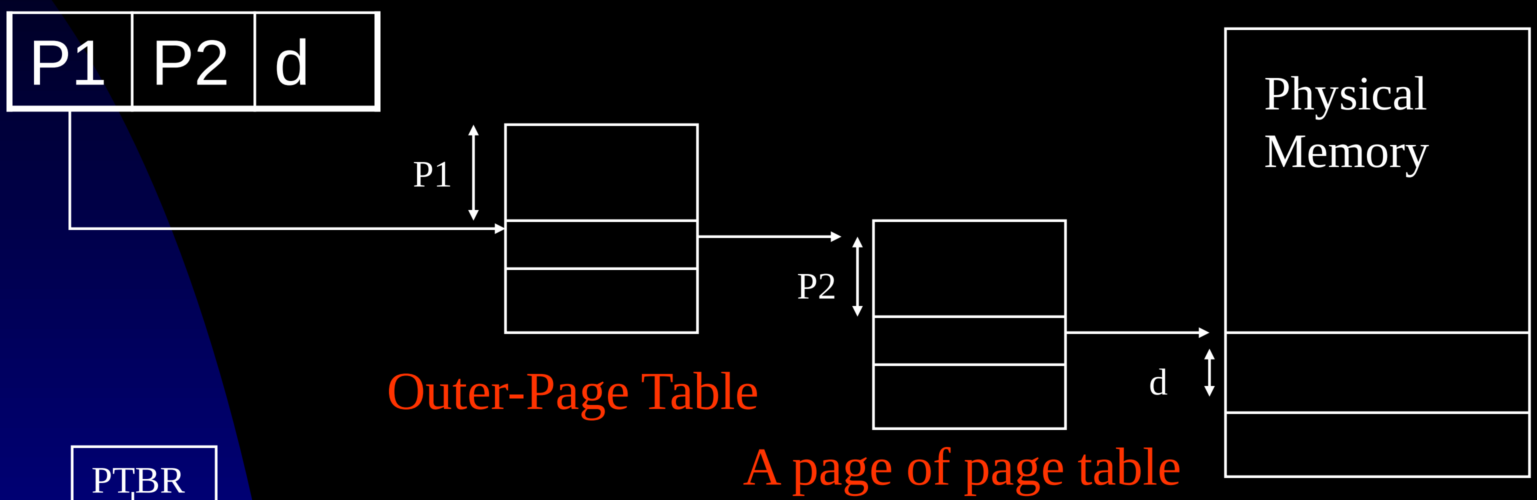
4KB per page   4B per entries   page table

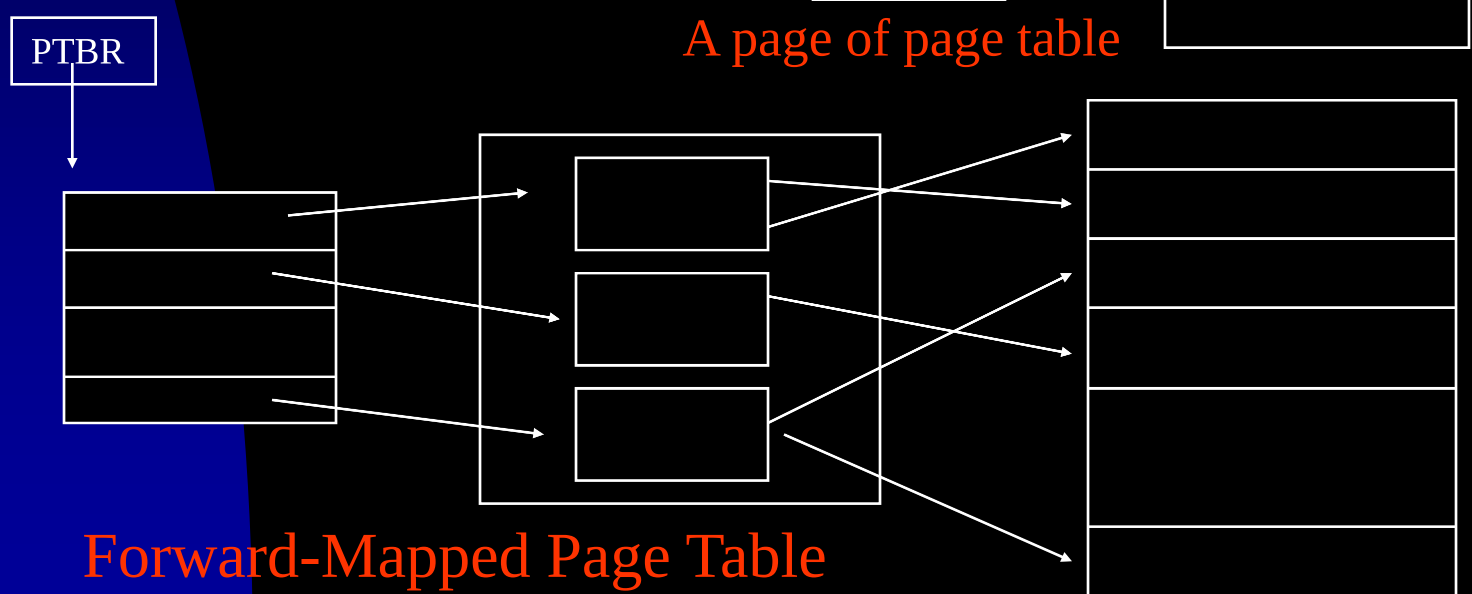
→ Even the page table must be divided into pieces to fit in the memory!

Multilevel Paging – Two-Level Paging

假設 32 bit，一個 page 4KB（12bit）
PTB1 用掉 10bit、PTB2 用掉 10bit

Logical Address





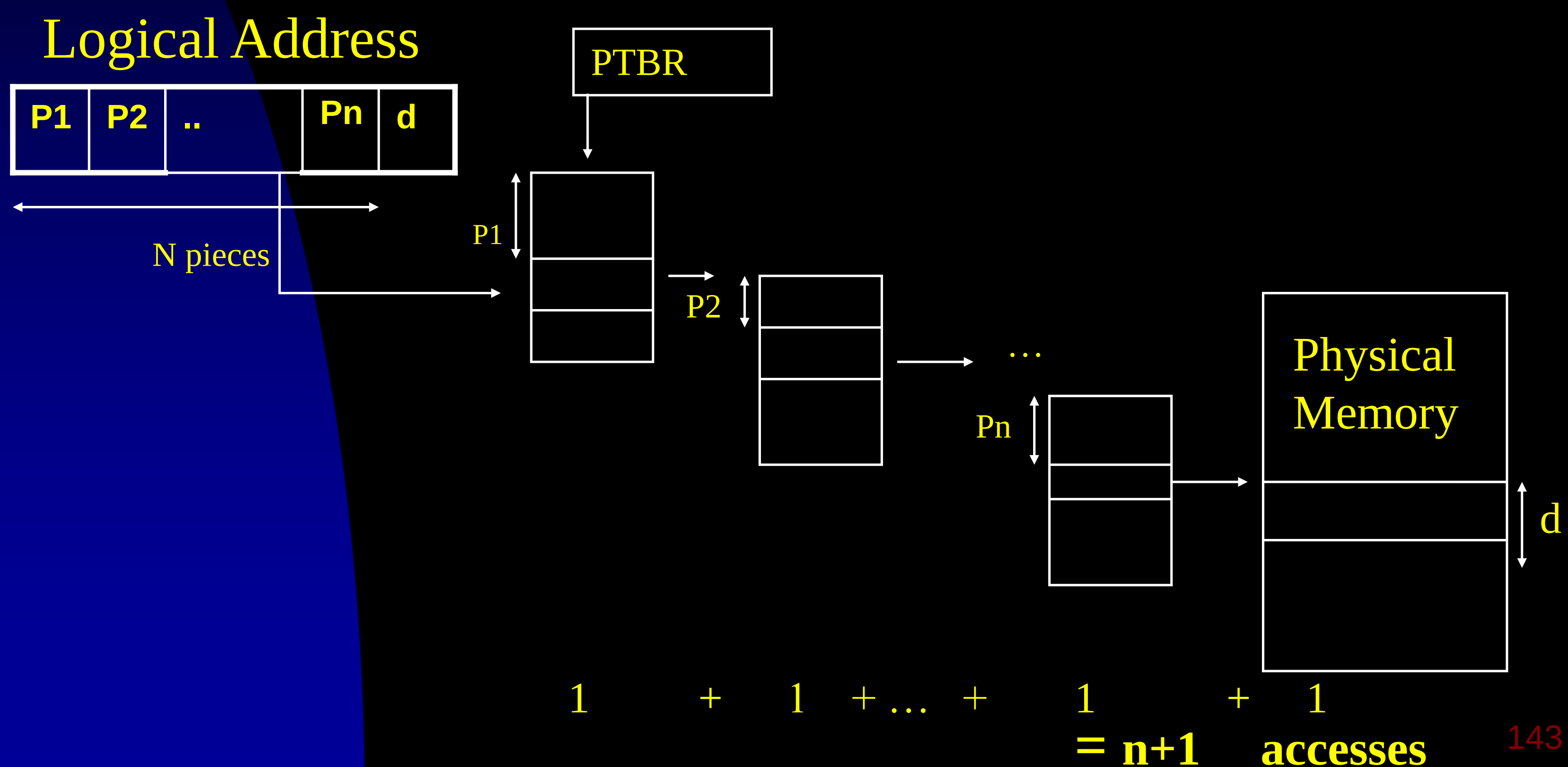
Forward-Mapped Page Table

Multilevel Paging – N-Level Paging

Assume 64bit, 2 + 10 + 10 + 10 + 10 + 10 + 12

7 次 memory access

- Motivation: Two-level paging is not appropriate for a huge logical address space!



Multilevel Paging – N-Level Paging

- Example
  - 98% hit ratio, 4-level paging, 20ns TLB access time, 100ns memory access time.
  - Effective access time = 0.98 X 120ns + 0.02 X 520ns = 128ns 是很可行的！時間沒有增加多少
- SUN SPARC (32-bit addressing) → 3-level paging
- Motorola 68030 (32-bit addressing) → 4-level paging
- VAX (32-bit addressing) → 2-level paging

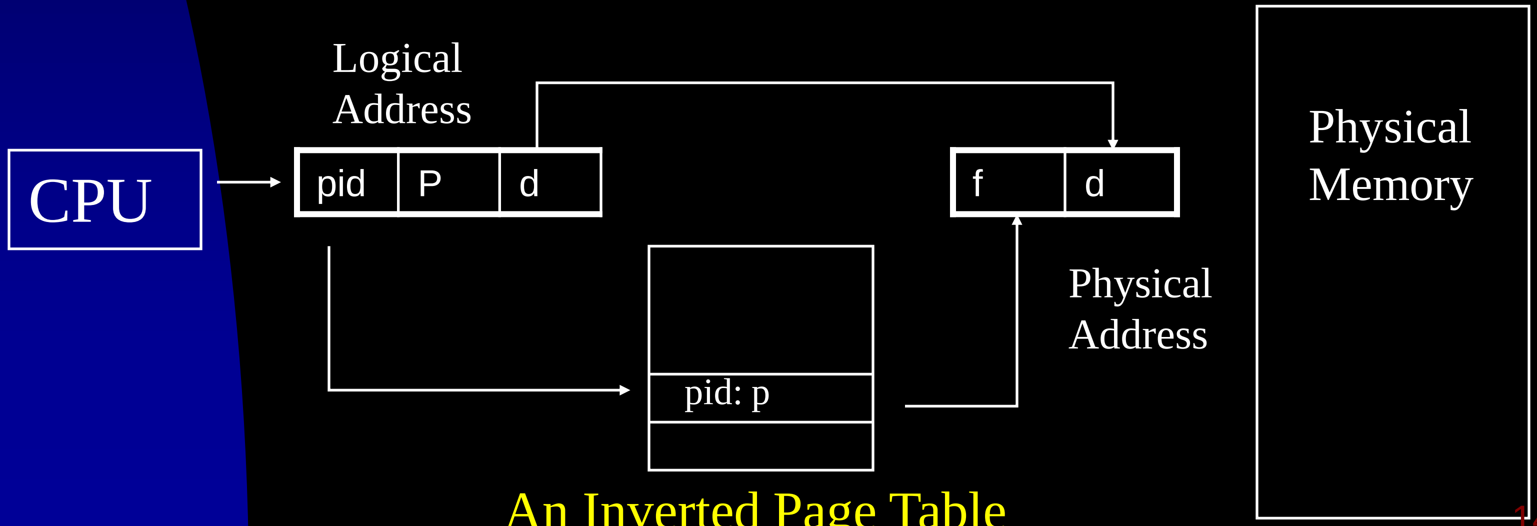
Hashed Page Tables

結省記憶體的空間

- Objective:
  - To handle large address spaces
- Virtual address → hash function → a linked list of elements
  - (virtual page #, frame #, a pointer)
- Clustered Page Tables
  - Each entry contains the mappings for several physical-page frames, e.g., 16.

Inverted Page Table

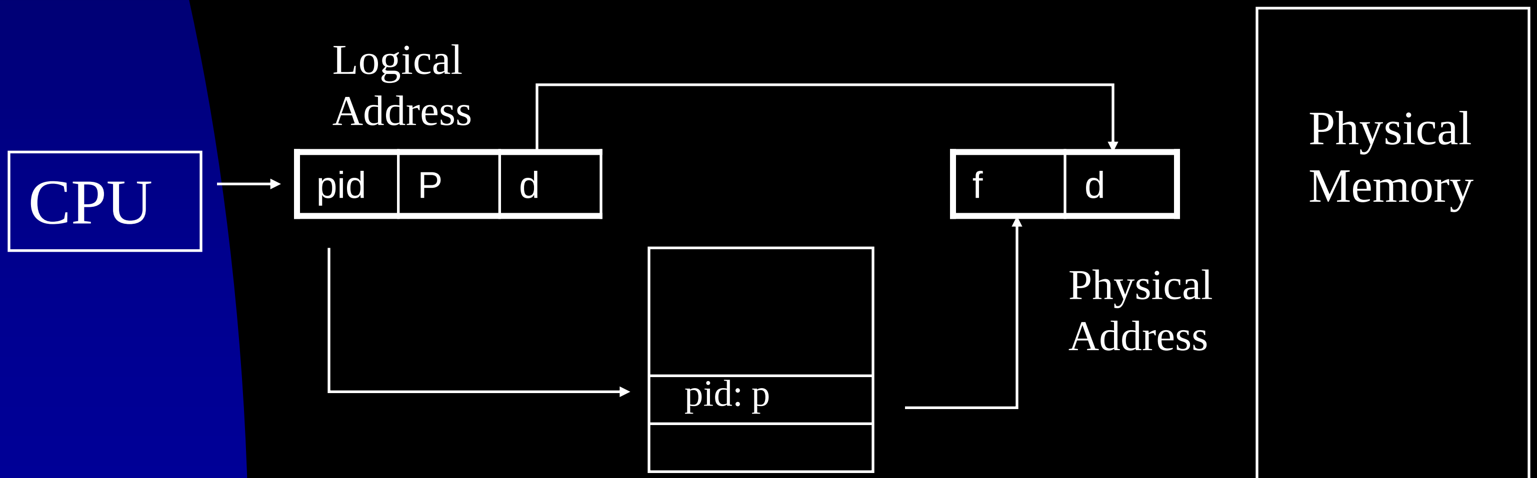
- Motivation
  - A page table tends to be big and does not correspond to the # of pages residing in the physical memory.
- Each entry corresponds to a physical frame.
  - Virtual Address: <Process ID, Page Number, Offset>



An Inverted Page Table

Inverted Page Table

- Each entry contains the virtual address of the frame.
  - Entries are sorted by physical addresses.
  - One table per system.
- When no match is found, the page table of the corresponding process must be referenced.
- Example Systems: HP Spectrum, IBM RT, PowerPC, SUN 64-bit UltraSPARC



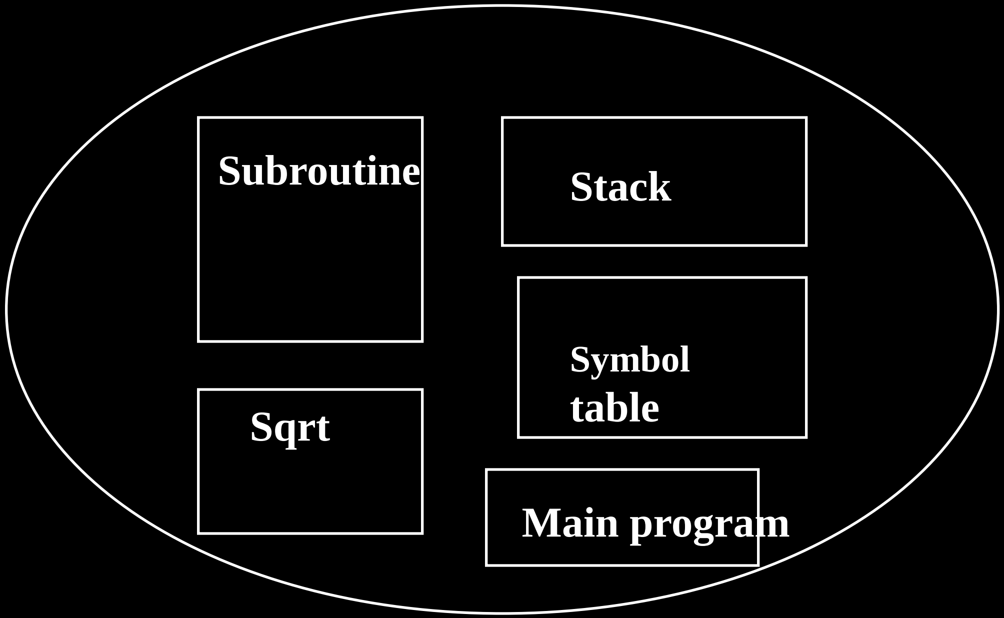
An Inverted Page Table

Inverted Page Table

- Advantage
  - Decrease the amount of memory needed to store each page table
- Disadvantage
  - The inverted page table is sorted by physical addresses, whereas a page reference is in a logical address.
    - The use of Hash Table to eliminate lengthy table lookup time: 1HASH + 1IPT
    - The use of an associate memory to hold recently located entries.
  - Difficult to implement with shared memory

Segmentation

- Segmentation is a memory management scheme that supports the user view of memory:
  - A logical address space is a collection of segments with variable lengths.



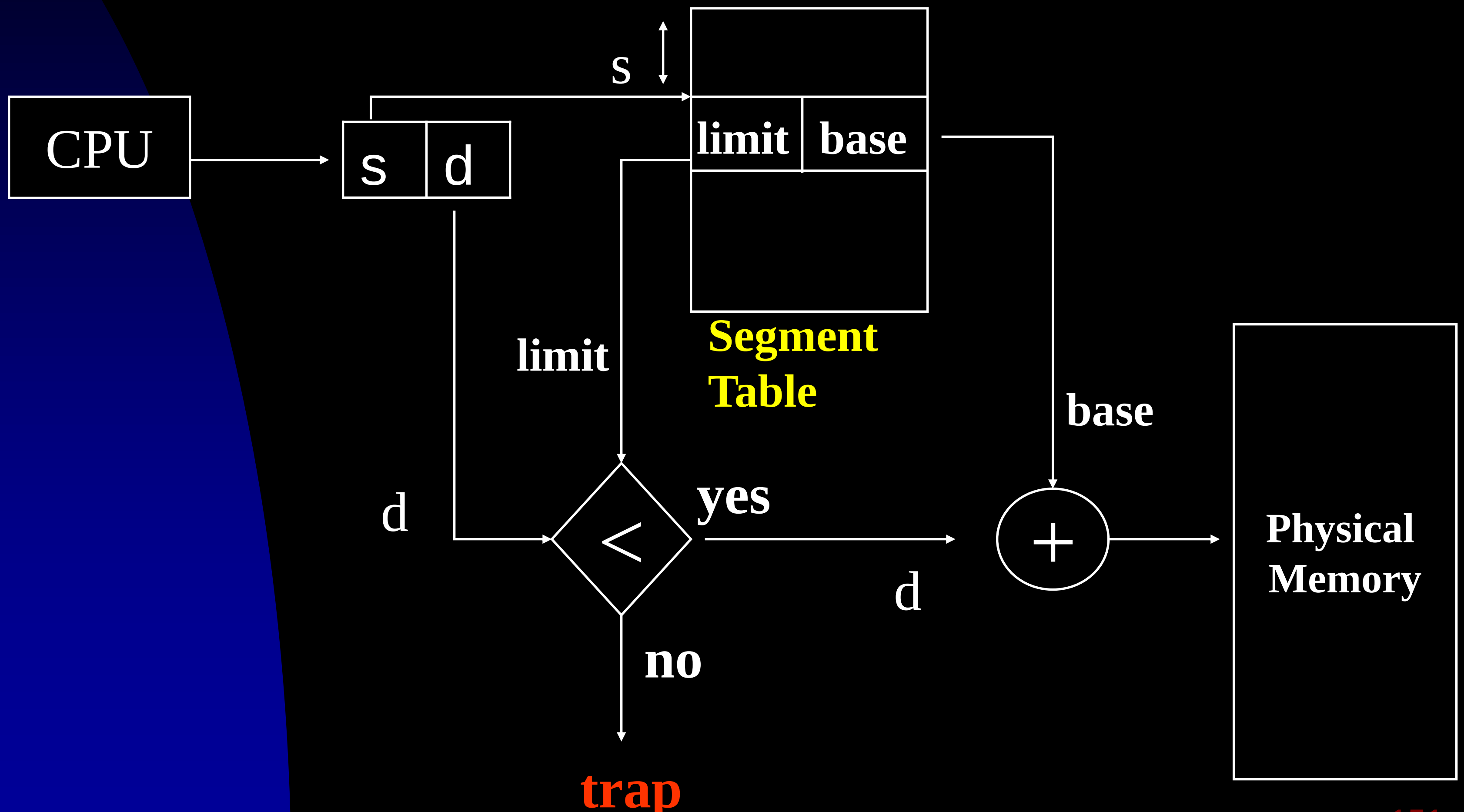
Segmentation

- Why Segmentation?
  - Paging separates the user's view of memory from the actual physical memory but does not reflect the logical units of a process!
  - Pages & frames are fixed-sized, but segments have variable sizes.
- For simplicity of representation,

  <segment name, offset> → <segment-number, offset>

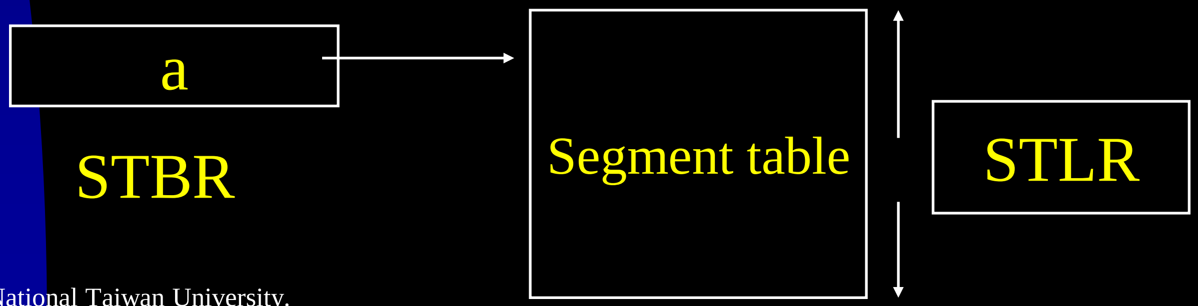
Segmentation – Hardware Support

- Address Mapping



Segmentation – Hardware Support

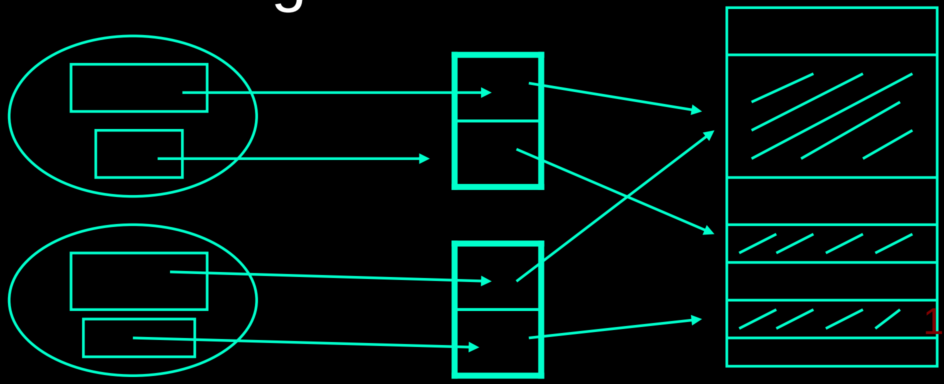
- Implementation in Registers – limited size!
- Implementation in Memory
  - Segment-table base register (STBR)
  - Segment-table length register (STLR)
  - Advantages & Disadvantages – Paging
    - Use an associate memory (TLB) to improve the effective memory access time !
    - TLB must be flushed whenever a new segment table is used !



Segmentation – Protection & Sharing

- Advantage:
  - Segments are a semantically defined portion of the program and likely to have all entries being "homogeneous".
    - Example: Array, code, stack, data, etc.

      → Logical units for protection !
  - Sharing of code & data improves memory usage.
    - Sharing occurs at the segment level.



Segmentation – Protection & Sharing

- Potential Problems
  - External Fragmentation
  - Segments must occupy contiguous memory.
  - Address referencing inside shared segments can be a big issue:

Seg#	offset

Indirect addressing?!!!

Should all shared-code segments have the same segment number?

- How to find the right segment number if the number of users sharing the segments increase! → Avoid reference to segment #

Segmentation – Fragmentation

- Motivation:

  Segments are of variable lengths!

  → Memory allocation is a dynamic storage-allocation problem.

  - best-fit? first-fit? worst-ft?

- External fragmentation will occur!!
  - Factors, e.g., average segment sizes

Size ↓ A byte

External Fragmentation ↓

Overheads increases substantially!

(base+limit "registers")

Segmentation – Fragmentation

- Remark:
  - Its external fragmentation problem is better than that of the dynamic partition method because segments are likely to be smaller than the entire process.
- Internal Fragmentation??

Segmentation with Paging

- Motivation :
  - Segmentation has external fragmentation.
  - Paging has internal fragmentation.
  - Segments are semantically defined portions of a program.

    → "Page" Segments !

Oracle SPARC Solaris

- Solaris over a 64-bit SPARC CPU computer
  - One hash table for the kernel and one for all user processes
    - Each entry has a base address and the number of pages for the entry
  - The procedure of a virtual memory translation: TLB → Translation Storage Buffer (TSB) → Interrupt happens to manipulate TSB and TLB

IA-32 Segmentation

- 8K Private Segments + 8K Public Segments
  - Page Size = 4KB or 4MB (*page size flag* in the page directory), Max Segment Size = 4GB
  - Tables:
    - Local Descriptor Table (LDT)
    - Global Descriptor Table (GDT)
  - 6 microprogram segment registers for caching

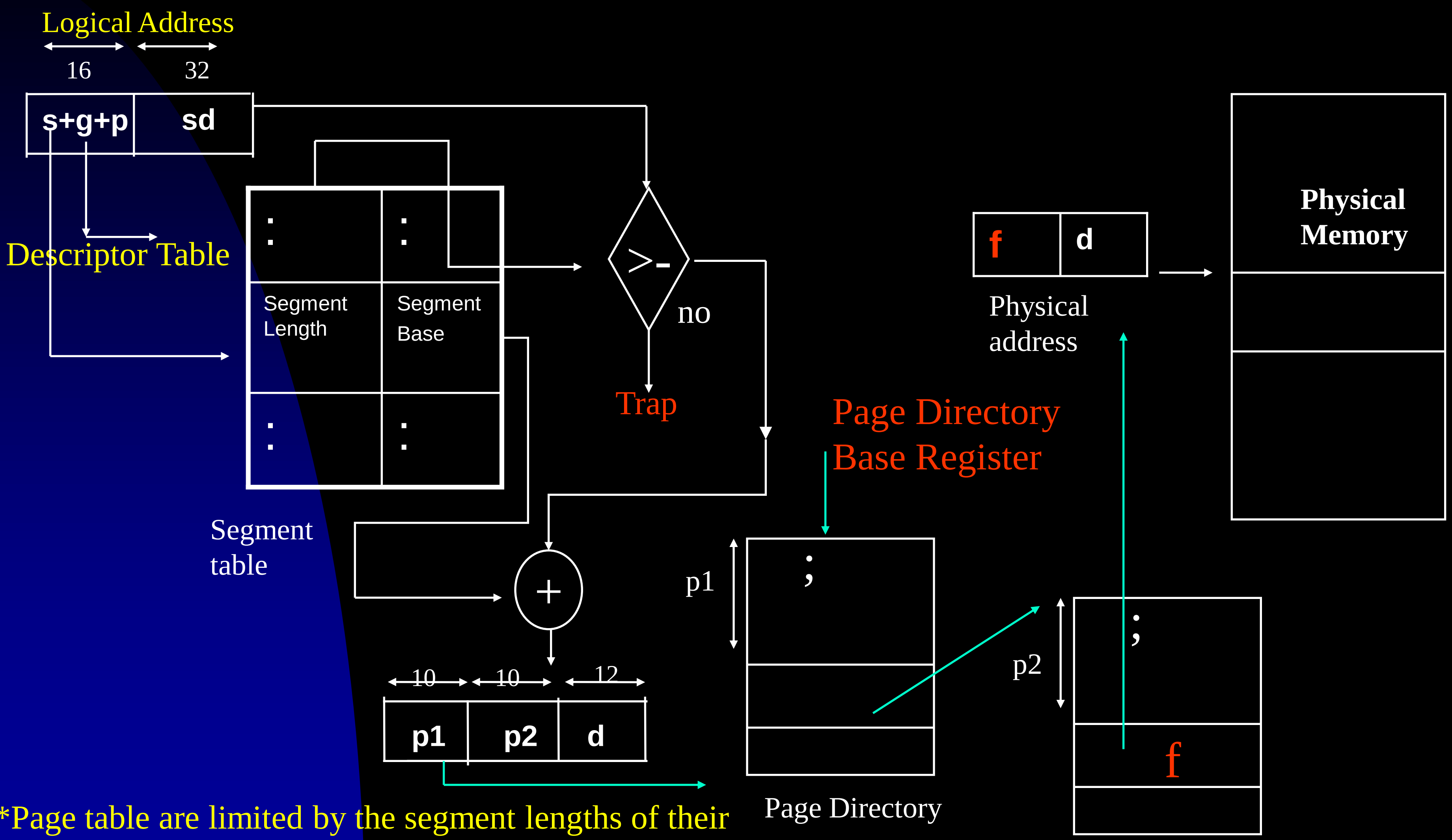
Logical Address

Selector			Segment Offset
s	g	p	sd
13	1	2	32

Linear Address

p1	p2	d
10	10	12

IA-32 Segmentation



*Page table are limited by the segment lengths of their segments. Consider the page size flag and the invalid bit of each page directory entry.

IA-32 Paging

- A Two-Level Paging Scheme
  - Page Directory and Page_Size flag

Linear Address

p1	p2	d
10	10	12

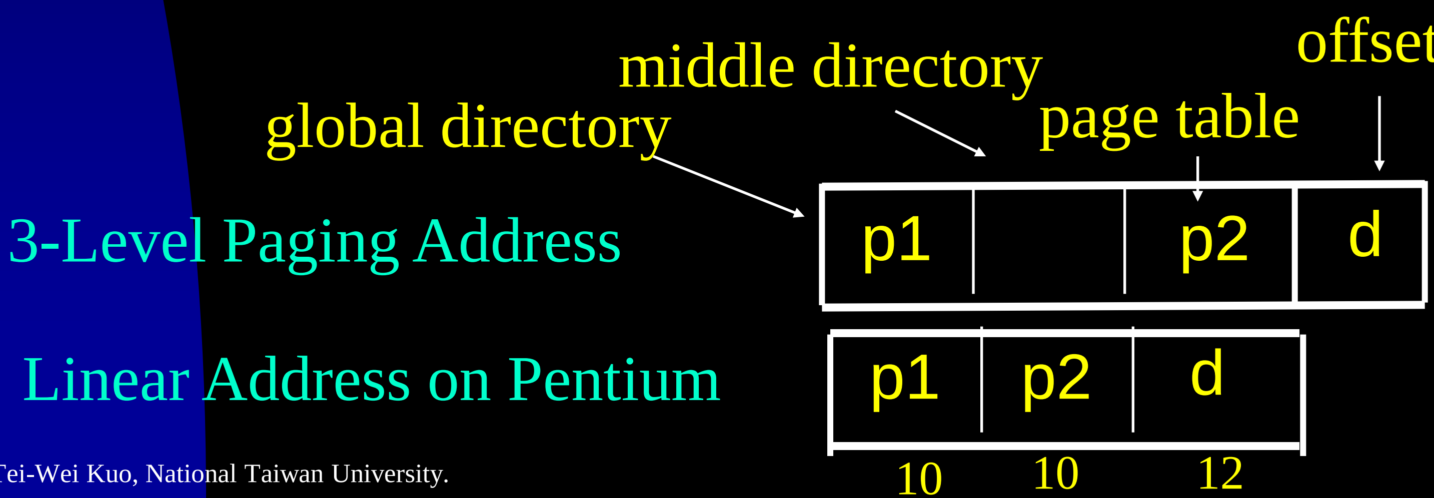
  - Invalid Bit in the Page Dir
    - Swapping support to the disk
- Page Address Extension – 3 Levels

Page Directory Pointer Table

	p1	p2	d
2	9	9	12

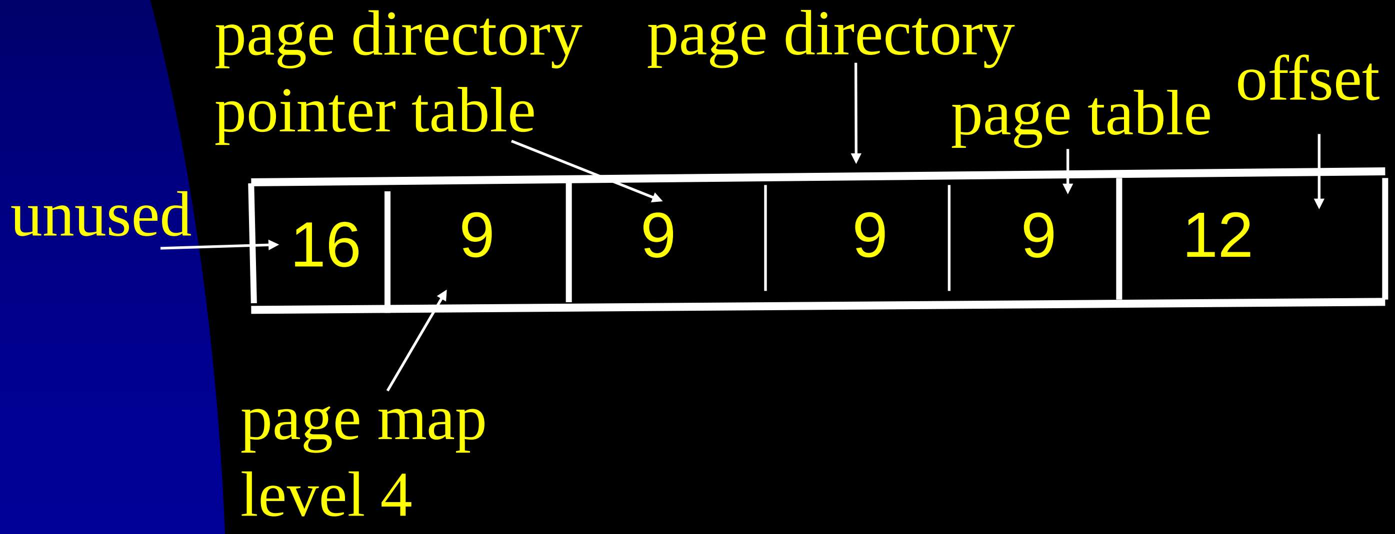
IA-32 and Linux

- Limitation & Goals
  - Supports over a variety of machines
    - Use segmentation minimally – GDT
      - One individual segment for the kernel code, kernel data, the user code, the user data, the task state segment, the default LDT
    - Protection: user and kernel modes



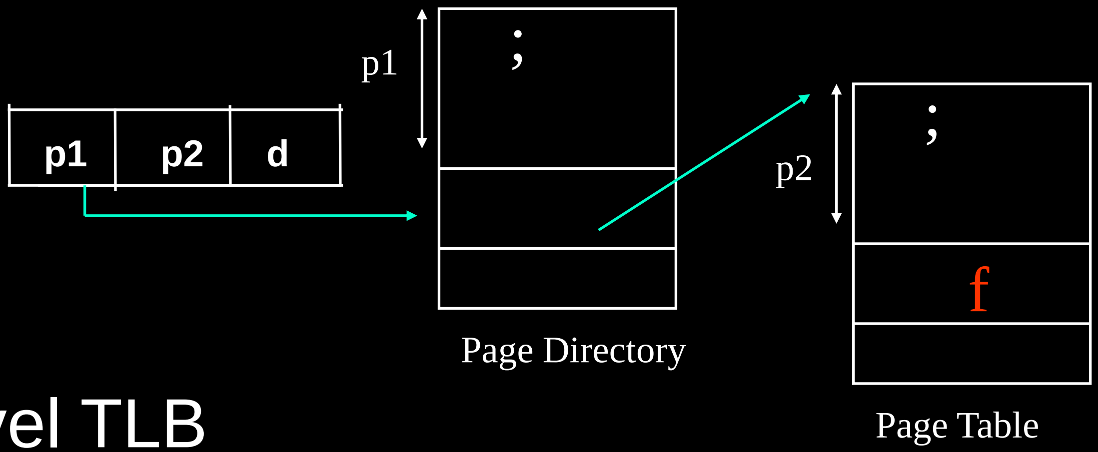
x86-64

- x86-64 is a 64-bit architecture based on IA-32 and proposed by AMD (and used by Intel).
  - Page Sizes: 4KB, 2MB, or 1GB



32-Bit ARM

- Paging:
  - 2-Level Paging: 4KB or 16KB Pages
  - 1-Level Paging: 1MB or 16MB Sections



  - 2-Level TLB
    - Micro TLBs – Data and Instructions
    - Main TLB

Paging and Segmentation

- To overcome disadvantages of paging or segmentation alone:
  - Paged segments – divide segments further into pages.
    - Segment need not be in contiguous memory.
  - Segmented paging – segment the page table.
    - Variable size page tables.
- Address translation overheads increase!
- An entire process still needs to be in memory at once!

→ Virtual Memory!!

Paging and Segmentation

- Considerations in Memory Management
  - Hardware Support, e.g., STBR, TLB, etc.
  - Performance
  - Fragmentation
    - Multiprogramming Levels
  - Relocation Constraints?
  - Swapping: +
  - Sharing?!
  - Protection?!