政大資科系

作業系統

Operating System

廖峻鋒

cfliao@nccu.edu.tw

Operating System

Main Memory

Chun-Feng Liao

廖峻鋒

Department of Computer Science

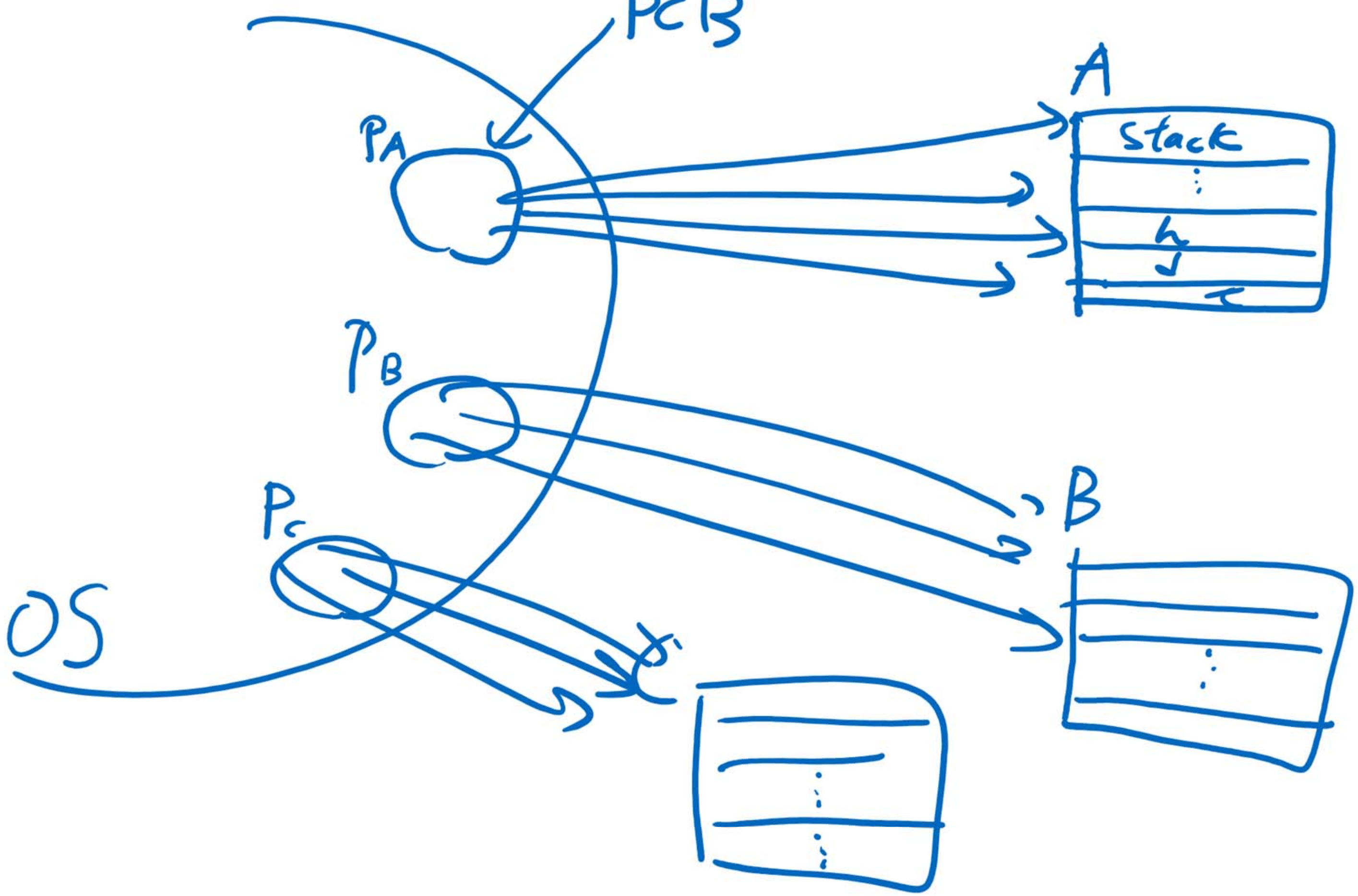
National Chengchi University

Outline

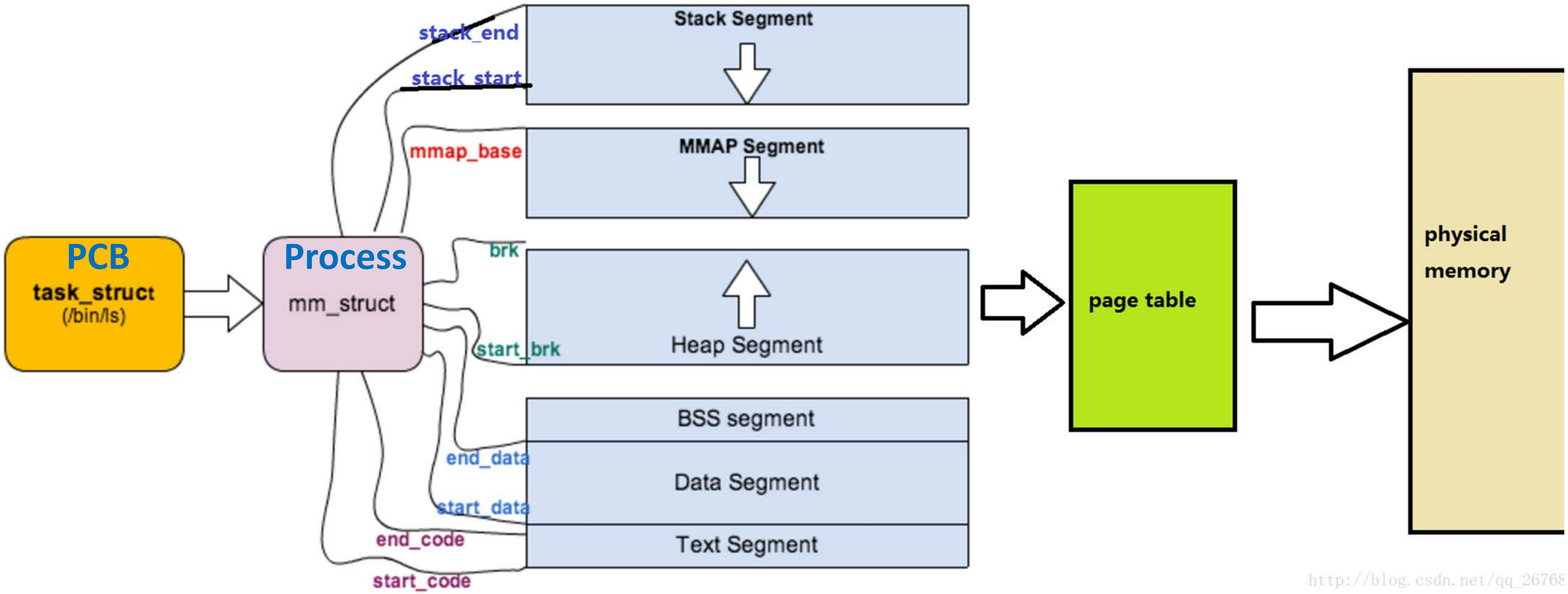
- Overview
- Memory Allocation
- Paging
- Page Table
- Swapping

Overview

- CPU可直接存取的儲存媒體
  - Registers
  - L1/L2 Cache
  - Main memory
- Speeds of memory hierarchy
  - Register access is done in one CPU clock (or less)
  - Main memory can take many cycles, causing a stall
  - Cache sits between main memory and CPU registers



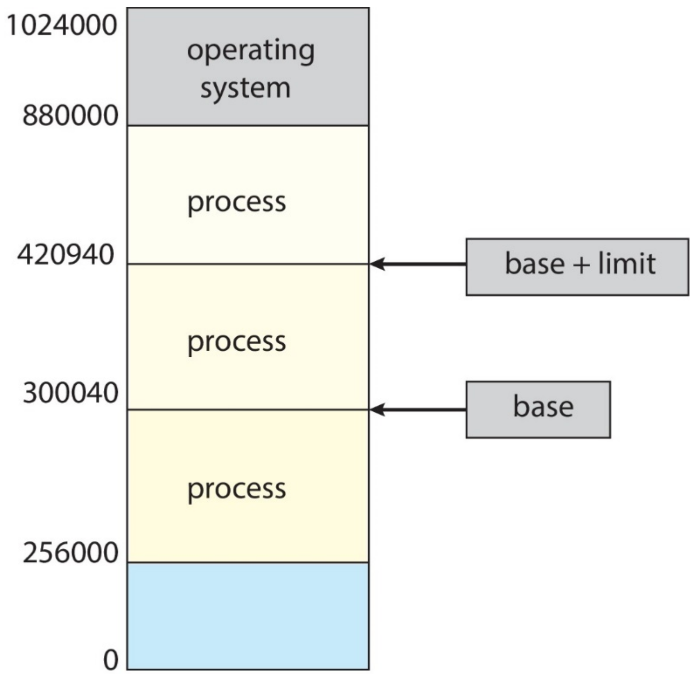
Process



https://github.com/torvalds/linux/blob/master/include/linux/mm_types.h#L402

Memory Protection

- Protection is required to ensure correct operation
  - Using base and limit registers to define the logical address space of a process



300040<=addr<300040+120900

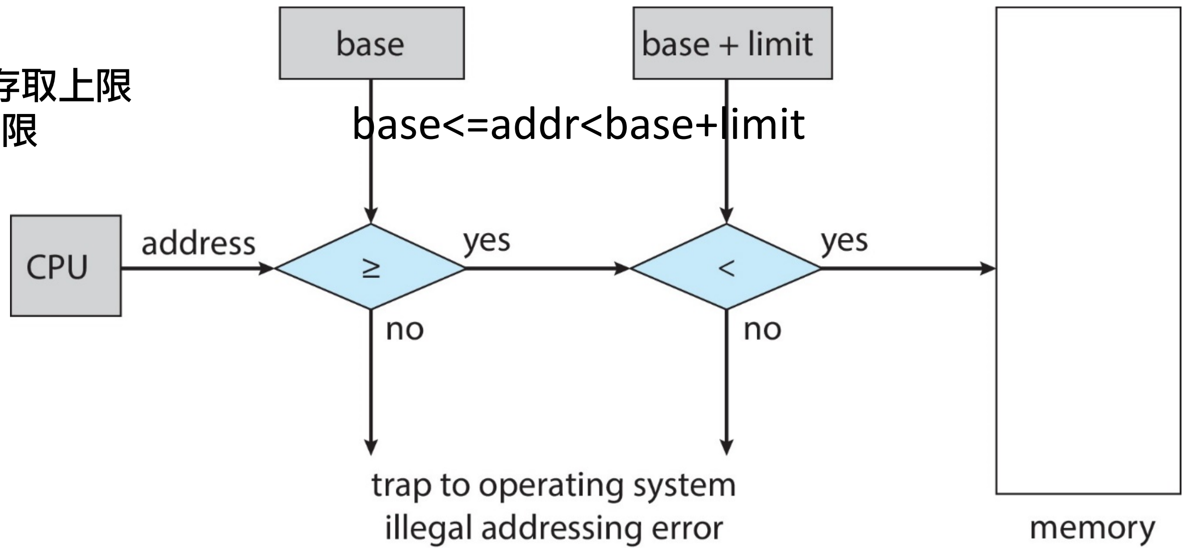
base<=addr<base + limit

Base: 限制了實體位址的存取下限
Base+Limit: 限制了實體位址的存取上限

Memory Protection

- CPU must check every access generated in user mode to be sure it is between base and limit for that process
- Loading the base and limit registers are privileged instructions (i.e. can be modified only in kernel mode)

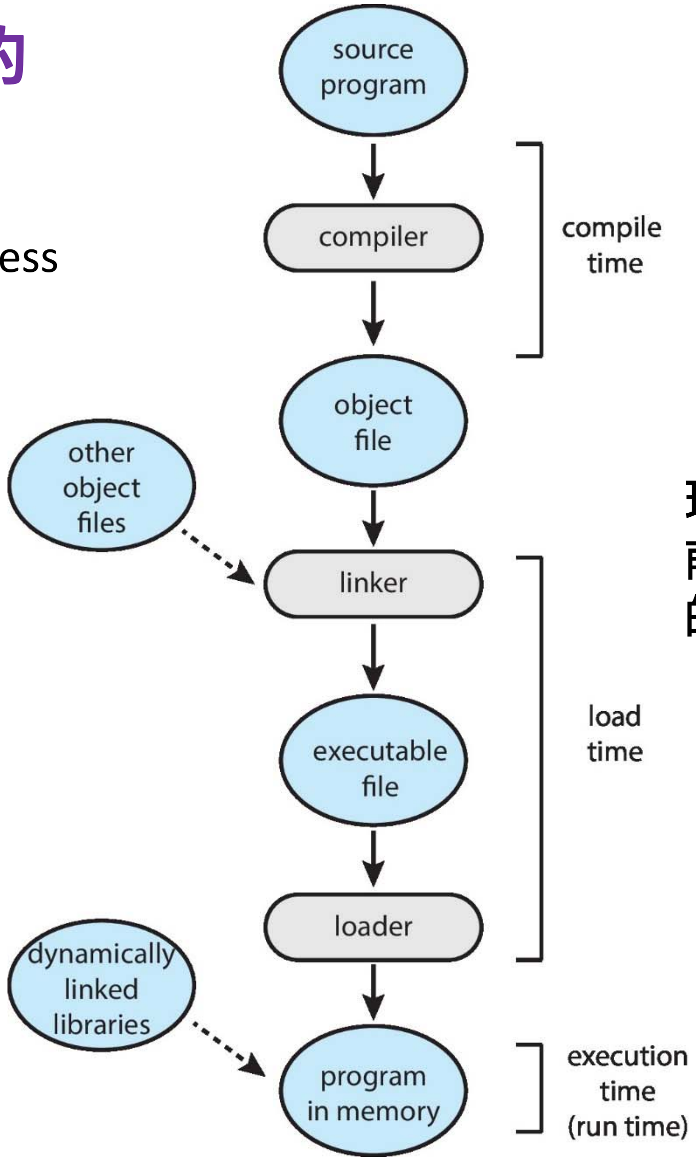
邊界檢查
Base+Limit: **限制了實體位址的存取上限**
Base: **限制了實體位址的存取下限**



確保process**只存取自己的**memory space

那時候決定Process的 Physical Address?

Address binding:「決定Process的Physical address的時機」



理論上load到記憶體中前，就要決定Process的記憶體位置了

有的Process在執行過程中，還會被OS移來移去

Compile Time Address Binding

- Compiler generates absolute address
- If (memory) location changes → recompile
- Example: MS-DOS .COM format binary

```
int data;
main( ) {
    data = 3 * 7;
    print(data);
}
```

Source Program

```
.BASE  0x1000
.START
PUSH     AX
MOVE     AX, 3
MULT     AX, 7
MOVE     (0x1020), AX
CALL     print, (0x1020)
POP      AX
.END
.SPACE (4)
```

寫死

Disk Image

0x1000	PUSH	AX
	MOVE	AX, 3
	MULT	AX, 7
	MOVE	(0x1020), AX
0x1010	CALL	print, (0x1020)
	POP	AX
0x1018		

Memory Content

.SPACE(4): every word has four bytes

Load Time Address Binding

- Compiler generates relocatable address representations
- Relocatable code 所有程式內結構的定址，以相對於.BS的位址來表示
  - Can be run from any memory location
  - If starting location changes → reload the code
    - 理由: .BS值load time產生，一旦load完，.BS值就不能再動

```
int data;
main( ) {
    data = 3 * 7;
    print(data);
}
```

Source Program

```
.START
PUSH    AX
MOVE    AX, 3
MULT    AX, 7
MOVE    (.BS+0x20), AX
CALL    print, (.BS+0x20)
POP     AX
.END
.SPACE (4)
```

Disk Image

.BS 0x2000		
	PUSH	AX
	MOVE	AX, 3
	MULT	AX, 7
	MOVE	(0x2020), AX
0x2010	CALL	print, (0x2020)
	POP	AX
0x2018		

Memory Content (After Load)

Execution Time Address Binding

執行時，Process程式不知道自已的實體位址→要靠MMU輔助

- Compiler generates logical address
- Special hardware (MMU) is needed for this scheme

MMU=Memory Management Unit, see Fig.9.4 and Fig.9.5

  - MMU transforms logical addr. into physical addr.
  - **執行時，程式可被任意搬動**
- Most general-purpose OS use this method

```
int data;
main( ) {
    data = 3 * 7;
    print(data);
}
```

Source Program

```
.START
PUSH    AX
MOVE    AX, 3
MULT    AX, 7
MOVE    (0x20), AX
CALL    print, (0x20)
POP     AX
.END
.SPACE (4)
```

Disk Image

```
0x2000  PUSH    AX
        MOVE    AX, 3
        MULT    AX, 7
        MOVE    (0x20), AX
0x2010  CALL    print, (0x20)
        POP     AX
0x2018
```

Memory Content

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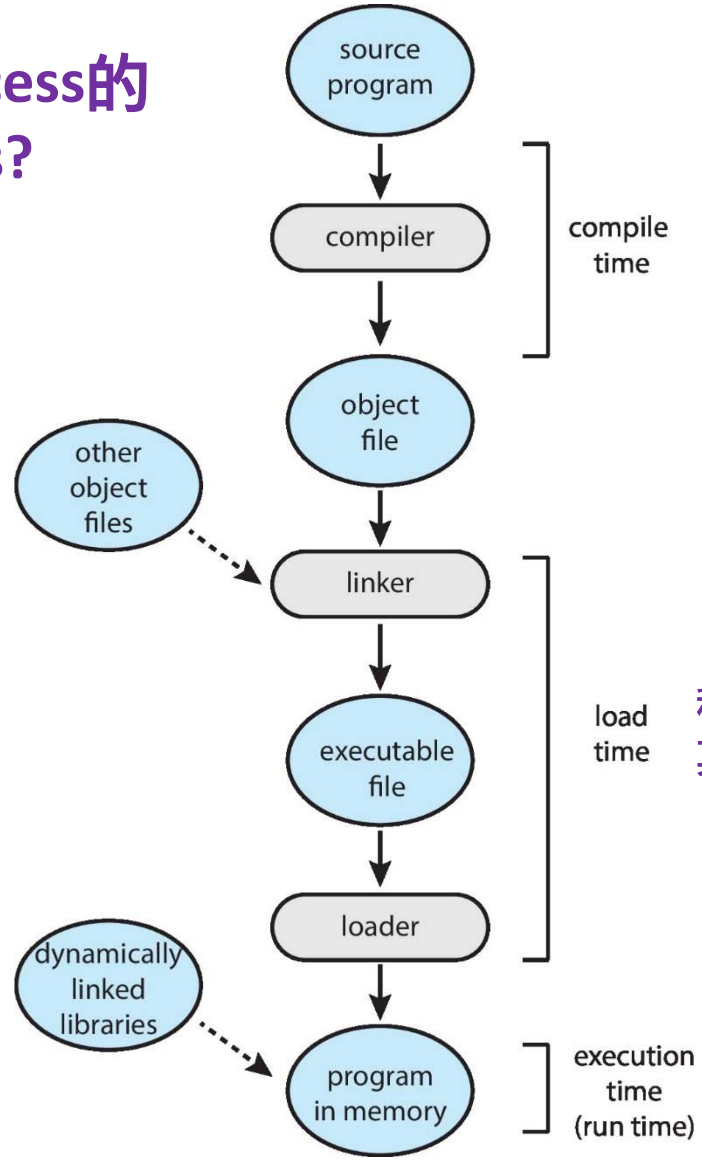
那時候決定Process的Physical Address?



整理

直接指定Physical Address
程式位址固定

程式起始位址於load time決定(.BS)
其它位址相對於.BS定址

程式位址隨時可變
程式中完全採用logical address
需要硬體輔助(MMU)

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Logical vs. Physical Address

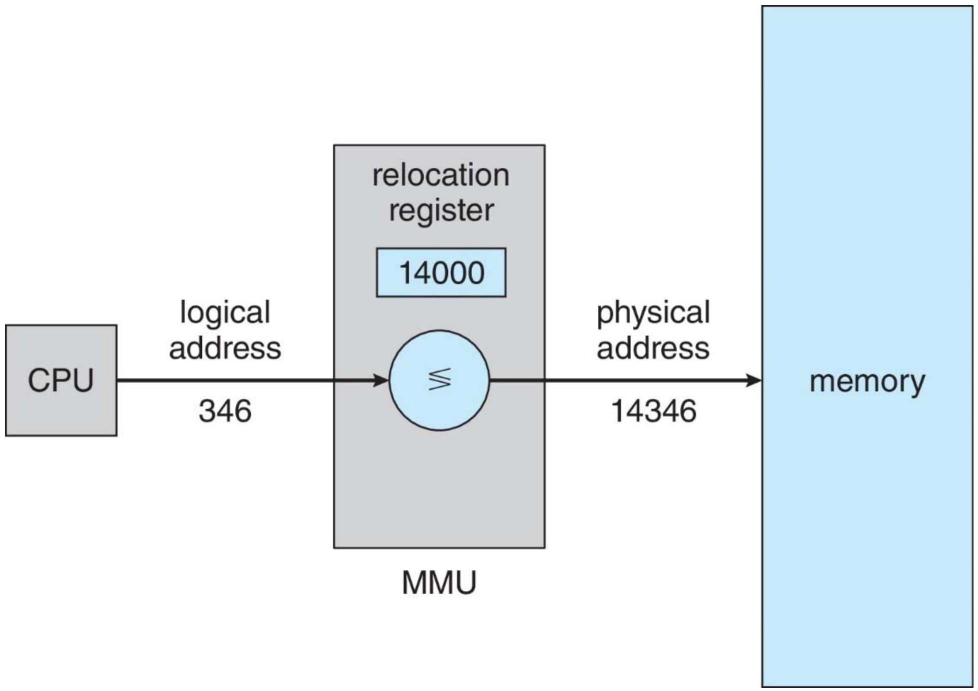
- Compile-time & load-time address binding
  - (Code in memory) logical addr = physical addr
- Execution-time address binding (DLL)
  - logical addr ≠ physical addr; must be assisted by MMU
  - The user program is only aware of logical addresses
    - Never sees the physical addresses

“執行時期”記憶體空間配置與管理

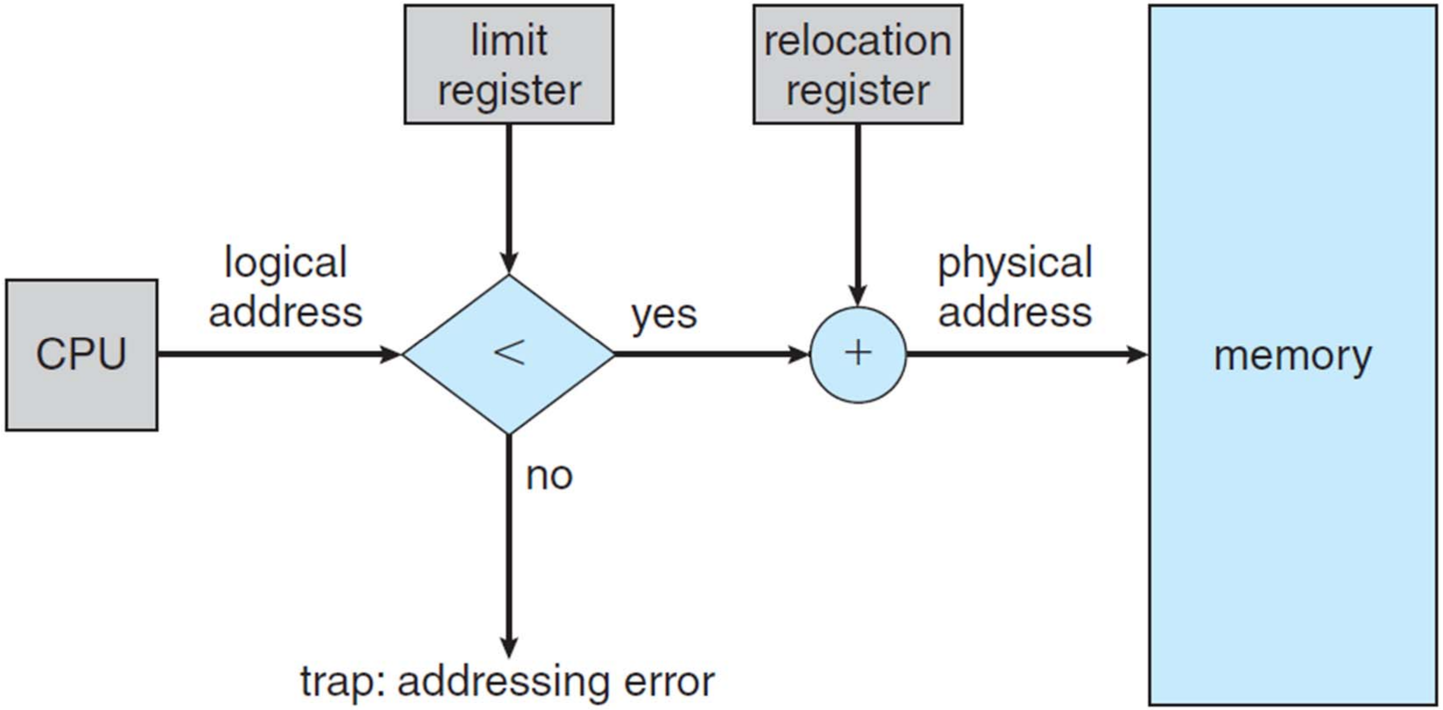
- Protecting the address space of a process
  - Developer writing programs using logical address
  - Starting from 0
- Address binding (Logical-Physical address mapping)
  - 使用硬體專責管理記憶體配置 (位址映射)
  - 標示每個程式的”0”是從那一個(實體)位址起算
  - MMU: Memory Management Unit
    - Handles logical-physical address mapping

Memory-Management Unit (MMU)

- Hardware device that maps logical to physical address
- MMU中包含多個relocation registers
  - The value in the relocation register is added to every address generated by a user process at the time it is sent to memory



加上Boundary Check



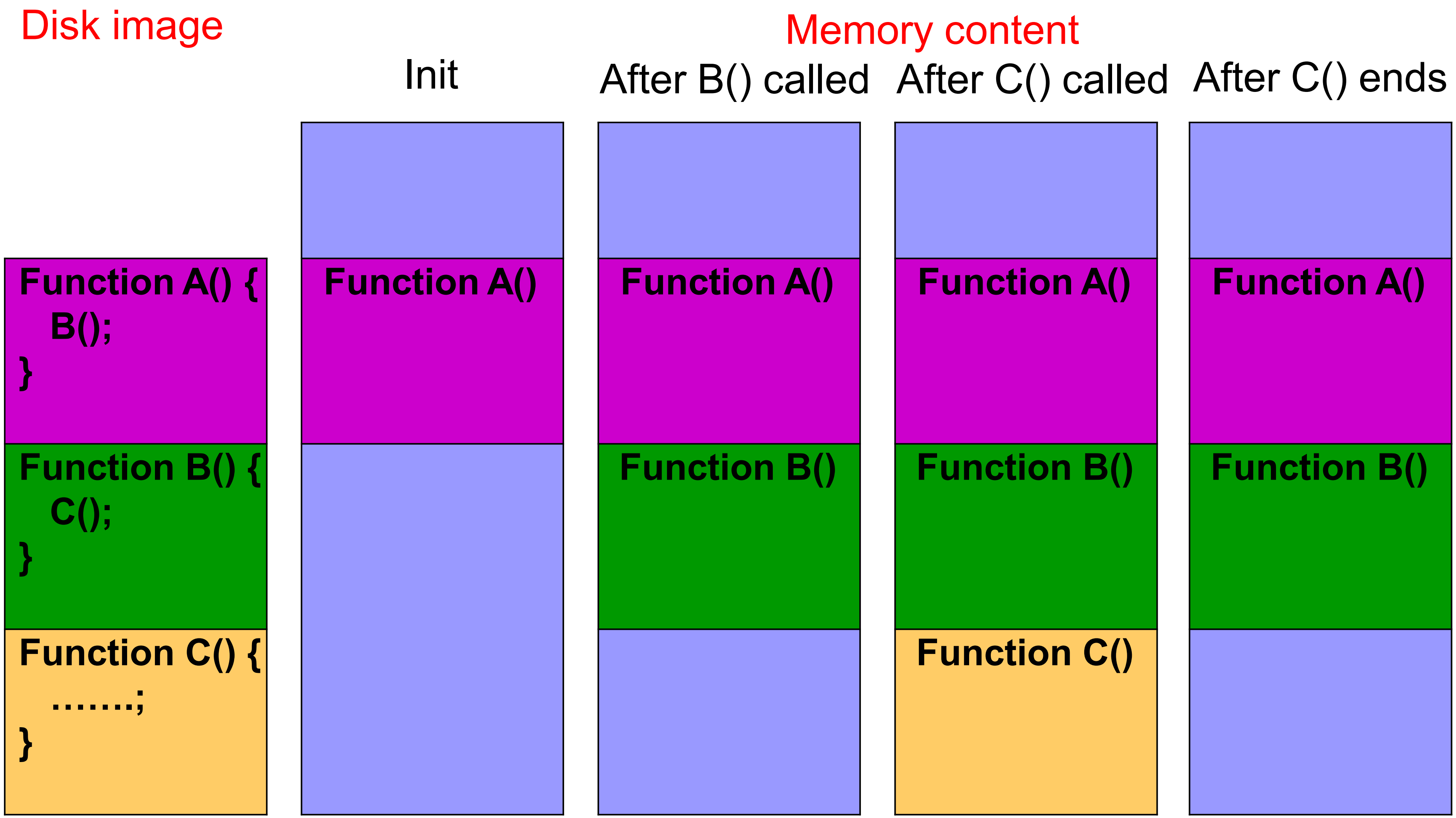
Dynamic Loading

- Definition
  - A routine is loaded into memory “only” when it is called
- Better memory-space utilization
  - Un-used routine is never loaded
  - Particularly useful when large amounts of code are infrequently used (e.g., error handling code)
- No special support from OS
  - Users must implement themselves
  - OS may provide help via library or API calls

```
plugin = dlopen(file_name, RTLD_NOW);
```

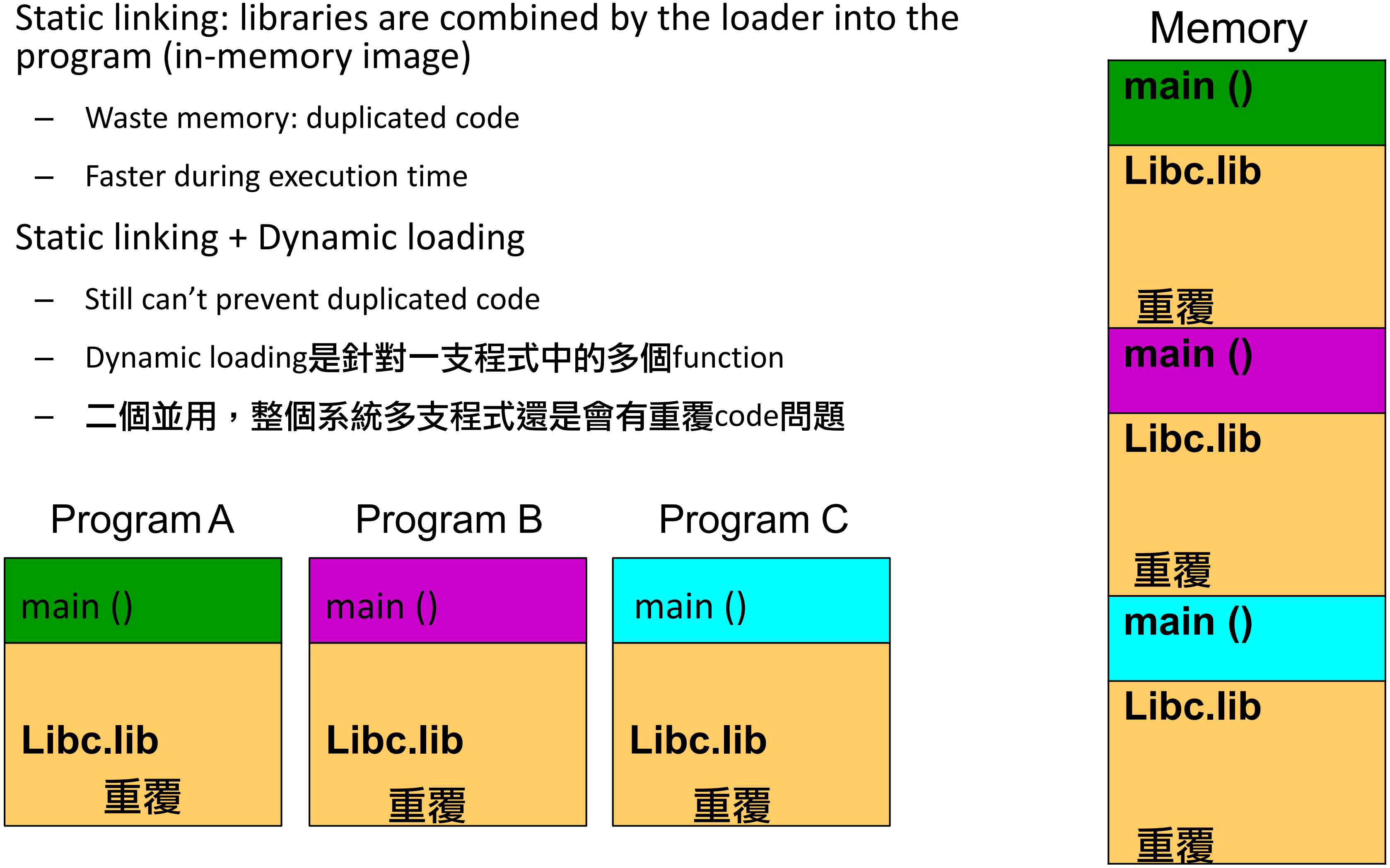
https://stackoverflow.com/questions/384121/creating-a-module-system-dynamic-loading-in-c

Dynamic Loading



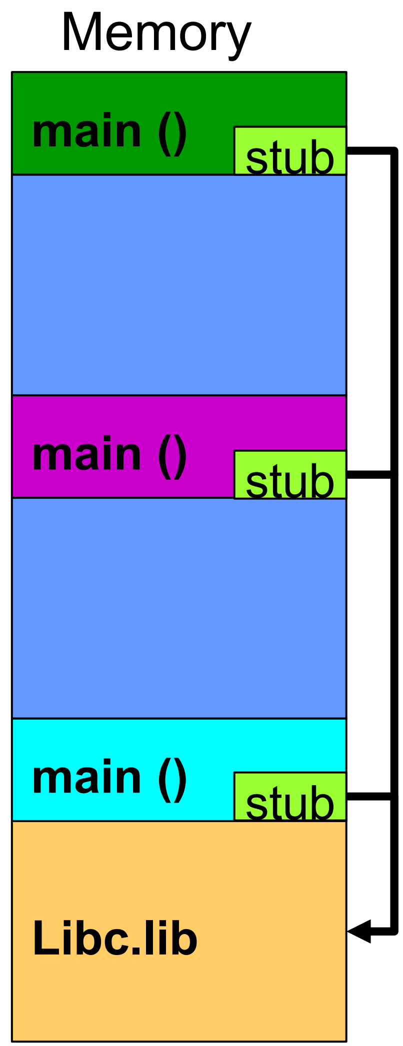
Static Linking

- Static linking: libraries are combined by the loader into the program (in-memory image)
  - Waste memory: duplicated code
  - Faster during execution time
- Static linking + Dynamic loading
  - Still can't prevent duplicated code
  - Dynamic loading是針對一支程式中的多個function
  - 二個並用，整個系統多支程式還是會有重覆code問題



Dynamic Linking

- Dynamic linking: Linking postponed until execution time
  - Only one shared code copy in memory
  - A stub is included in the program in-memory image for each lib reference
  - Stub call → check if the referred lib is in memory → if not, load the lib → execute the lib
- Ex: DLL (Dynamic link library) on Windows



Example

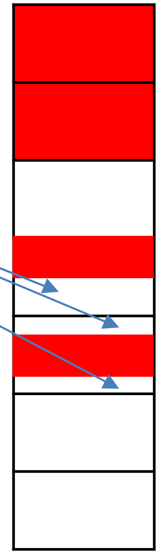
```
#include <windows.h>
#include <stdio.h>

// Import function that adds two numbers
extern "C" __declspec(dllimport) double AddNumbers(double a, double b);

int main(int argc, char *argv[])
{
   double result = AddNumbers(1, 2);
   printf("The result was: %f\n", result);
   return 0;
}
```

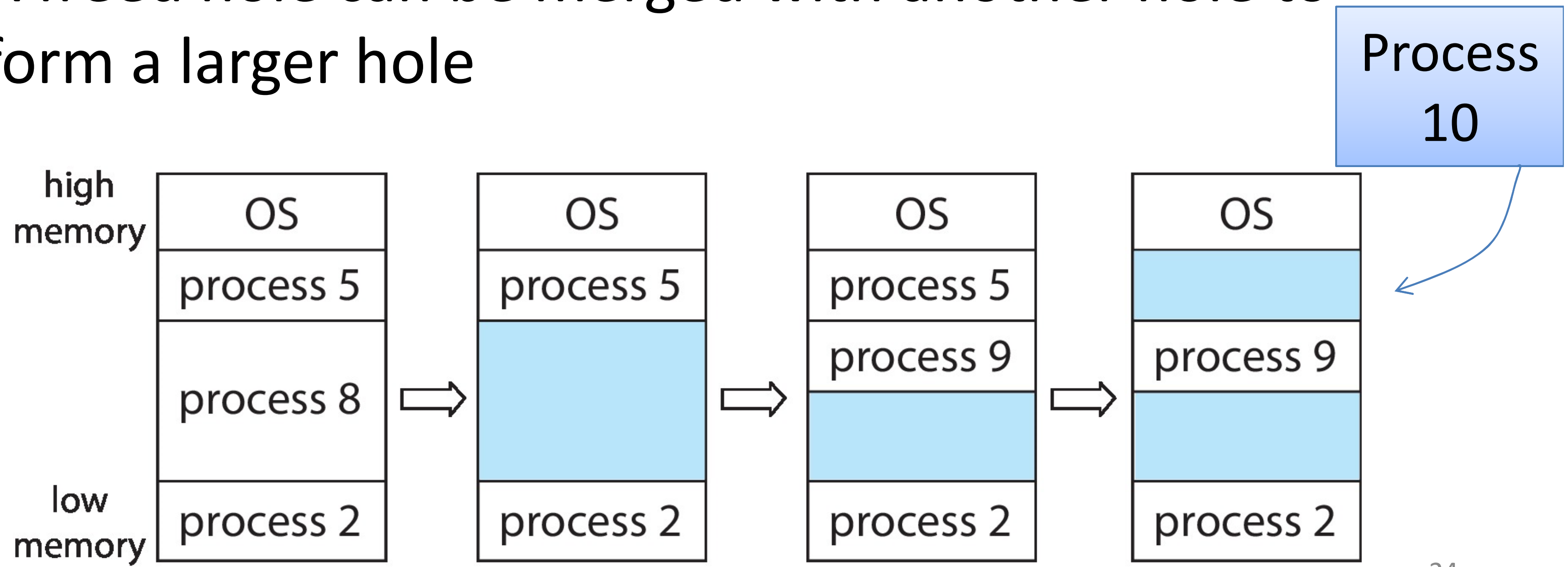
Memory Allocation

- Fixed-partition allocation (paging):
  - Each process loads into one partition of fixed-size
  - Degree of multi-programming is bounded by the number of partitions
  - May have internal fragmentation
- Variable-size partition
  - May have external fragmentation
  - Hole: block of contiguous free memory
  - Holes of various size are scattered in memory



Multiple Partition (Variable-Size) Method

- When a process arrives, it is allocated a hole large enough to accommodate it
- The OS maintains info. on each in-use and free hole
- A freed hole can be merged with another hole to form a larger hole



Problem of
Dynamic Storage Allocation

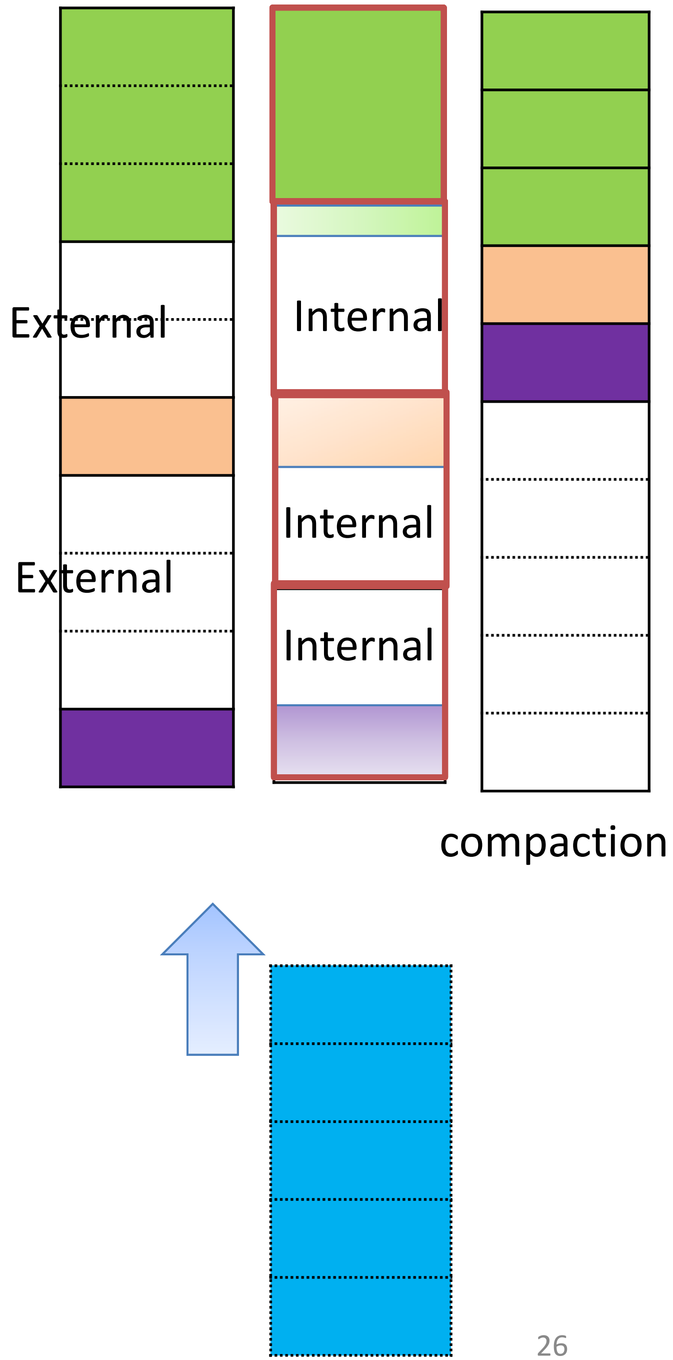
- How to satisfy a request of size n from a list of free holes
  - First-fit – allocate the 1st hole that fits
  - Best-fit – allocate the smallest hole that fits
    - Must search through the whole list
  - Worst-fit – allocate the largest hole
    - Must also search through the whole list
- First-fit and best-fit better than worst-fit in terms of speed and storage utilization

Fragmentation

- External fragmentation
  - Total free memory space is big enough to satisfy a request, but is not contiguous
  - Occur in variable-size allocation
- Internal fragmentation
  - Memory that is internal to a partition but is not being used
  - Occur in fixed-partition allocation
- Solution: compaction
  - Move the memory contents to place all free memory together in one large block at execution time
  - Valid only if binding is done at execution time

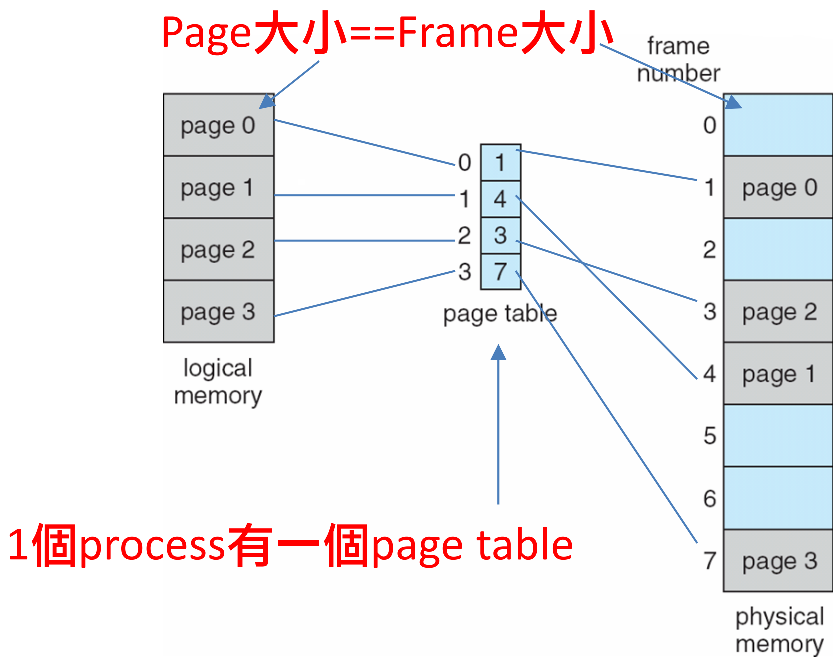
    (why?)

    Load time binding → .BS決定後就不能再改!



Paging

- Method
  - Divide physical memory into fixed-sized blocks called frames
  - Divide logical address space into blocks of the same size called pages
  - A program of n pages, need n free frames and load the program
  - A page table (for each process) to translate logical to physical addresses



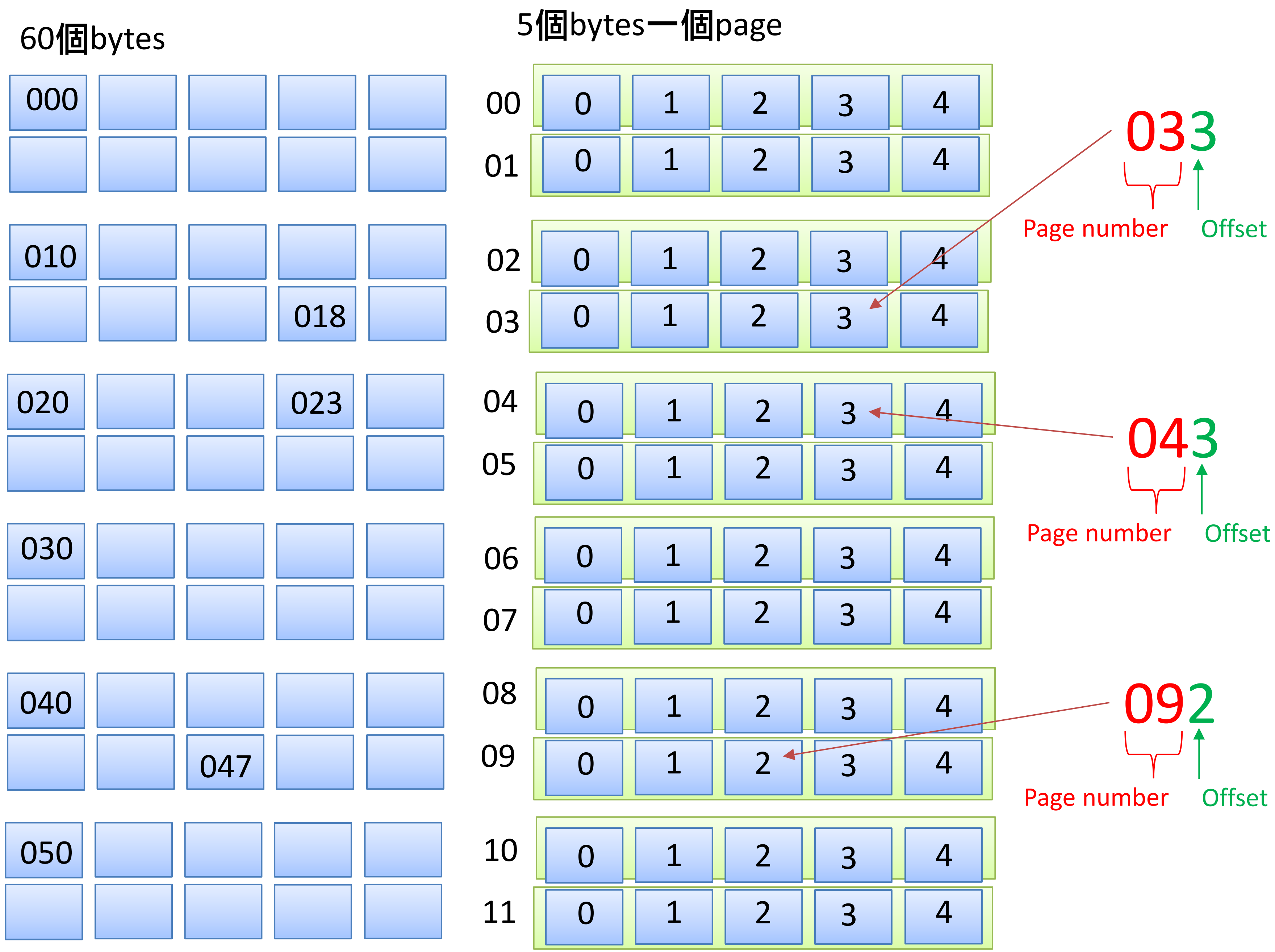
Paging

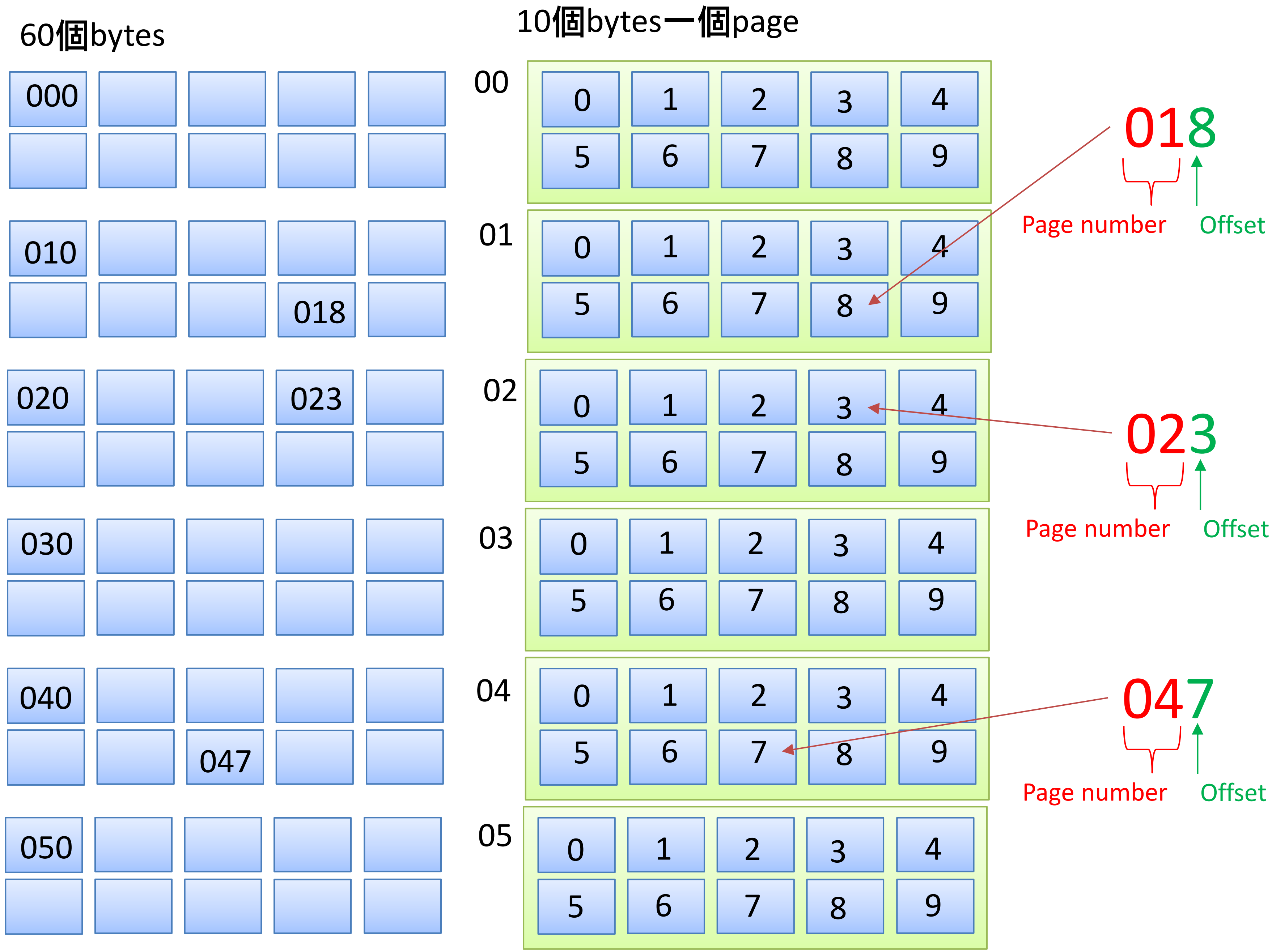
- Benefit:
  - Allow the physical-address space of a process to be non-contiguous 整個process分成好幾塊來放
  - Avoid external fragmentation (frame size == page size)
  - Limited internal fragmentation (within size)
- Note
  - Page size == Frame size
  - (Process) Page 數量 未必 == (全系統) Frame 數量
    - Page number > Frame number → virtual memory
    - Frame number > Page number → multi-process

Example

- How many pages (frames) are needed?
  - Process size = 72766 bytes
  - Page size = 2048 bytes

$$\left\lceil \frac{72766}{2048} \right\rceil = 36$$


60個bytes
000
010
018
020
023
030
040
047
050
5個bytes一個page
00
01
02
03
04
05
06
07
08
09
10
11
0
1
2
3
4
033
Page number
Offset
043
Page number
Offset
092
Page number
Offset


60個bytes
10個bytes一個page
000
010
018
020
023
030
040
047
050
00
01
02
03
04
05
0 1 2 3 4
5 6 7 8 9
018
Page number
Offset
023
Page number
Offset
047
Page number
Offset

Address Translation Scheme

page number	page offset
p	d
m - n bits Page的數量 (順便當索引)	n bits Page的大小

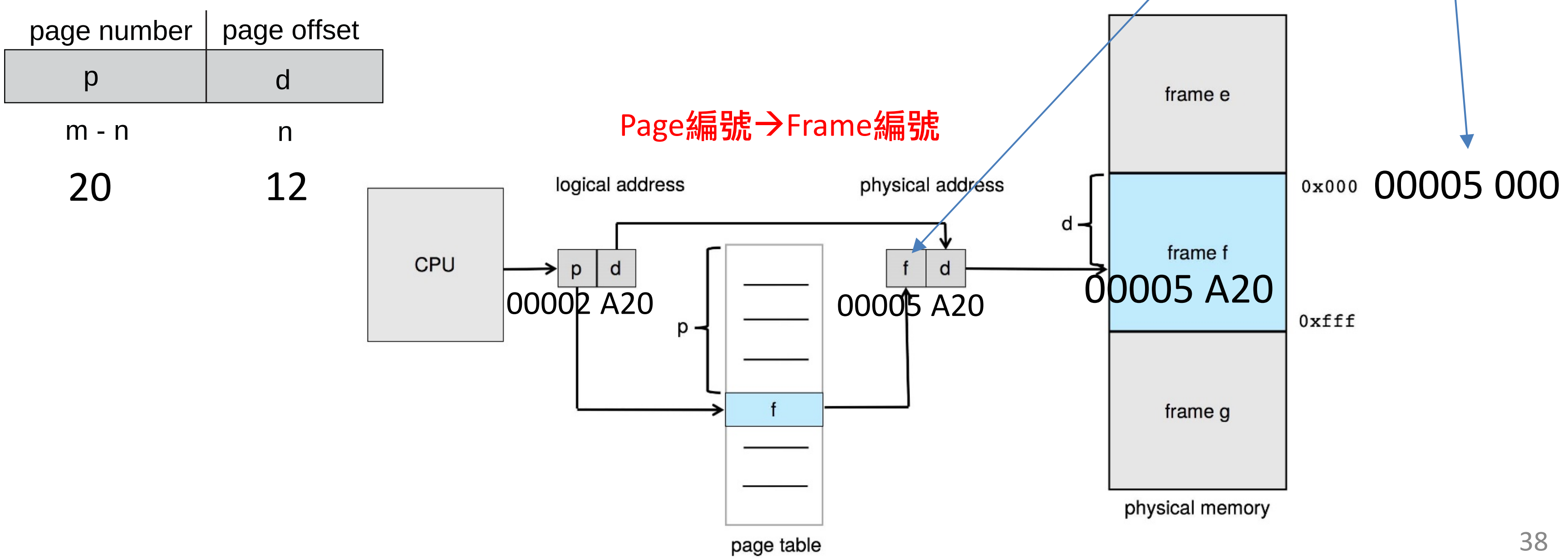
- Address is divided into two parts:
  - Page number (p)
    - Used as an index into a page table
    - m-n bits means a process can allocate at most 2^{m-n} pages (有幾個pages)

  → $\text{page number } (2^{m-n}) \times \text{ page size } (2^{n}) = \text{logical memory size } (2^{m})$

  - Page offset (d)
    - combined with (page) base address to define the physical memory address that is sent to the memory unit
    - n bits means the page size is 2^{n} (1個page的大小; 通常故意設成2的n次方, why?)

Page Table

- Entry
  - Key: page number; Value: frame number
    - Frame number is the base address of a page in physical memory d補0
- A structure maintained by OS for each process
  - Page table includes only pages owned by the process
  - A process cannot access memory outside its space



Address Translation Scheme

- 假定: Page size:1KB(2^{10}) & Page 2 對到 frame 5

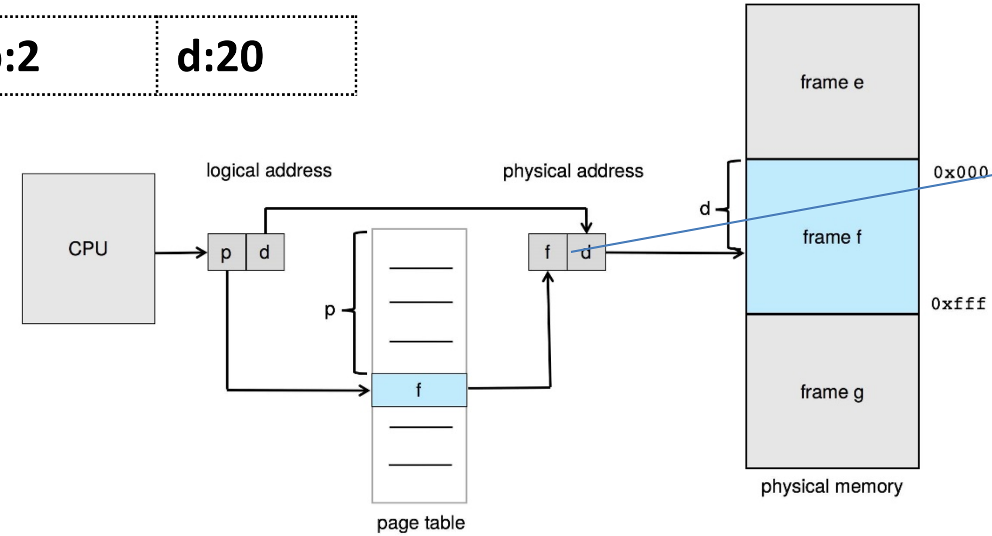
  page size $2^{10} \Rightarrow n = 10$

- Given 13 bits logical and physical address and d=20, what is physical address?

  13 bits logical address: $m=13 \Rightarrow m\text{-}n=3$

page number	page offset	
p	d	值
m - n 3	n 10	位數

3 bits	10 bits
p:2	**d:20**



3 bits	10 bits
f:5	**d:20**
101	**0000010100**

Example

logical: 1 page 4 bytes $\Rightarrow n = 2$;

Page共4個 $\Rightarrow$ 只需2bits $\Rightarrow$ m-n=2

$\Rightarrow$ logical位址長度=2+2=4bits

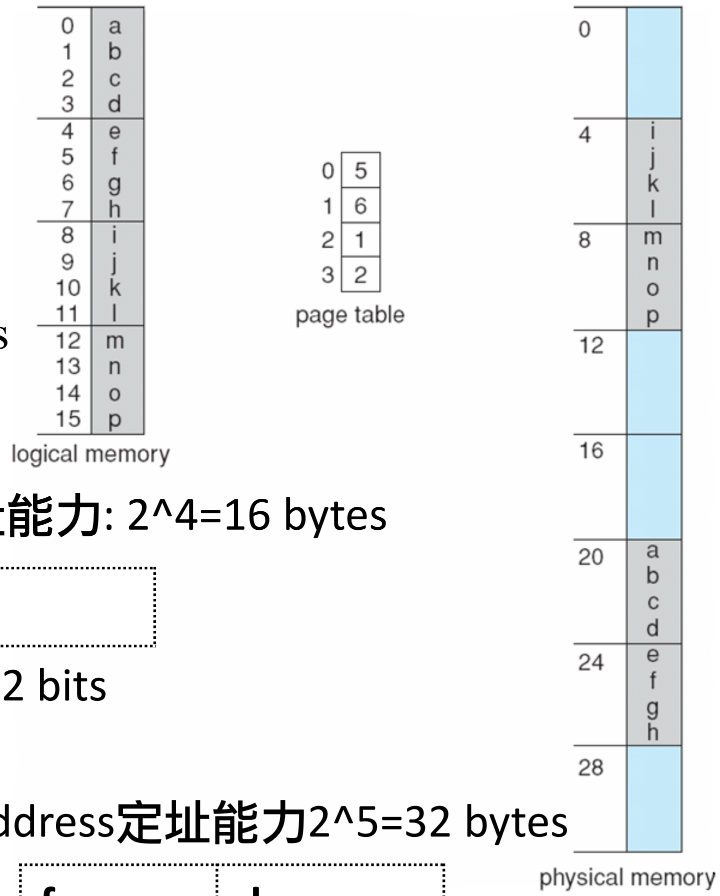
Frame共8個(2^3)

page size=frame size=4bytes; (n=2 $\Rightarrow 2^2$=4)

physical memory=32bytes $\Rightarrow \dfrac{32}{4} = 8$ physical frames

16 bytes

32 bytes



Logical address定址能力: 2^4=16 bytes

p	d
4-2=2 bits	2 bits

physical address定址能力2^5=32 bytes

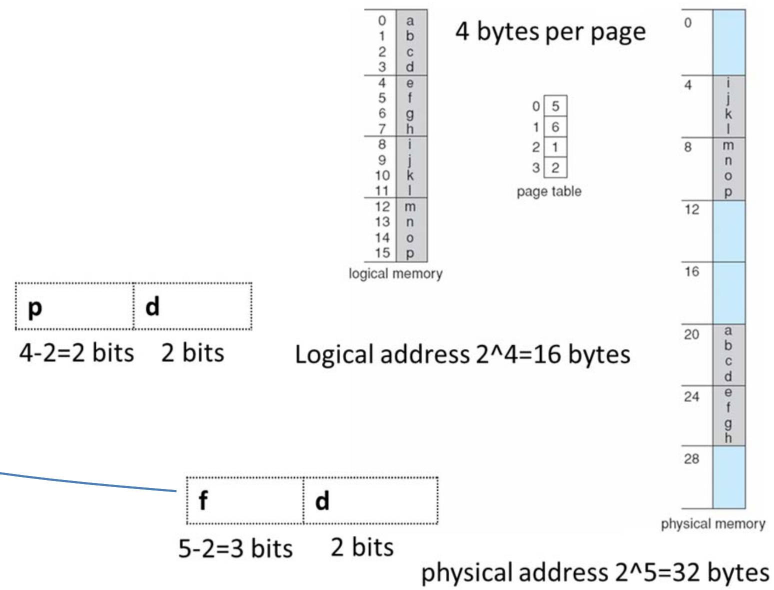
f	d
5-2=3 bits	2 bits

Page的數量(索引)　　Page的大小

page number	page offset
p	d
m - n	n

Address Translation

- Total number of pages does not need to be the same as the total number of frames
  - Frame size = page size
  - Total # pages determines the logical memory size
  - Total # frames depending on the physical memory size



Example

- Given 32 bits logical address, 36 bits physical address and 4KB page size

x bits (p)	y bits (d)	Logical (32)
z bits (f)	y bits (d)	Physical (36)

$$\text{logical: } x + y = 32$$

$$\text{physical: } z + y = 36$$

$$\text{page size: } 4\text{KB} = 2^2 \times 2^{10} = 2^{12} \Rightarrow y = 12$$

$$x = 32 - 12 = 20$$

$$z = 36 - 12 = 24$$

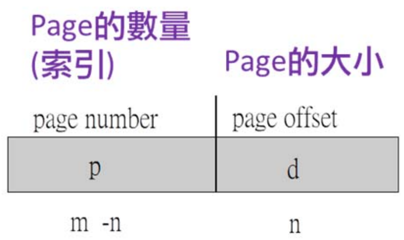
Page的數量(索引)　　Page的大小

page number	page offset
p	d
m - n	n

Example

- Given 32 bits logical address, 36 bits physical address and 4KB (2^{12}) page size
  - Page table entries $32-12=20 \Rightarrow 2^{20}$ entries
  - Max program (logical) memory 2^{32} bytes
  - Total physical memory 2^{36} bytes
  - Number of bits for page number (p) 20
  - Number of bits for frame number (f) 24
  - Number of bits for page offset (d) 12

20 (p)	12 (d)	logical
24 (f)	12 (d)	physical

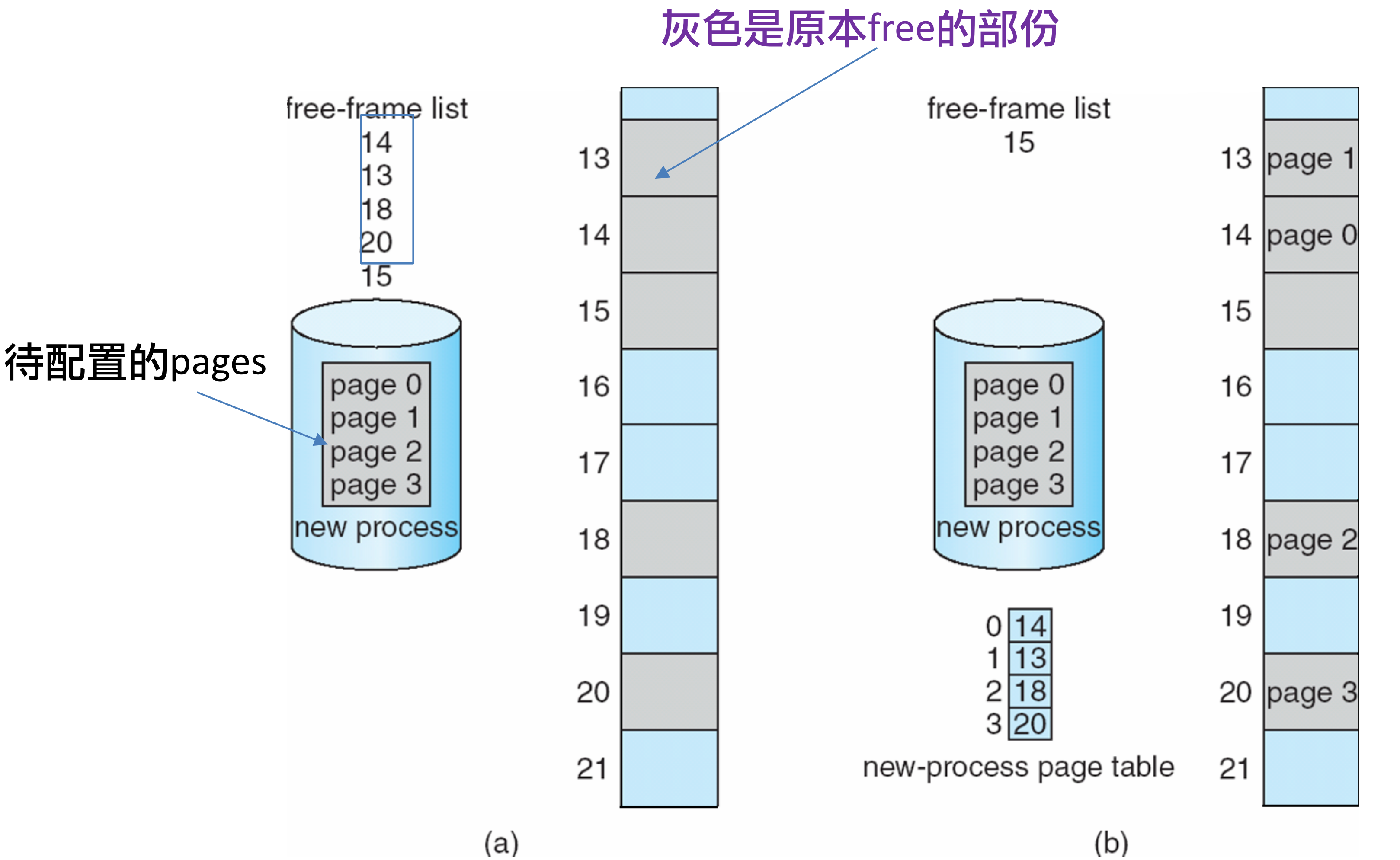


Free-Frame List

- When a page fault occurs, the OS brings the desired page from disk into memory
- Free-frame list
  - a pool of free frames for satisfying such requests.

- OS typically allocate free frames using a technique known as **zero-fill-on-demand** -- the content of the frames zeroed-out before being allocated
- When a system starts up, all available memory is placed on the free-frame list

Page的配置: Free-frame List



Before allocation

After allocation

Page (Frame) Size

- The page (frame) size is defined by hardware
  - Typically a power of 2
  - Ranging from 512 bytes to 16MB / page
  - 4KB / 8KB page size is commonly used $1K = 1 \times 1024 = 1 \times 2^{10}$
- Internal fragmentation issue
  - Larger page size → More space waste
- In practice, page size has grown over time
  - Memory, process, data sets have become larger
  - Better I/O performance (during page fault)
  - Make page table smaller (page table is a pure overhead)
    - Page size愈大，切出來的pages就愈少→page table愈小

Page Table Summary

- Address abstraction
  - Paging helps separate user's (process's) view of memory and the actual physical memory
    - User view's memory: one single contiguous space
    - Actually, user's memory is scatter out in physical memory
- OS maintains
  - One page table for each process
  - One frame table for managing physical memory
    - One entry for each physical frame
    - Indicate whether a frame is free or allocated
    - If allocated, to which page of which process or processes

Implementation of Page Table

- Memory: stores the page tables

(方便CPU直接找到Page table)

- 如何找到Page Table: page-table base register (PTBR)
  - Stores the physical address of the page table
    - 直接指向現正處理process的page table
  - The value is stored in PCB (Process Control Block)
  - Changing the value of PTBR during context-switch
- 1 memory reference == 2 memory reads
  - One for the page table and one for the real address
  - Can be enhanced by using TLB (Translation Lookaside Buffer)
    - Implemented with fast associative memory (HW)
      - Key: page number; value: frame number
    - TLB == Page Table 的cache

Translation Look-aside Buffer (TLB)

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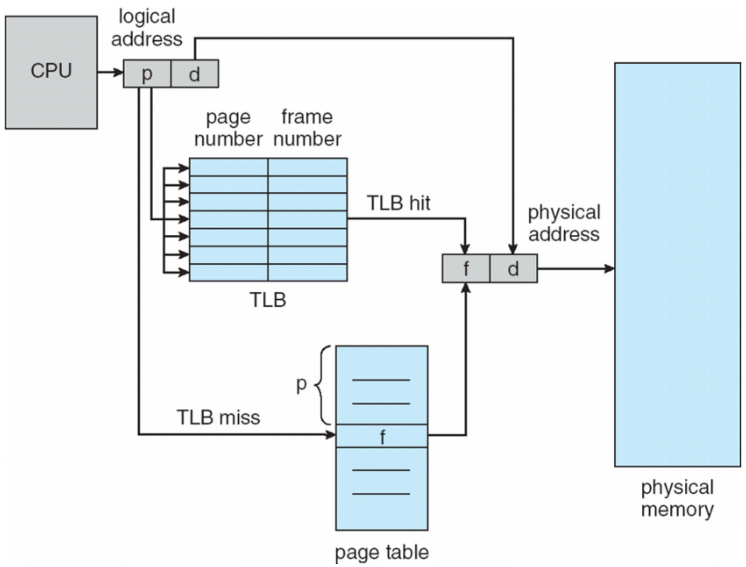
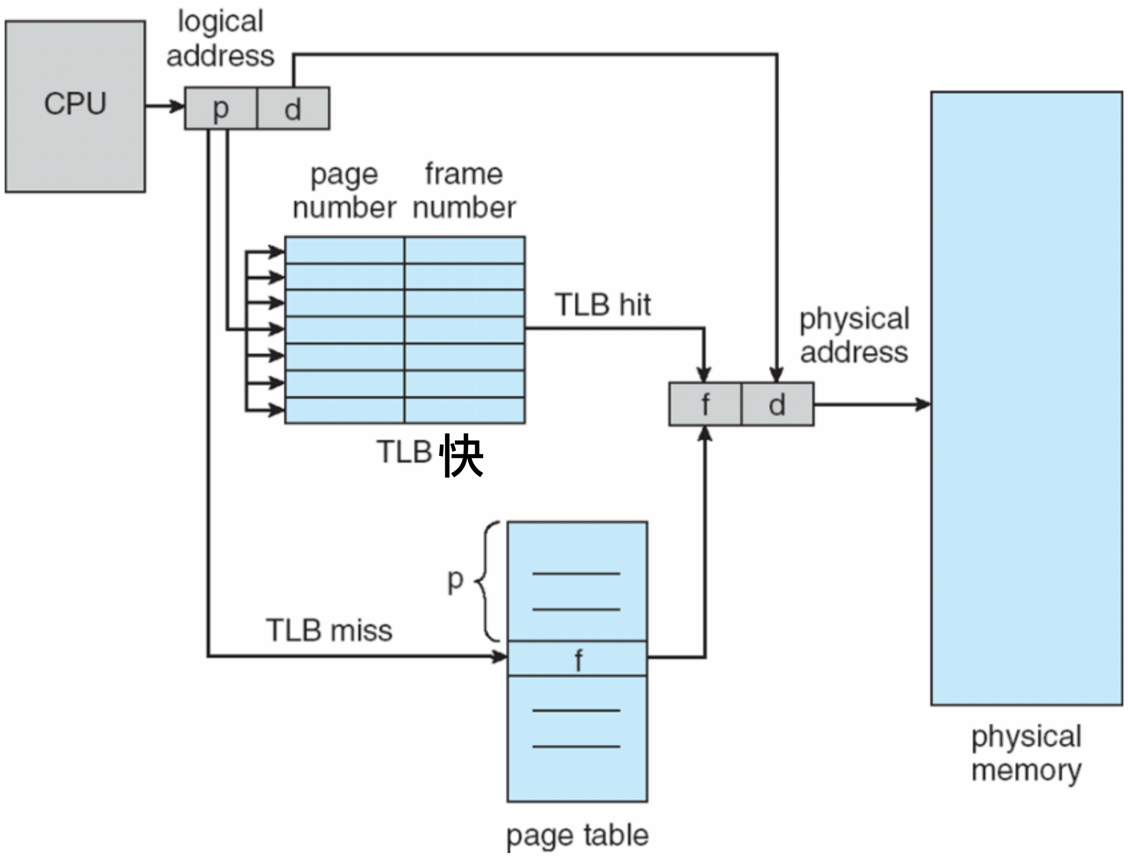
- A cache for page table shared by all processes
  - 先找cache，miss才查memory上的page table
  - Issue: page numbers are specific to each process
- TLB must be flushed after a context switch
  - Otherwise, TLB entry must has a PID field (address-space identifiers (ASIDs))

每個不同的process有相同的page number:
Process A的page 2和Process B的page 2內容不同
(指向不同的physical address!)




logical
address
CPU
p
d
page
number
frame
number
TLB hit
physical
address
f
d
TLB 快
p
TLB miss
f
page table
physical
memory

慢

Effective Memory-Access Time

- Assume
  - 20 ns for TLB search
  - 100 ns for memory access
- Effective Memory-Access Time (EMAT)
  - 70% TLB hit-ratio:

No TLB: 200ns

$$EMAT = \underbrace{0.70 \times (\overset{TLB}{20} + \overset{Mem}{100})}_{Hit} + \underbrace{(1-0.70) * (\overset{TLB}{20}+\overset{PT}{100}+\overset{Mem}{100})}_{Miss} = 150 \text{ ns}$$

  - 98% TLB hit-ratio

$$EMAT = \underbrace{0.98 \times 120}_{Hit} + \underbrace{0.02 \times 220}_{Miss} = 122 \text{ ns}$$

Memory Protection

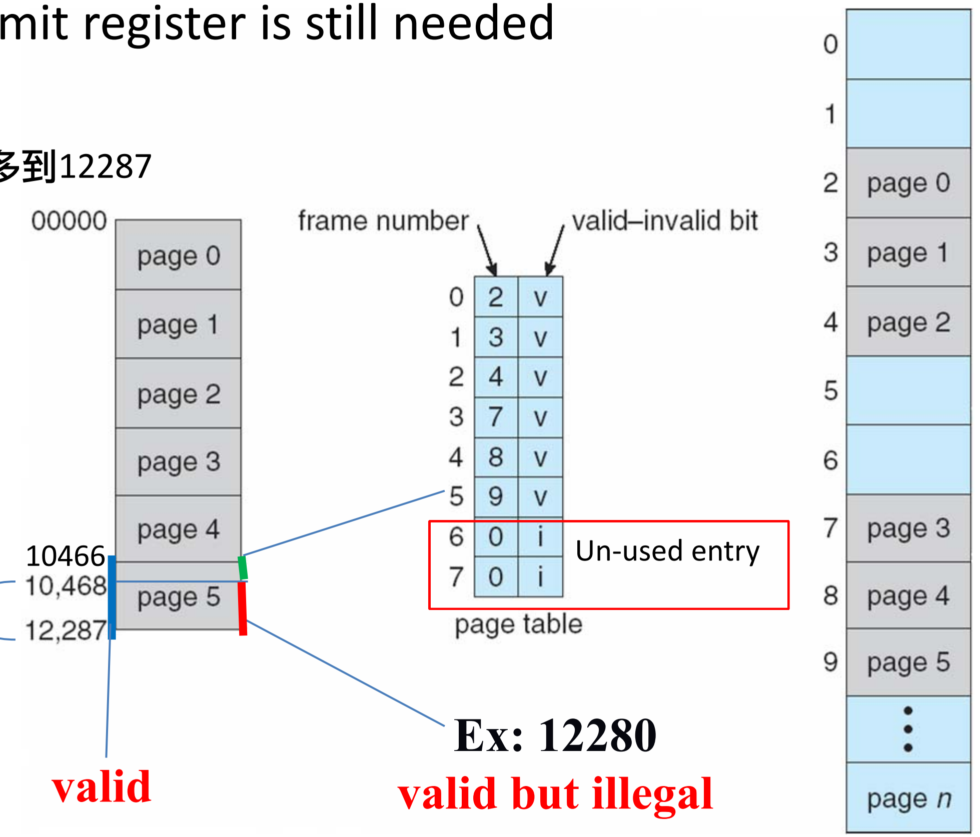
- Each page is associated with a set of protection bit in the page table
  - E.g., a bit to define read/write/execution permission
- Common use: valid-invalid bit
  - Valid: the page/frame is in the process' logical address space, and is thus a legal page
  - Invalid: the page/frame is not in the process' logical address space
    - 結合Virtual Memory使用時，有不同定義!
      - invalid代表in logical address space but not in memory

Valid-Invalid Bit

- Potential issues:
  - Unused PT entry: Un-used entry causes memory waste → use page table length register (PTLR) 計算Page Table長度
  - Internal overflow: Process memory may NOT be on the boundary of a page → memory limit register is still needed

在右邊的例子中，page 5邏輯位址最多到12287
10466-12287都是valid

程式只佔到10468; 所以
10469-12287都是無意義資料

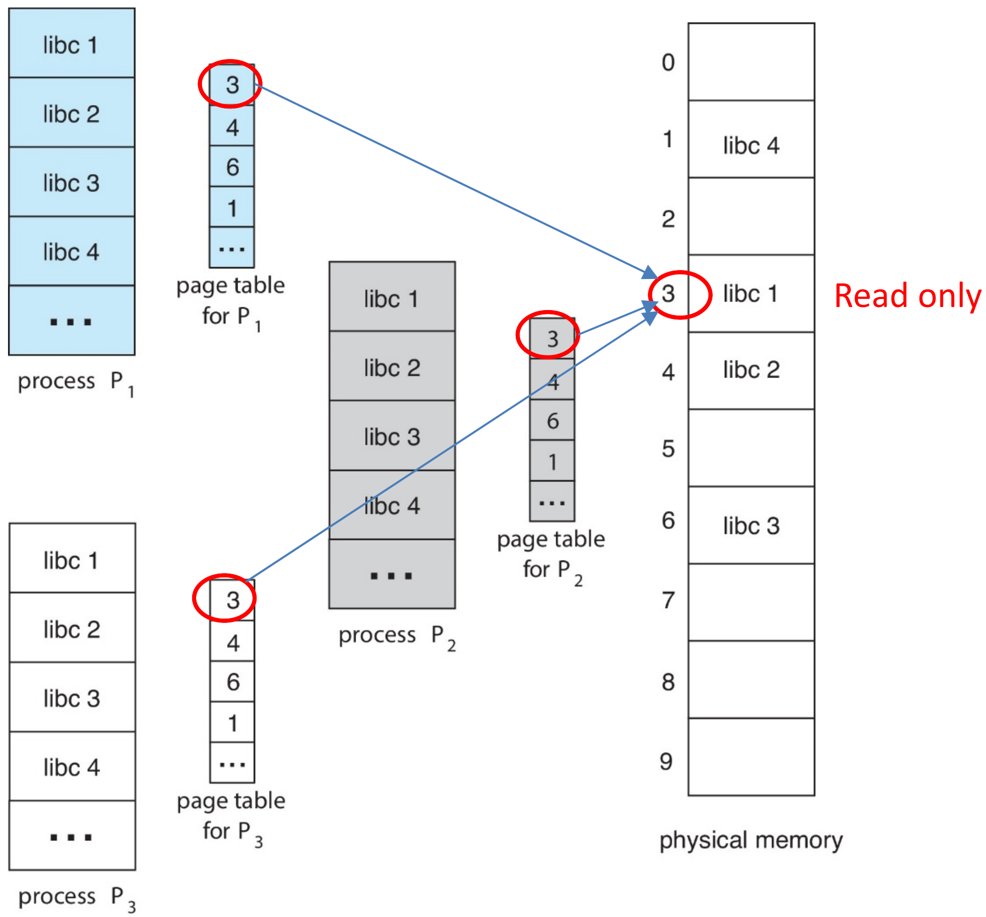


Shared Pages

- Paging allows processes share common code, which must be reentrant
  - The shared code never change during execution (immutable)
  - One copy of the code is kept in physical memory
  - Two (or more) virtual addresses are mapped to one physical address
- Process keeps a copy of its own private data and code

Shared Pages by Page Table

不同process的page table entry指向同一個physical frame



Page Table 太大的問題

- Page table could be huge and difficult to be loaded
  - 4GB (2^32) logical address space with 4KB (2^12) page
    - 1 million (2^20) page table entry

$$2^{20} \approx 1\text{MB}$$

  - Assume each entry need 4 bytes (32bits)
    - Total size=4MB

1M個entries, 每個4bytes, 每個process要1份!

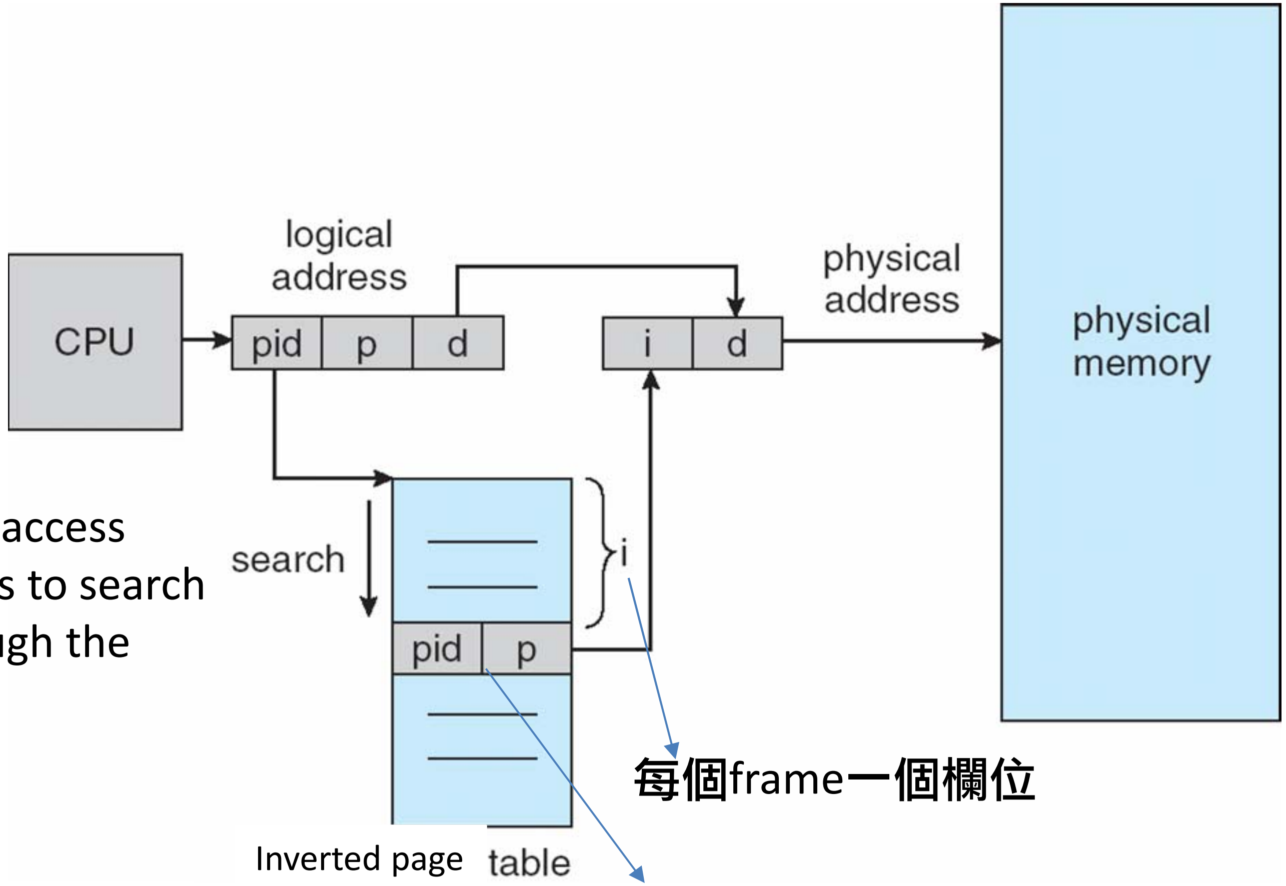
  - 狀況: Page Table (4M)遠比1個Page (4K)大 →page table要連續，又造成external frag問題! 若不連續，要設計機制找，效能差
    - Need to break it into several smaller page tables, better within a single page size (i.e. 4KB) 最好每個Page Table片段不大於一個Page
    - Or reduce the total size of page table
- Solutions:
  - Inverted Page Table (frame table) → Hard to support shared paging
  - Hierarchical Paging → Additional memory reference、64bit定址不適用
  - Hash Page Table → Additional memory reference

Inverted Page Table

- Maintains an inverted page table (frame table) for the whole memory
  - One entry for each real frame of memory
  - Maintains NO page table for each process
- Each entry in the inverted page table has
  - (PID, Page Number)
- Eliminate the memory needed for page tables but increase memory access time
  - Each access needs to search through the table (linearly)
  - Solution: use hashing (**例如**: **同一個**”page number”**的放在同一排**)
- Hard to support shared page/memory
  - Why?

因為一個frame只能與一個(PID, Page Number)對應

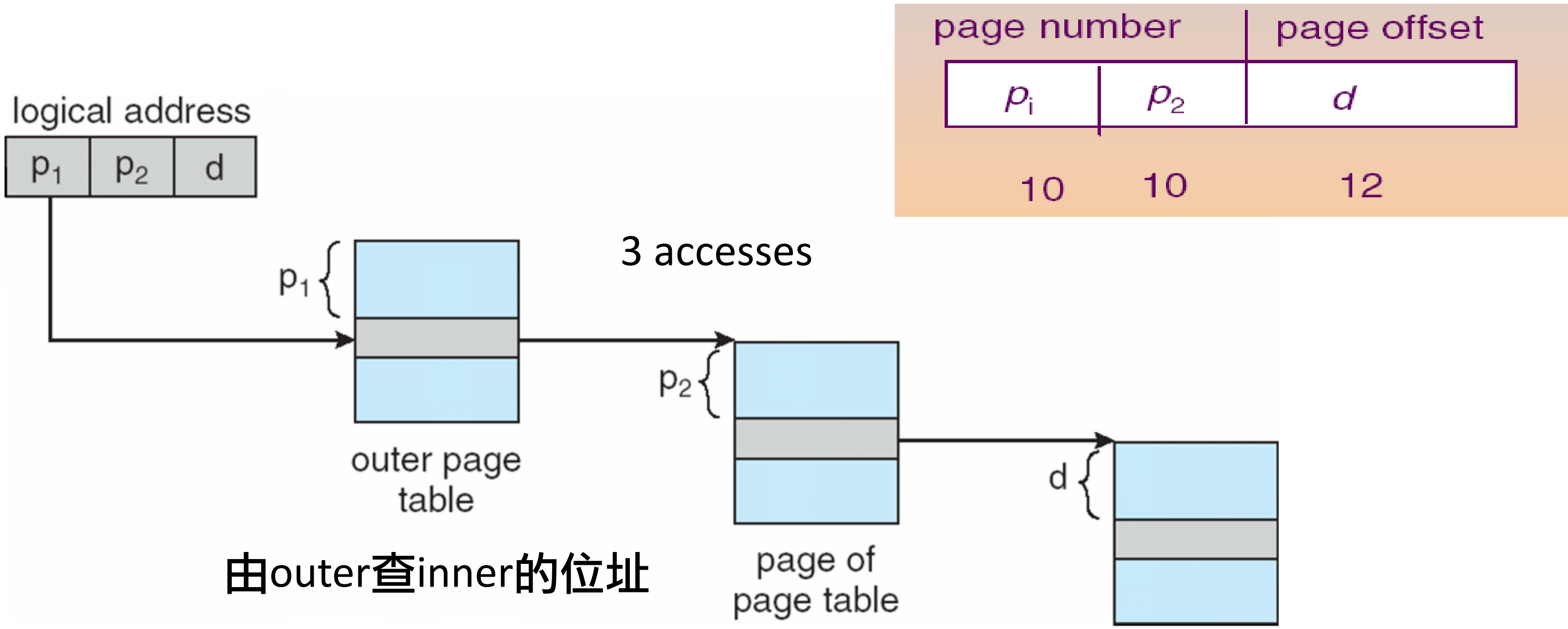
Inverted Page Table



Each access needs to search through the table

如果要多個共用一個frame, 這裡勢必要能存多個(pid,p)值

Paging the page table



3 accesses

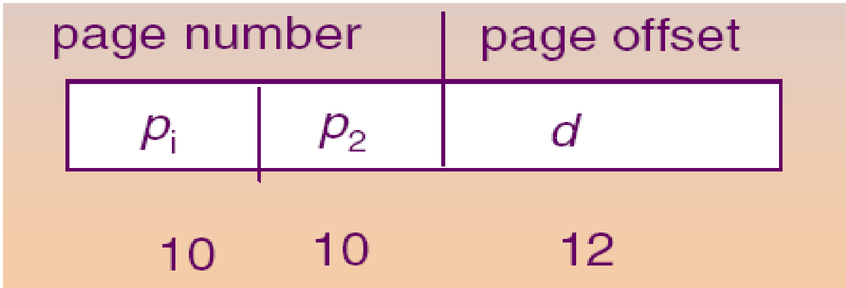
由outer查inner的位址

由inner查page base位址

和原來有何不同: 原來:所有page table entries連續不間斷地放在一起，要「整體」共同進出記憶體
階層式: 因為page table本身也分頁了，所以PT可以頁為單位進出記憶體 (結合demand paging)

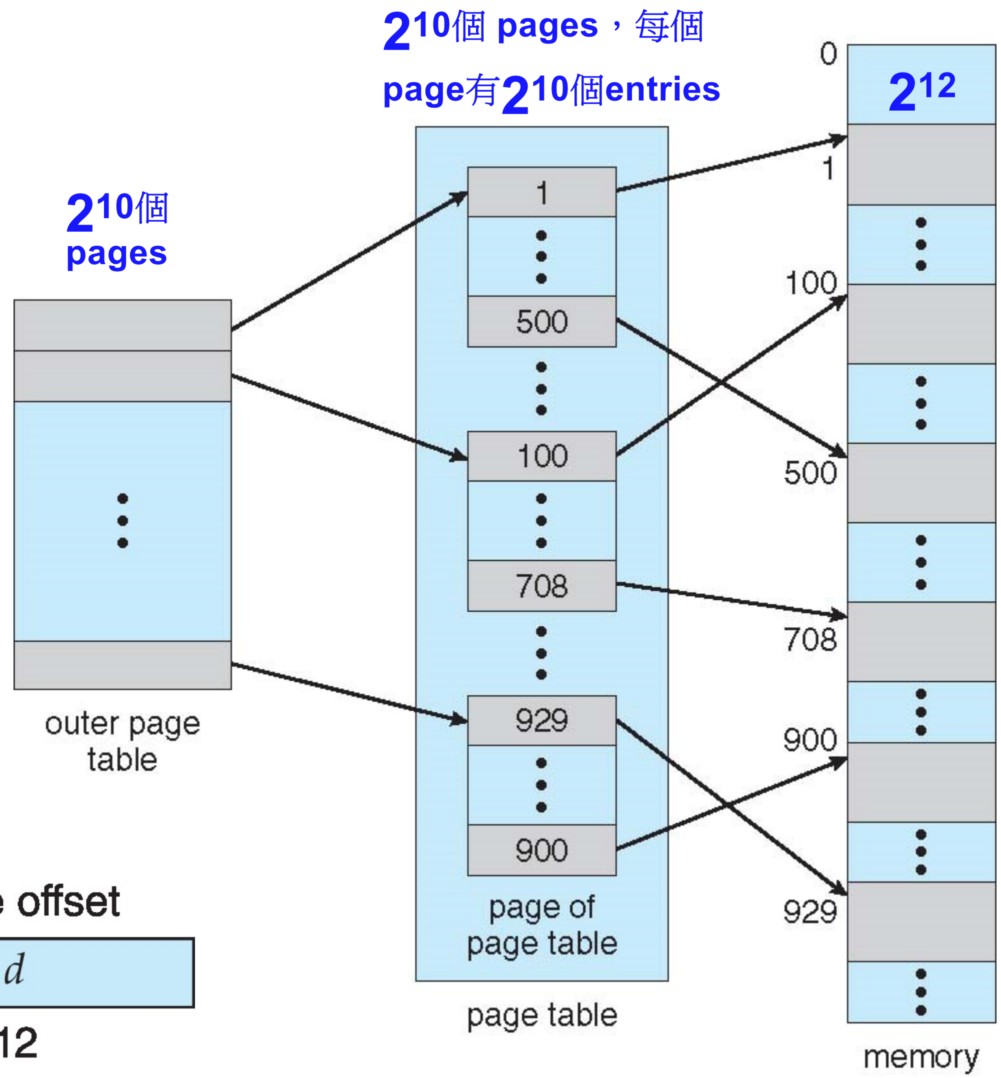
Hierarchical Paging

- Break up the logical address space into multiple page tables
  - Paging the page table
  - i.e. n-level page table
- Ex: Two-level paging (32-bit address with 4KB (2^12) page size)
  - 12-bit offset (d) → 4KB (2^12) page size
  - 10-bit outer page number →1K (2^10) page table entries
  - 10-bit inner page number → 1K (2^10) page table entries
  - 3 memory accesses
    - PT 2次+M1次



Two-Level Page Table Example

把page table再分頁的好處在那裡?
- 通常程式只會用到少量集中的pages，所以只有少量的page table entries才會被查詢，所以不需要所有page table entries同時都在記憶體中
- Multi-level paging將page table切到可以裝在一個page，結合demand paging，可以用到時再載入memory，有效節省了記憶體空間
  - 否則: 要一次全部載入



page number		page offset
p_1	p_2	d
10	10	12

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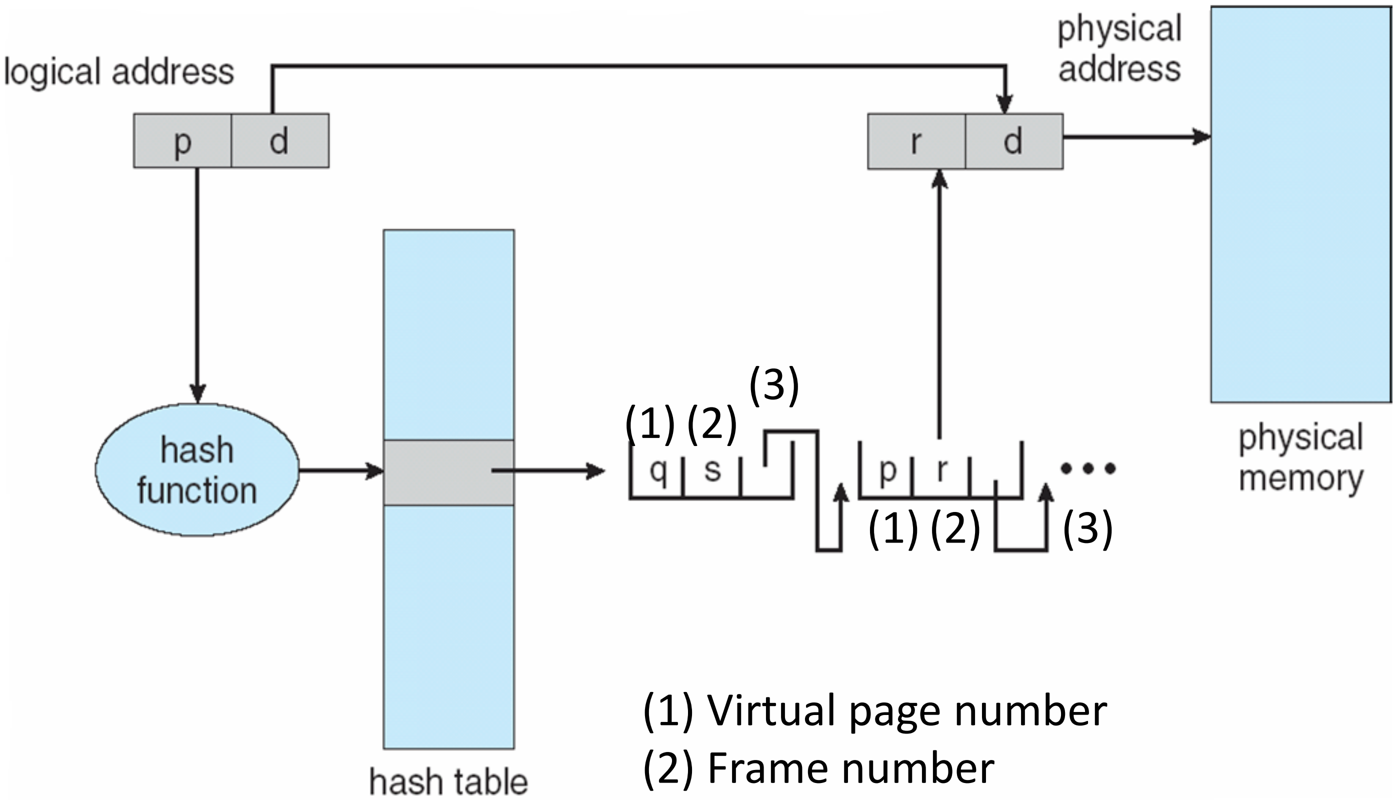
64-bit Logical Address Space

- How about 64-bit address?
  - assume each entry needs 4 bytes
  - 42 (p1) + 10 (p2) + 12 (offset)
    - outer table requires 2^42 x 4B = 16TB contiguous memory!!!
  - 12 (p1)+10 (p2)+10 (p3)+10 (p4)+10 (p5)+12 (offset)
    - outer table requires 2^12 x 4B = 16KB contiguous memory
    - 6 memory accesses!
- For 64-bit computers, hierarchical page tables are generally considered inappropriate

Hashed Page Table

核心想法: 由hash值找出list所在，再逐一比對(1)，match(1)後再由(2)+d找出physical

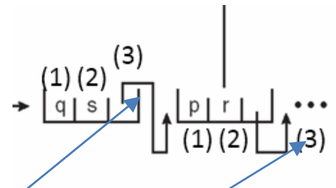


(1) Virtual page number
(2) Frame number
(3) Pointer to the next entry

Hashed Page Table

- Commonly-used for address > 32 bits
- 做法
  - Virtual page number is hashed into a hash table
  - Each entry in the hashed table contains

    (Virtual Page Number, Frame Number, Next Pointer)



- Hash table size
  - Larger hash table →smaller chains in each entry
- Problems
  - Pointers waste memory Ex: 64位元中一個pointer需8 bytes (64bits=8bytes)
  - Traverse linked list waste time & cause additional memory references

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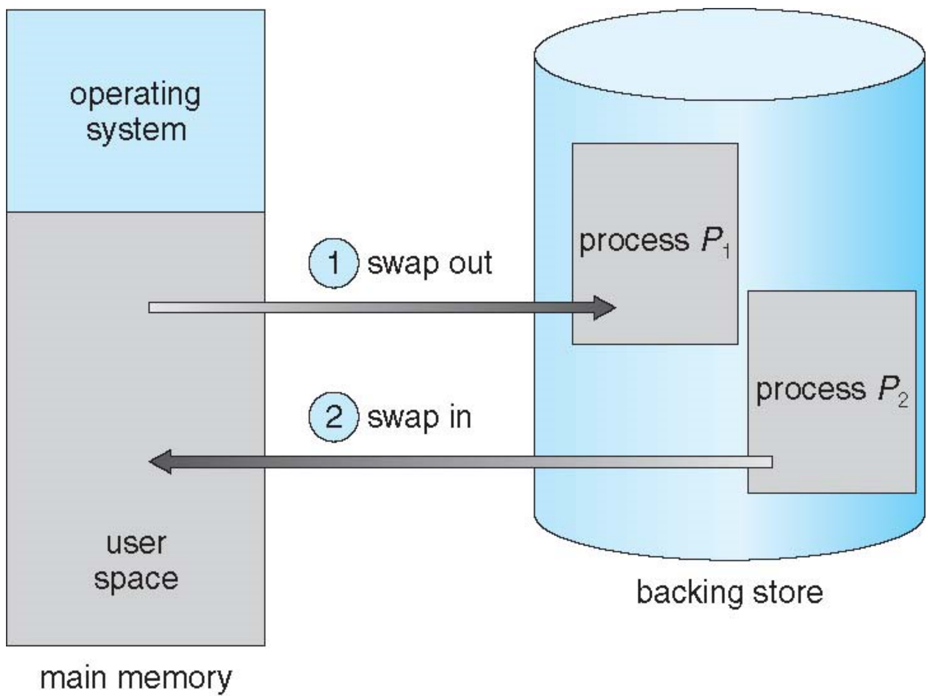
Swapping

- Definition
  - A process can be brought out of memory to a backing store, and later brought back into memory for continuous execution
  - 和paging的不同: swapping是process為單位共同進出記憶體; (demand) paging是以頁為單位進出記憶體
- Backing store
  - A chunk of disk, separated from file system, to provide direct access to these memory images
- Why Swap?
  - Free up memory
  - Roll out, roll in: swap lower-priority process with a higher one

Process Swapping to Backing Store

- Major part of swap time is <u>transfer time</u>
- Total transfer time is directly proportional to the <u>amount of memory</u> swapped

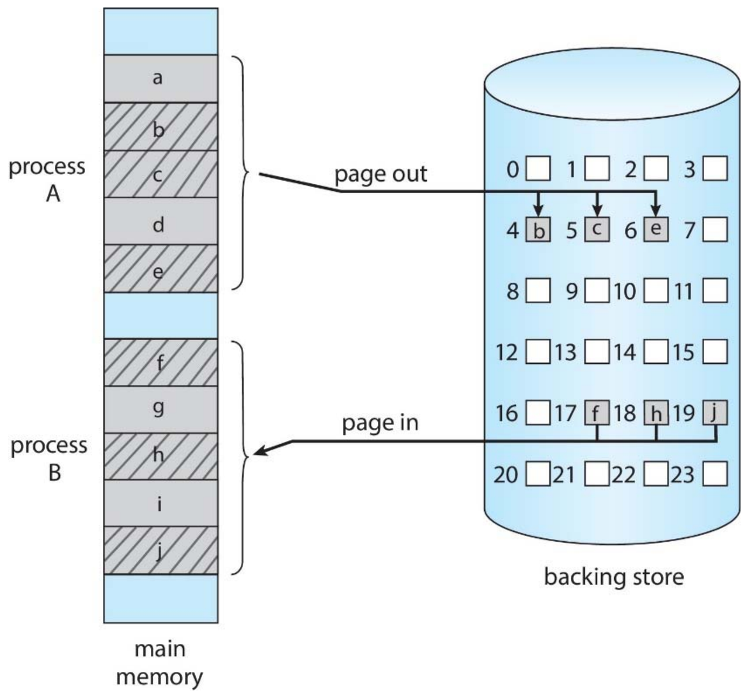


Swapping on Mobile Systems

- Usually does not support
  - Flash memory based
    - Small amount of space
    - Limited number of write cycles
    - Poor throughput between flash memory and CPU on mobile platform
- Use other methods to free memory if low
  - iOS ***asks*** apps to voluntarily relinquish allocated memory
    - Read-only data thrown out and reloaded from flash if needed
    - Failure to free can result in termination
  - Android terminates apps if low free memory, but first writes **application state** to flash for fast restart
  - Both OSes support paging as discussed below

Swapping with Paging = Demand Paging

- Swap only part of a process
  - Some pages belonging to the process
  - Typically combined with virtual memory



Q & A