政大資科系

作業系統

Operating System

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Operating System

Virtual Memory

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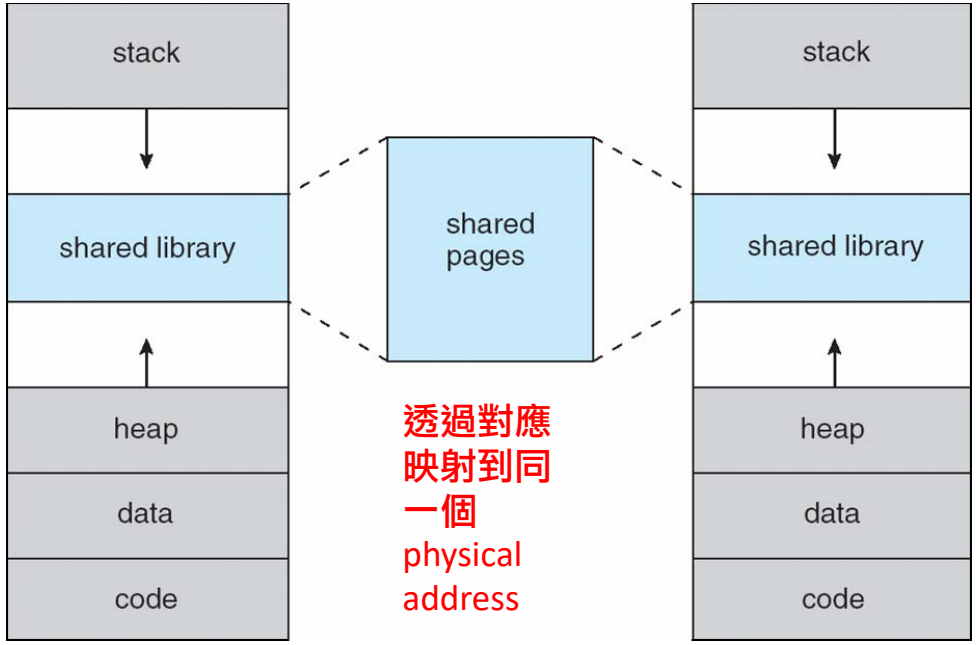
Motivation

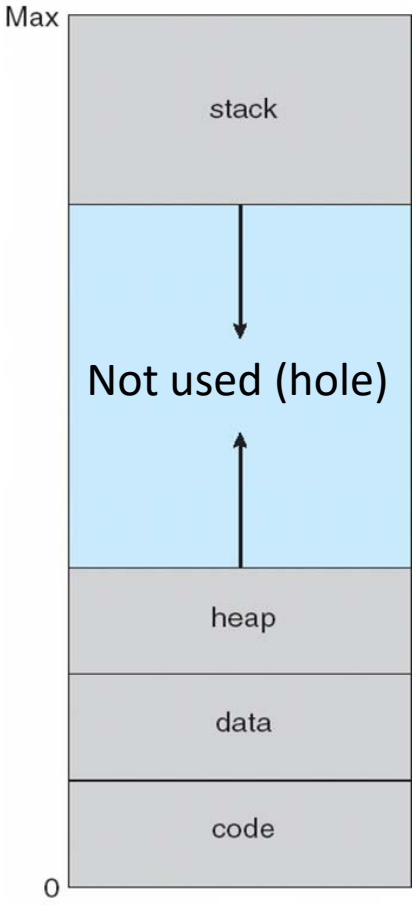
- Entire program rarely used at the same time
  - Many code for handling unusual errors or conditions
  - Certain program routines or features are rarely used
  - Arrays, lists and tables allocated but not used
- Execute partially-loaded program
  - Each program takes less memory → more programs run at the same time → increase utilization

Motivation

- Use cases for Virtual-Physical address mapping
  - Shared library
  - IPC (shared memory)
  - Fork() copy on write
    - Speeding up process creation



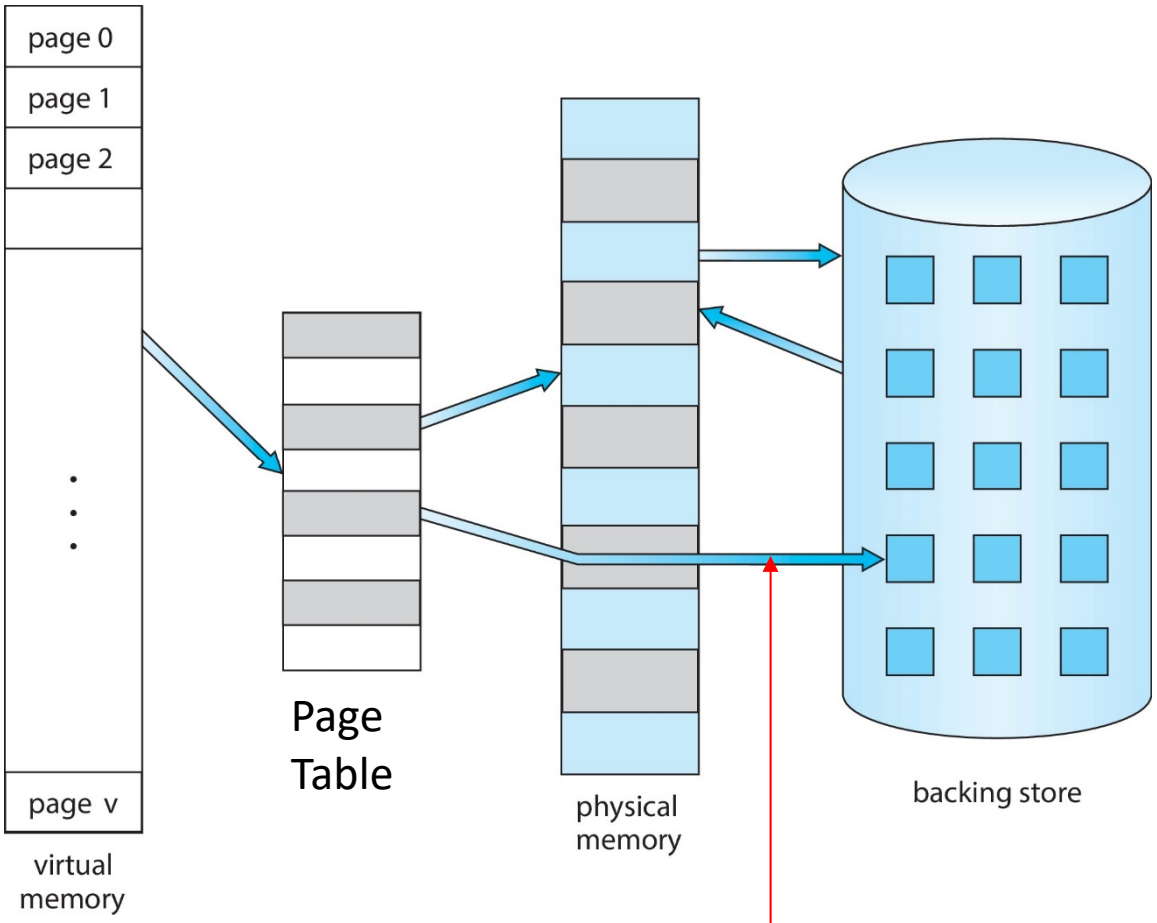
Virtual address of a process



Virtual Memory

- Separating logical memory and physical memory
  - To run an extremely large process
    - Logical address space can be much larger than physical address space
  - To increase CPU/resources utilization
    - higher multiprogramming degree
  - To simplify programming tasks
    - Free programmer from memory limitation
  - To start programs faster
    - less I/O would be needed to load or swap (因為只載入process的一部份)

Virtual Memory > Physical Memory



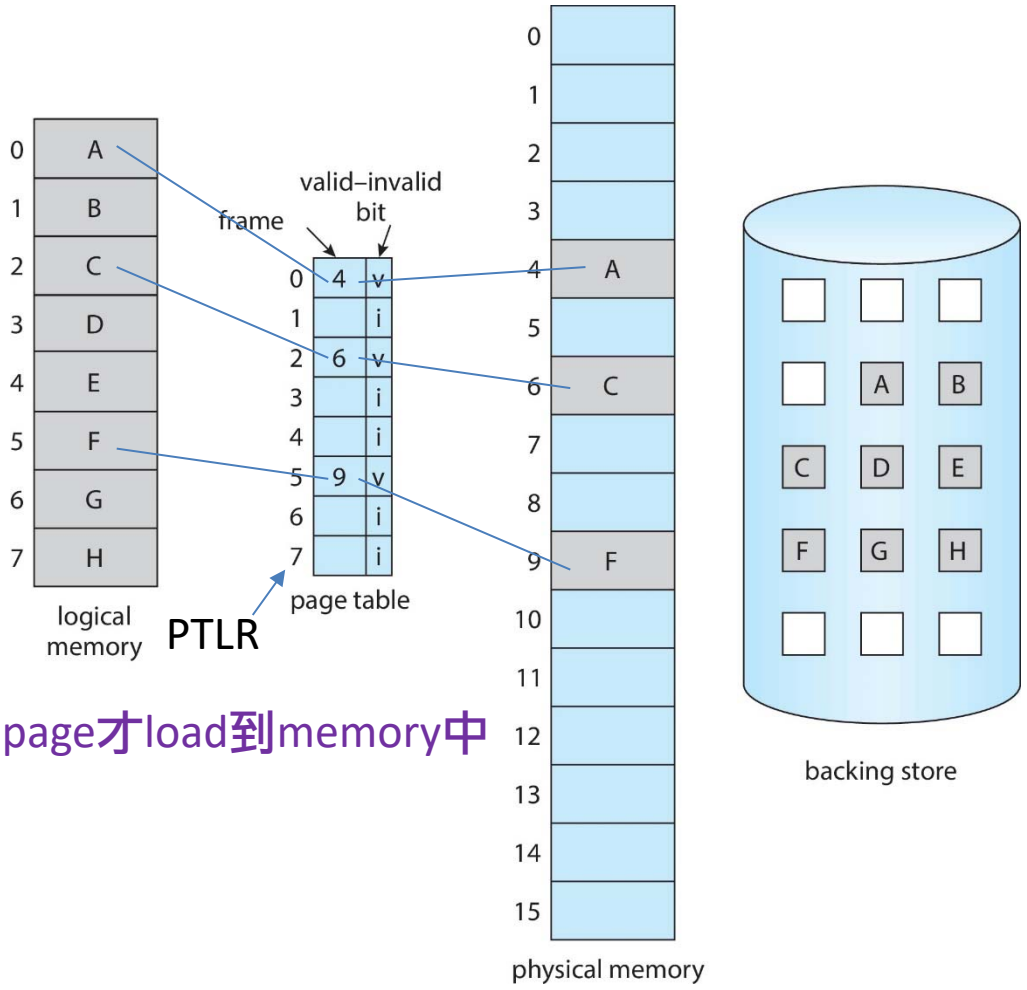
有些virtual memory space事實上存在disk上
但應用程式沒感覺到

Demand Paging

Core idea: Page用到時才載入

- A page is brought into memory only when it is needed
  - Less I/O needed → Faster response
  - Less memory needed → More users
- Page is needed when there is a reference to the page
  - Illegal reference → abort
    - Internal overflow or (invalid and >PTLR)
  - Not-in-memory → bring to memory via paging
    - invalid and <=PTLR
- Pure demand paging
  - Start a process with no page
  - Never bring a page into memory until it is required

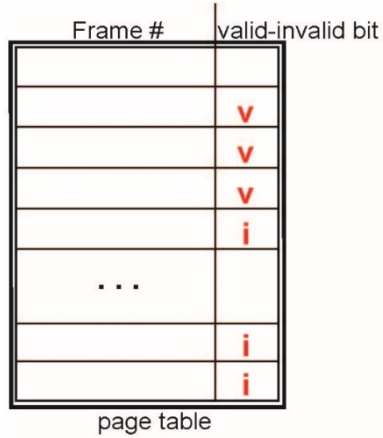
Demand Paging



用到的page才load到memory中

Demand Paging

- Demand Paging和Swapping不同
  - Swapper manipulates the entire process
  - Pager is concerned with the individual pages of a process
- Hardware support
  - Page Table: a valid-invalid bit
    - 1 valid → page in memory
    - 0 invalid → page not in memory
      - 可能illegal或只是不在mem; 視PTLR而定
    - Initially, all such bits are set to 0
  - Secondary memory (swap space, backing store):
    - Usually, a high-speed disk (swap device) is used

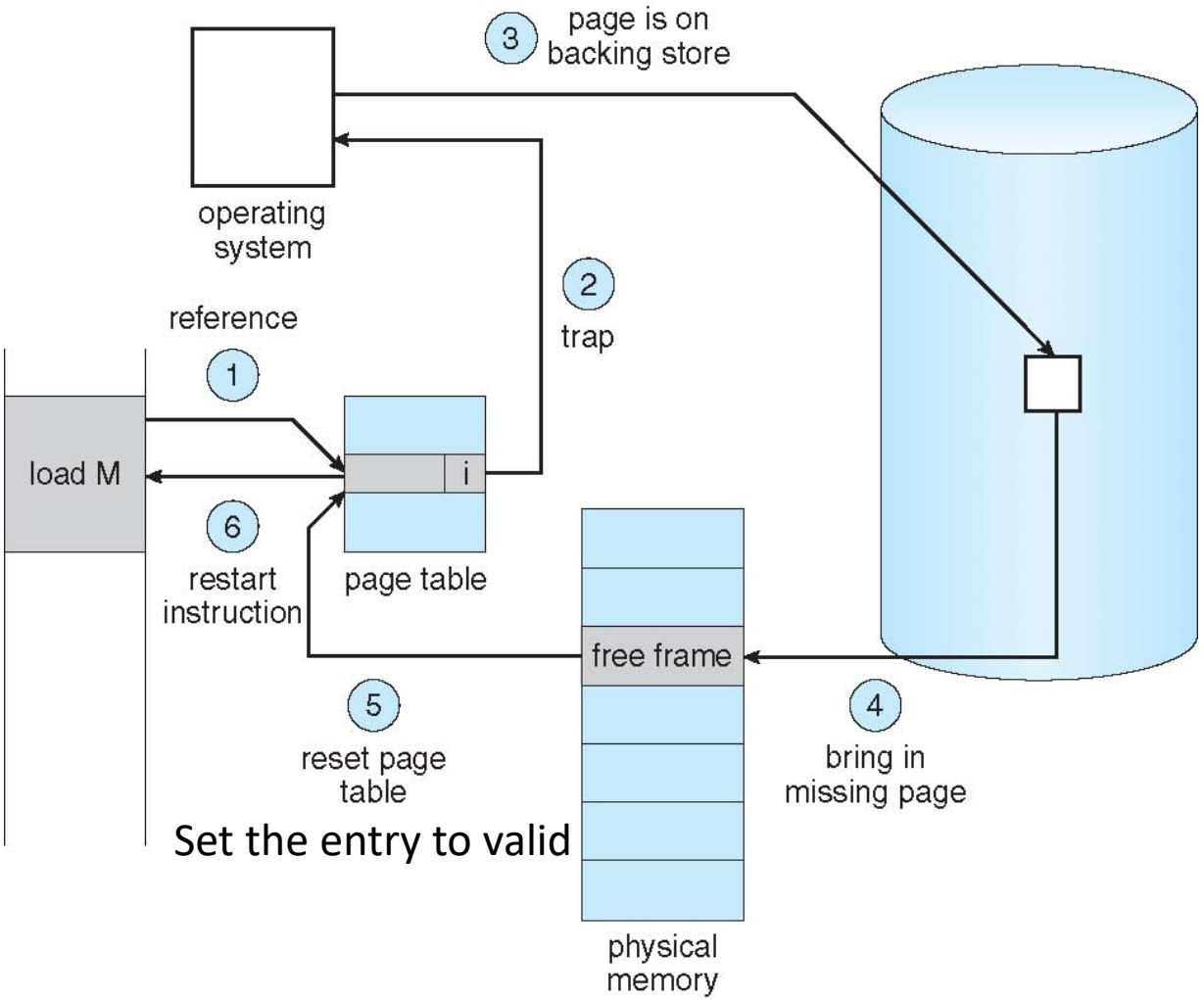


Page Fault Process

- First reference to a page will trap to OS
  - page-fault trap

1. OS looks at the internal table (in PCB) to decide
   - Illegal → abort (違規存取)
   - just not in memory → continue
2. Get an empty frame (from free frame list)
3. Read the page from disk into the frame
4. Reset the page table entry: set to valid (1)
5. Restart instruction

Handling a Page Fault



Demand Paging Performance

- Three major task components of the page-fault time
  1. Service the page-fault interrupt
  2. Read in the page (from disk)
  3. Restart the process
- 1 and 3 can be reduced with careful coding
- 2 is the most time consuming part

Demand Paging Performance

存取記憶體　存取記憶體失敗+Page-in

- Effective Access Time (EAT): (1 – p) x ma + p x pft
  - p: page fault rate, ma : mem. access time, pft : page fault time
- Example: ma = 200ns, pft = 8ms
  - EAT = (1 - p) * 200ns + p * 8ms

    = 200ns + 7,999,800ns x p　8ms = 8000000 ns
- Access time is proportional to the page fault rate
  - If one out of 1,000 causes a page fault, then

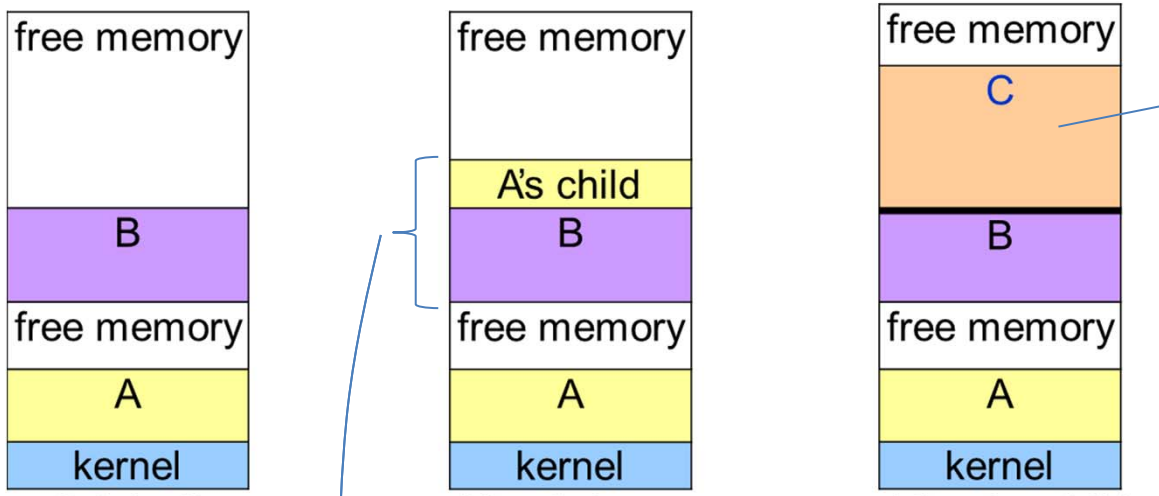
    EAT = 8200ns → slowdown by a factor of 40!　200ns vs. 8200ns
  - For degradation less then 10% (220ns):　確保EAT<220ns

    220 > 200+ 7,999,800 x p , p < 0.0000025

    one access out of 399,990 to page fault

Copy-on-Write

- Memory space of fork():
  - Old implementation: A's child is an exact copy of parent
  - Current implementation: use copy-on-write technique to store differences in A's child address space



A和B唯讀部份的內容是相同的
→ Shared paging

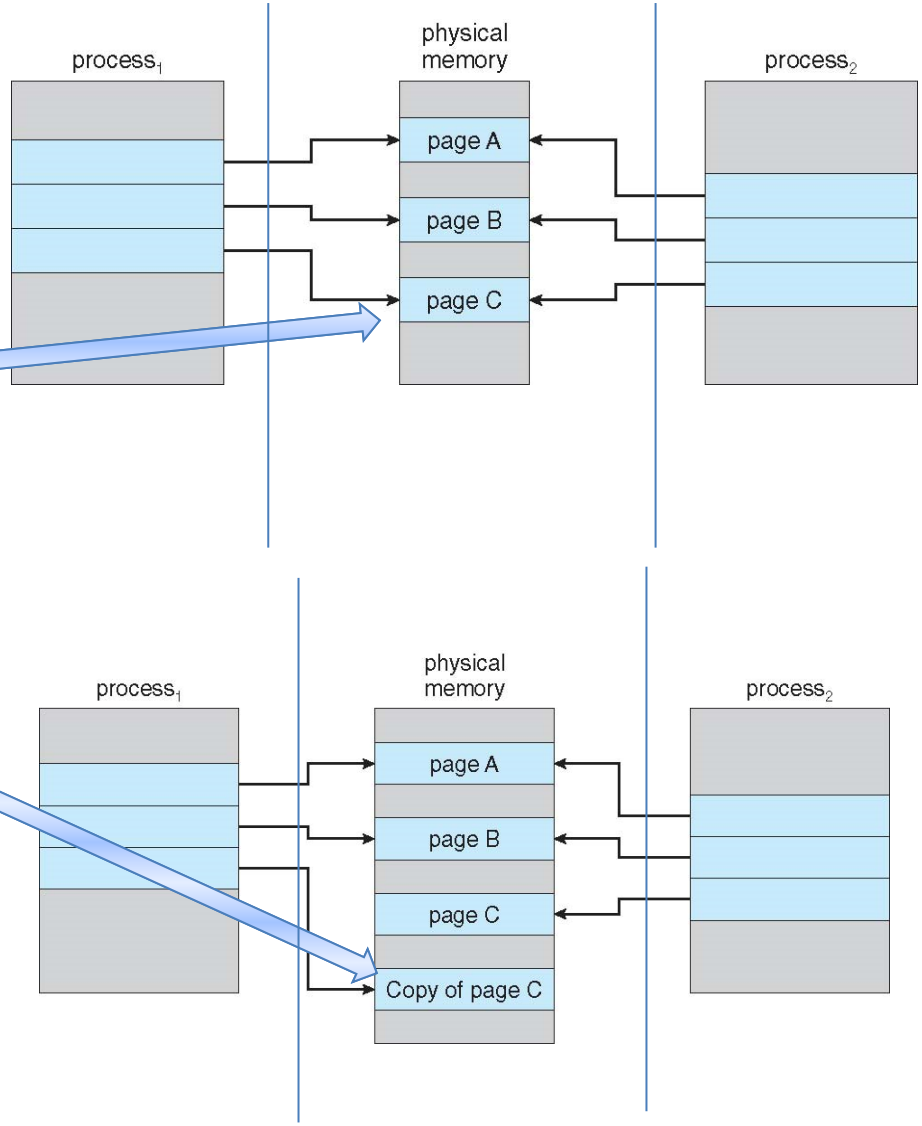
Copy-on-Write

- COW allows efficient process creation (e.g., fork())
- Allows both parent and child processes to initially share the same pages in memory
  - Not copy until a modification on the child process

Copy-on-Write

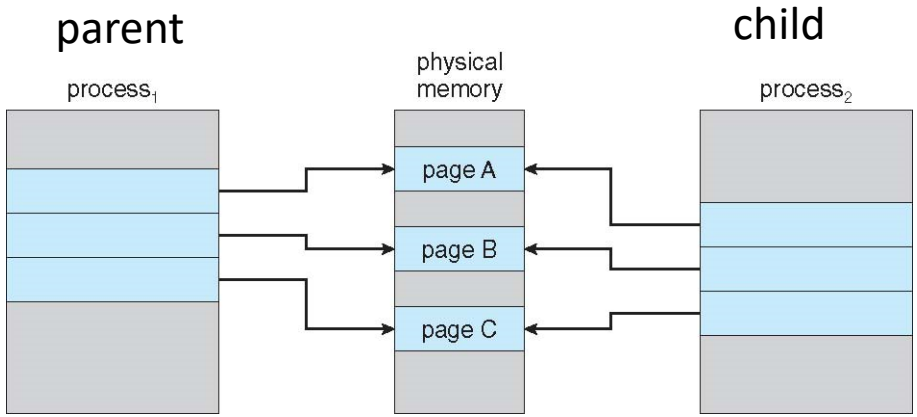
```
#include <stdio.h>
void main( )
{
    int A;
    /* fork child process */
    A = fork( );

    if (A == 0) {
       /* child process */
       int test1=0;
    }
    printf("process ends");
}
```



另一種做法: vfork()

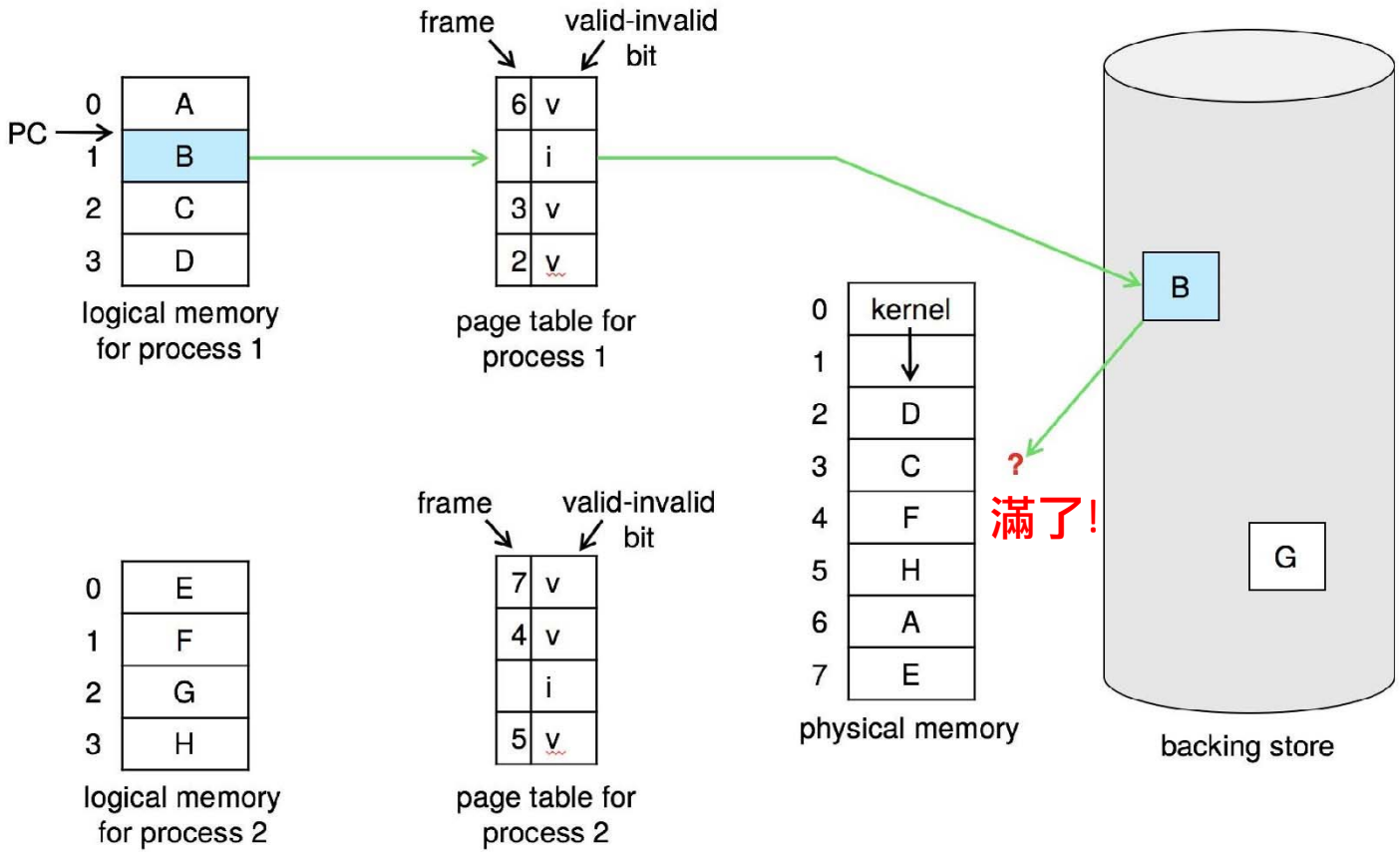
- vfork(): Virtual Memory Fork
  - Child share memory with the parent
  - Parent suspends after vfork()
  - No copy-on-write: modification visible to the parent
  - No memory copying, extremely efficient
  - Mainly used to implement shell (why?)



Case: Windows 10

- Windows 10 implements most of the memory-management features described thus far, including
  - shared libraries, demand paging, and copy-on-write

Need For Page Replacement



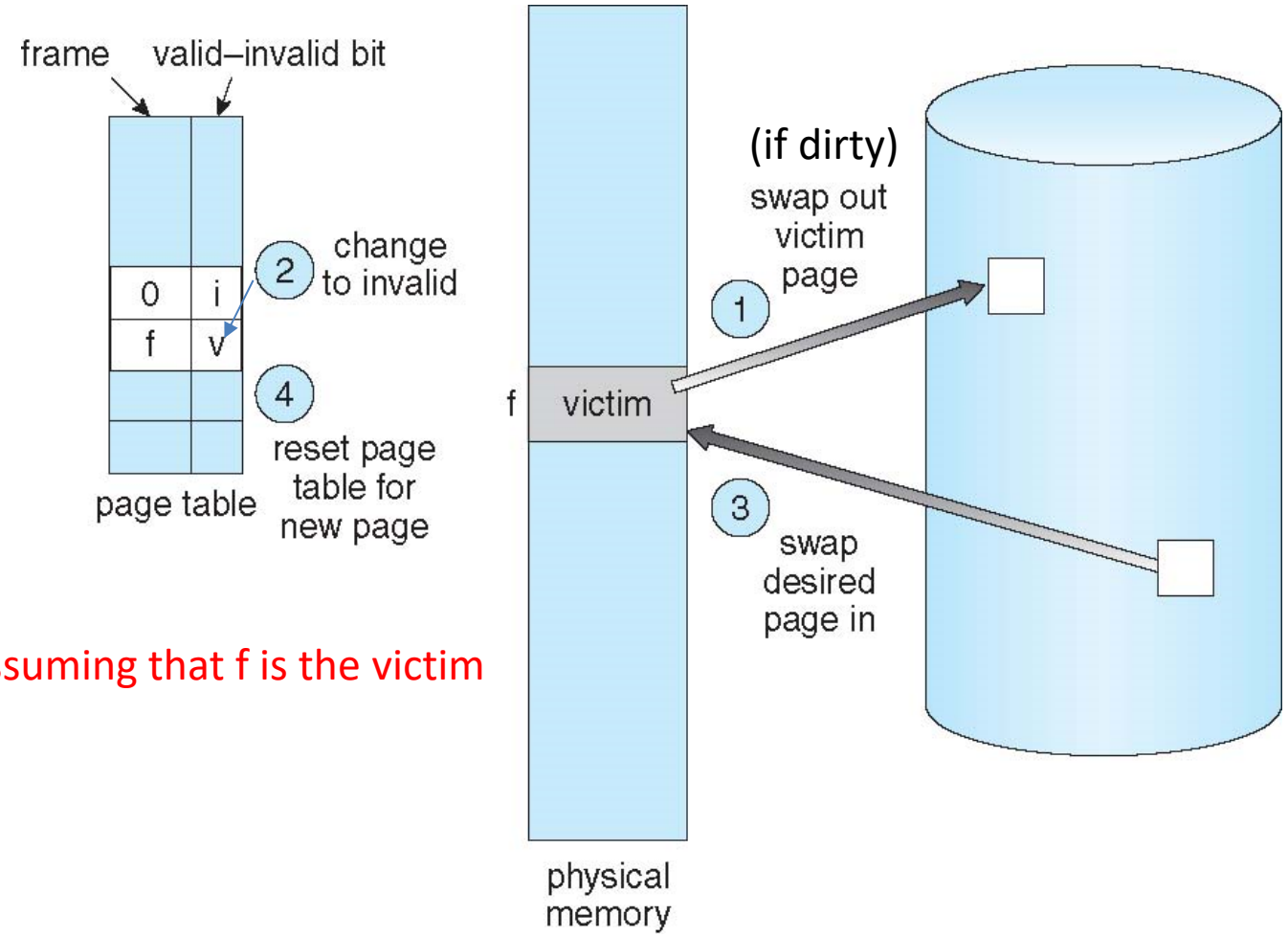
Page Replacement

- When a page fault occurs and no free frame
  - Swap out a process: freeing all of the process's frames
  - Page replacement: find one not currently used and free it
    - Write back: use dirty bit to reduce overhead of page transfers – only modified pages are written to disk (有被改過的page，才需要回寫)
- Two issues
  - Page-replacement algorithm:
    - Select which frame to be replaced
  - Frame-allocation (section 10.5, P.413):
    - Determine how many frames to be allocated to a process (initially)

Page Replacement (Page Fault) Steps

1. Find the desired page on disk
2. Find a free frame in memory
   - If there is a free frame, use it
   - If there is no free frame, use a page replacement algorithm to select a victim frame
   - Write back the victim frame if dirty
3. Read the desired page into the (newly) free frame
4. Update the page & frame tables
5. Resume the process

Page Replacement



Assuming that f is the victim

Page Replacement Algorithms

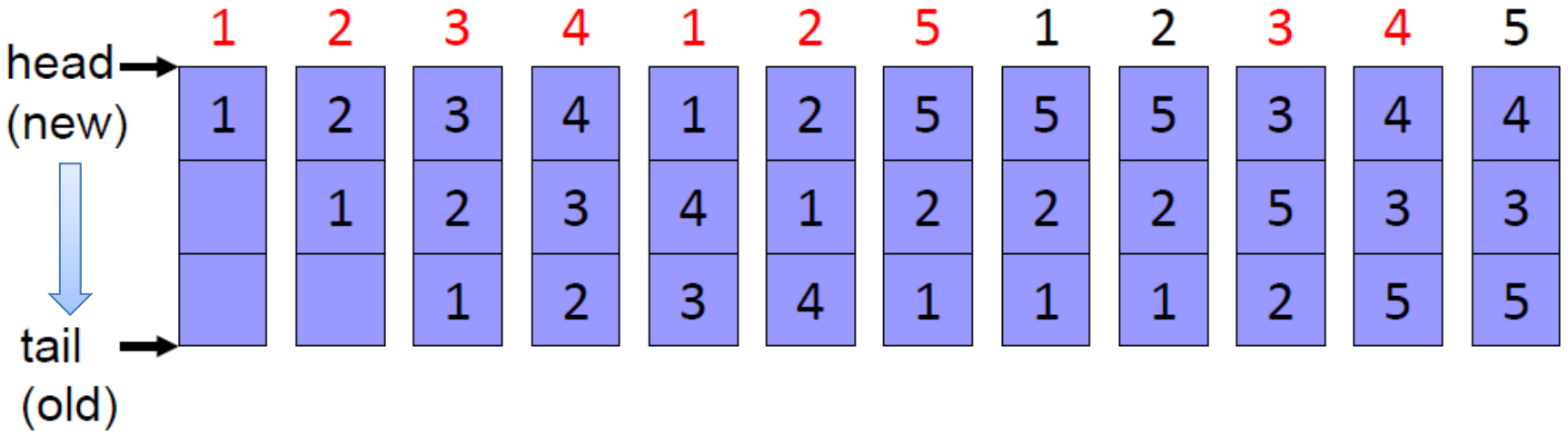
- Goal
  - Lowest page-fault rate
- Evaluation
  - Test with reference string
  - Compute the number of page faults

Replacement Algorithms

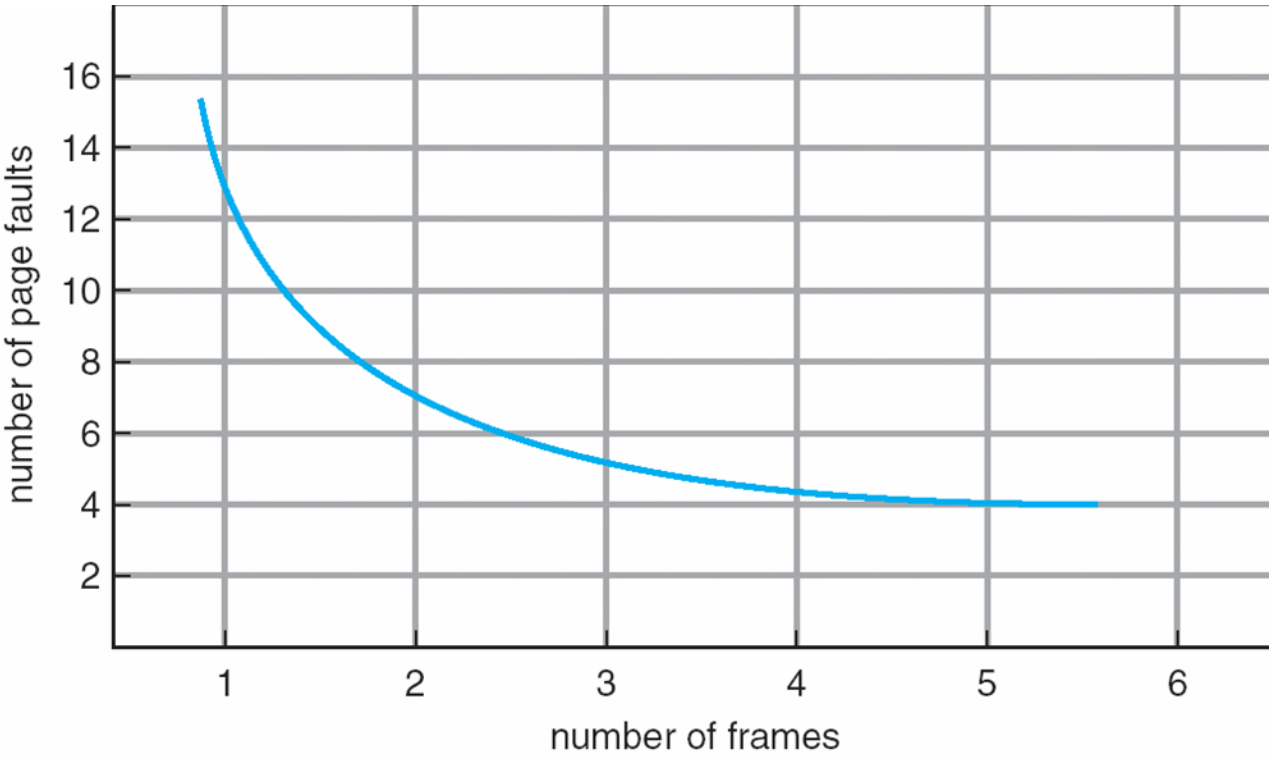
- FIFO algorithm
- Optimal algorithm
  - 取代掉未來最久不會用到的page
- LRU algorithm
  - 取代掉最久沒被用的 (根據歷史資料)
- Counting algorithm
  - LFU (Least frequently used) 合計被用到最少次
  - MFU (Most frequently used) 合計被用到最多次

First-In-First-Out (FIFO) Algorithm

- The oldest page in a FIFO queue is replaced
  - Reference string: 1,2,3,4,1,2,5,1,2,3,4,5
- 3 frames (available memory frames = 3)
  - 9 page faults



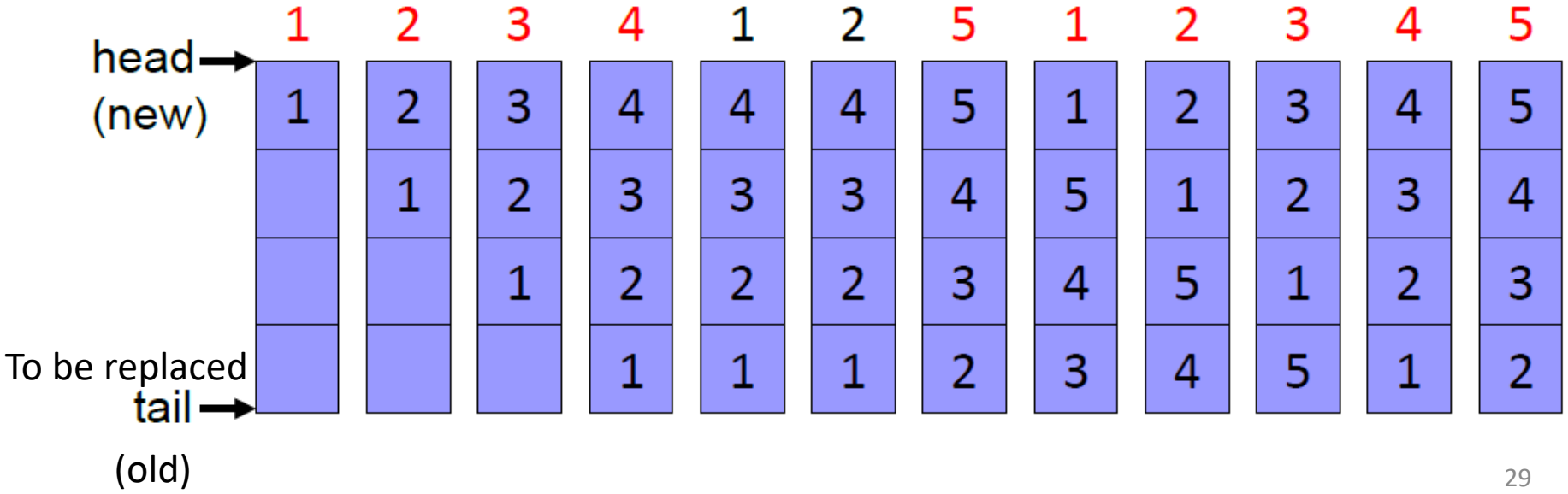
(理論上的) Graph of Page Faults vs the Number of Frames



實體記憶體愈充足，page fault理論上要愈少

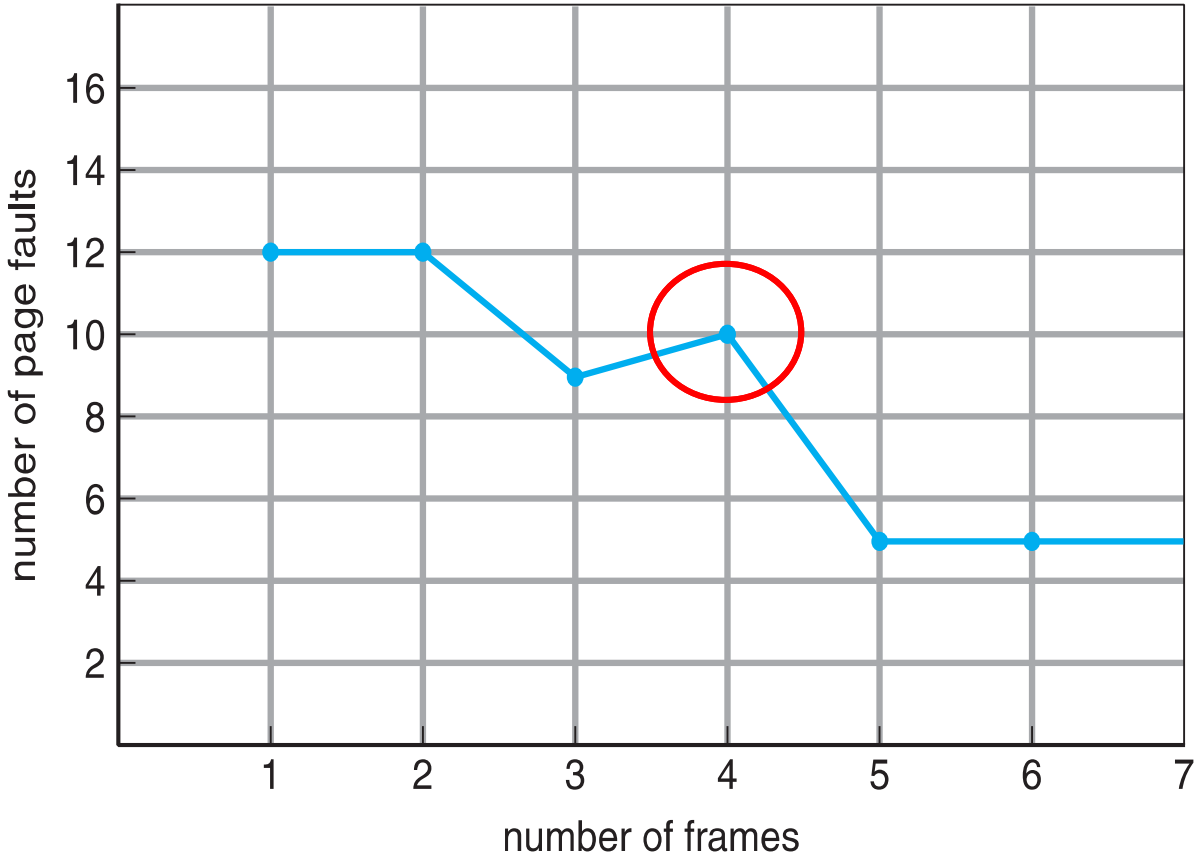
FIFO Illustrating Belady's Anomaly

- Does more allocated frames guarantee less page fault?
  - Reference string: 1,2,3,4,1,2,5,1,2,3,4,5
  - 4 frames (available memory frames = 4)
  - 10 page faults!
- Belady's anomaly
  - Greater allocated frames → more page fault



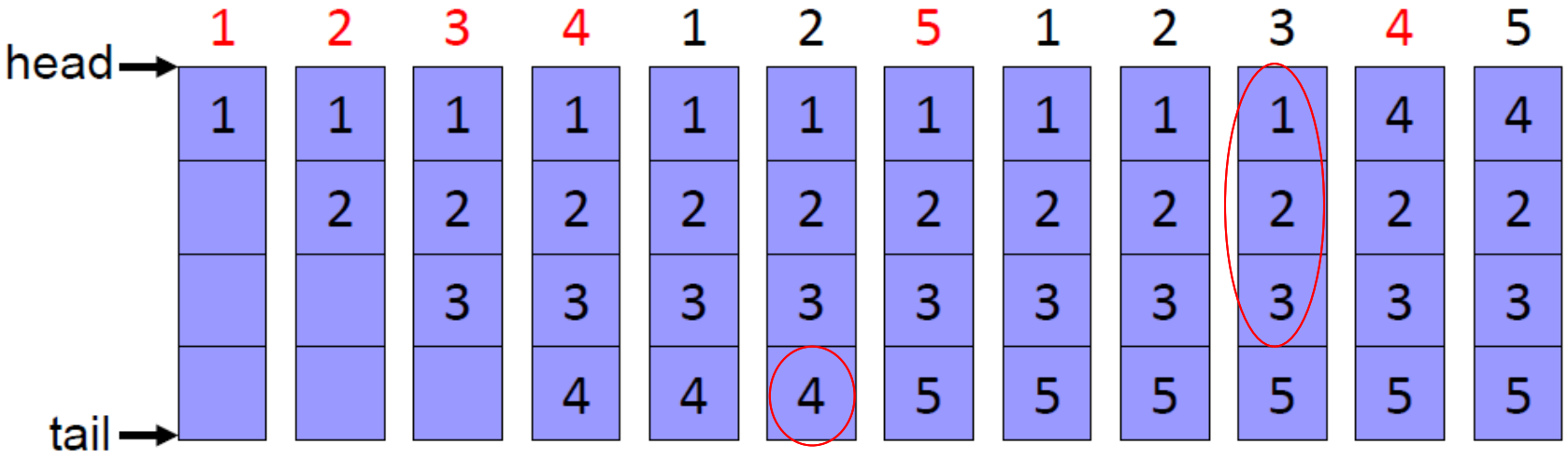
FIFO Illustrating Belady's Anomaly

想像: cache的entries 愈多，理論上應該hit rate愈高，但FIFO某些情況下，entries多反而會降低hit rate!



Optimal (Belady) Algorithm

- Replace the page that will not be used for the longest time
  - need future knowledge
- 4 frames: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5 → 6 page faults!
- In practice, we don't have future knowledge
  - Only used for reference & comparison 實務上無法實現!



LRU Algorithm (Least Recently Used)

- An approximation of optimal algorithm:
  - Looking backward, rather than forward
    - 直覺意義: 過去反映未來
  - Replaces the page that has not been used for the longest period of time
  - Often used, and is considered as quite good

LRU Implementations

- Counter implementation
  - page referenced: timestamp is copied into the counter
  - replacement: remove the one with oldest counter
    - linear search is required
- Stack implementation
  - page referenced: move to top of the double-linked list
  - replacement: remove the page at the bottom

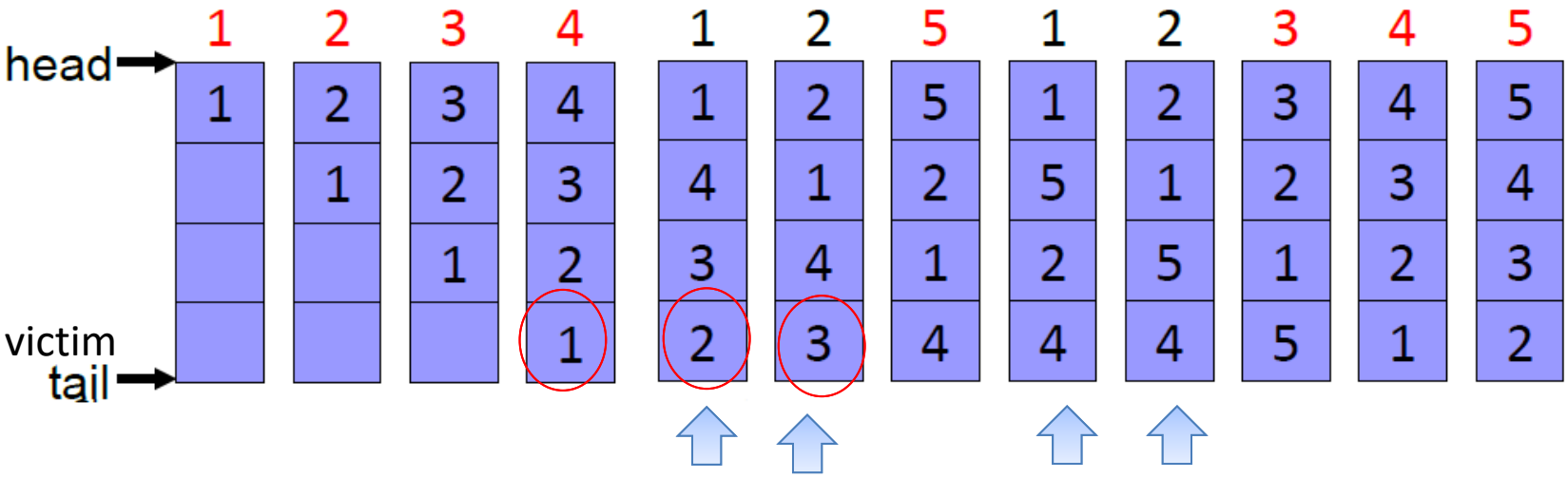
紀錄最近被用的時間

new

old

LRU Example

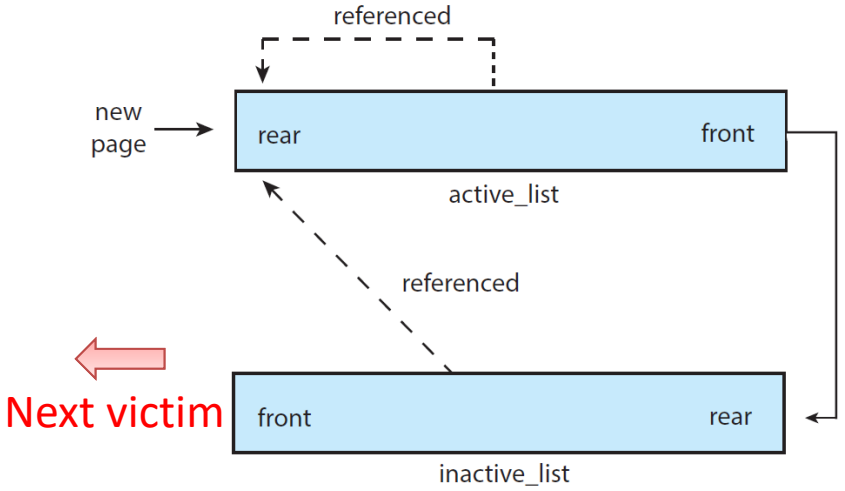
- LRU
  - 4 frames: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5 → 8 page faults!



最近有被access的話就提升到queue head

Case: Linux

- Linux maintains two types of page lists: an active list and an inactive list
  - The front of inactive_list is the candidate of next victim
  - Initially a page is put to the rear of active_list
    - Gradually, the page moves toward the front of inactive_list
  - When referenced, the page is moved to the rear of active_list



P.413

Allocation of Frames

- 一個Process要配置多少記憶體?
- Fixed allocation
  - Equal allocation 平均分配
    - 100 frames, 5 processes → 20 frames/process
  - Proportional allocation 依需求
    - Allocate according to the size of the process
- Priority allocation
  - using proportional allocation based on priority, instead of size

Frame Allocation

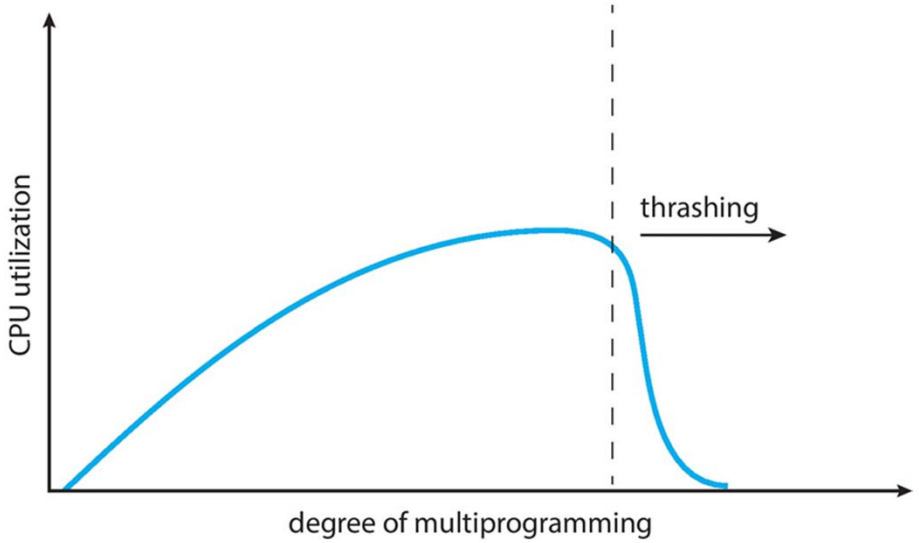
- Local allocation: each process select from its own set of allocated frames (victim只從自己現有的來選)
- Global allocation: process selects a replacement frame from the set of all frames (victim全部系統一起考量來選)
  - One process can take away a frame of another process
    - e.g., allow a high-priority process to take frames from a low-priority process
  - Good system performance and thus is common used
  - A minimum number of frames must be maintained for each process to prevent trashing

P.419

Definition of Thrashing

- If a process does not have “enough” frames
  - the process does not have # frames it needs to support pages in active use
  - Very high paging activity
- A process is thrashing if it is spending more time on paging than executing

花在放出載入分頁的時間比真正計算時間多



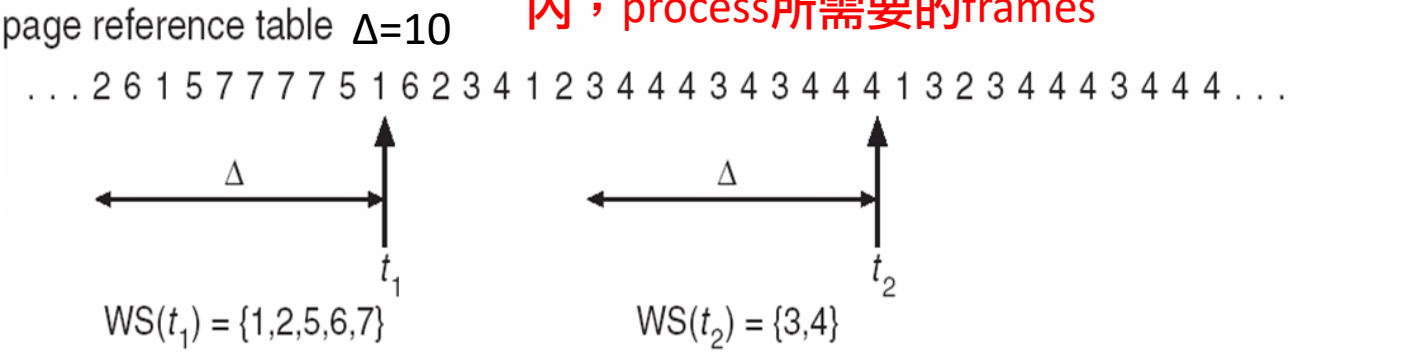
Thrashing

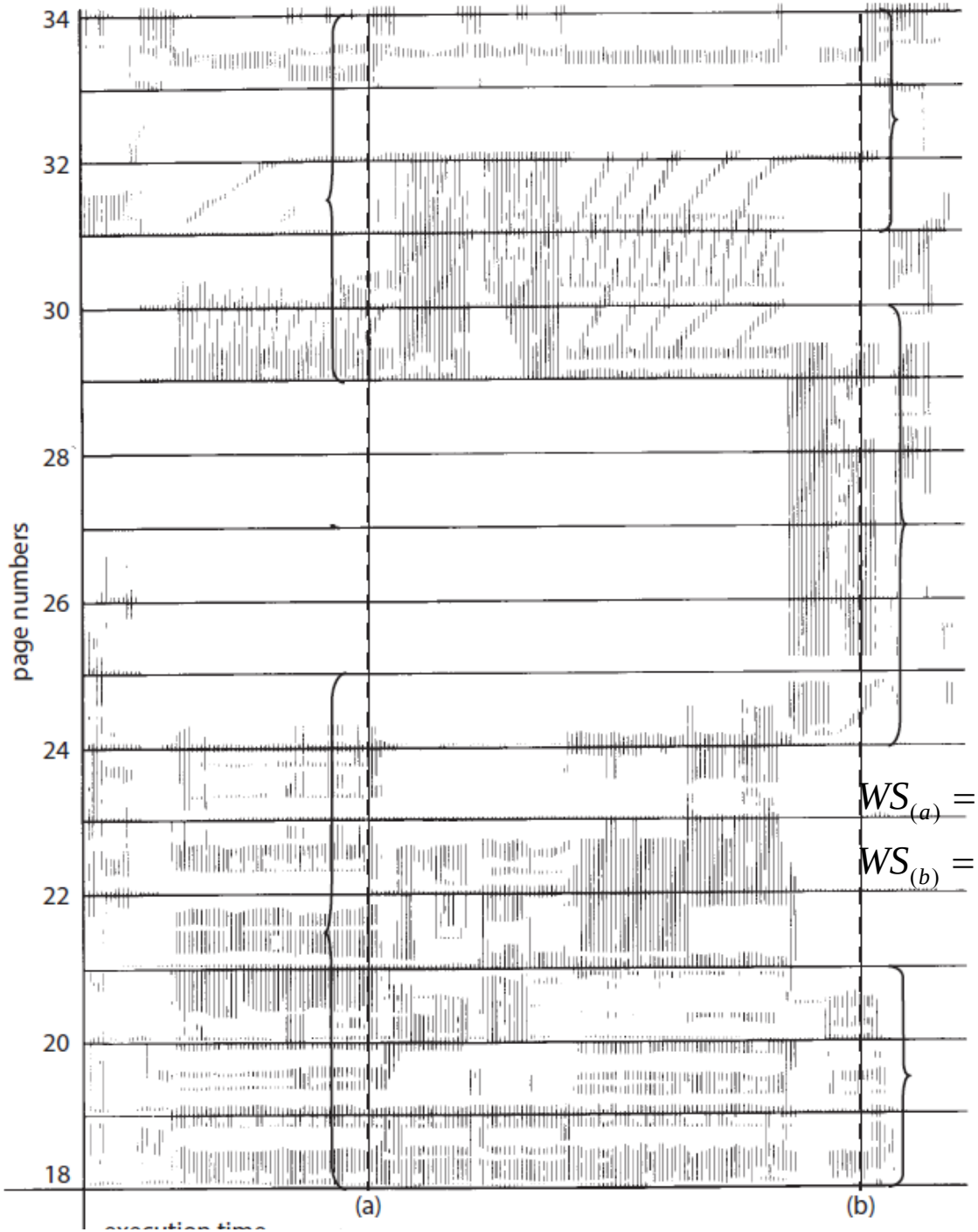
- Performance problem caused by thrashing (Assume global replacement is used) 不良連鎖反應
  - processes queued for I/O (page fault)
    - low CPU utilization
    - OS increases the degree of multiprogramming
    - new processes take frames from old processes
    - more page faults and thus more I/O
    - CPU utilization drops even further
- To prevent thrashing, must provide enough frames for each process:
  - Working-set model, Page-fault frequency

Working-Set Model

- Locality: a set of pages that are actively used together
- 程式執行時有其固定的locality model
  - program structure (subroutine, loop, stack)
  - data structure (array, table)
- Working-set model (based on locality model)
  - working-set window: a parameter Δ (delta)
  - working set: set of pages in most recent Δ page references (an approximation locality)

直覺意義: working set的size就是某一段時間內，process所需要的frames





Example

$WSS_a = 13$

$$WS_{(a)} = \{18, 19, 20, 21, 22, 23, 24, 29, 30, 31, 32, 33, 34\}$$

$$WS_{(b)} = \{18, 19, 20, 24, 25, 26, 27, 28, 29, 31, 32, 33, 34\}$$

$WSS_b = 13$

Working-Set Model

- Prevent thrashing using the working-set size
  - WSS_i : working-set size for process *i*
  - D = Σ WSSi (total demand frames)
  - If D > m (available frames) →thrashing
  - The OS monitors the WSSi of each process and allocates to the process enough frames
    - if D << m, 代表available frames還很多, increase degree of MP
    - if D > m, 代表memory不足, suspend some processes
- Good parts
  - Prevent thrashing while keeping the degree of multiprogramming as high as possible
  - Optimize CPU utilization
- Bad part
  - Tracking WS is too expensive

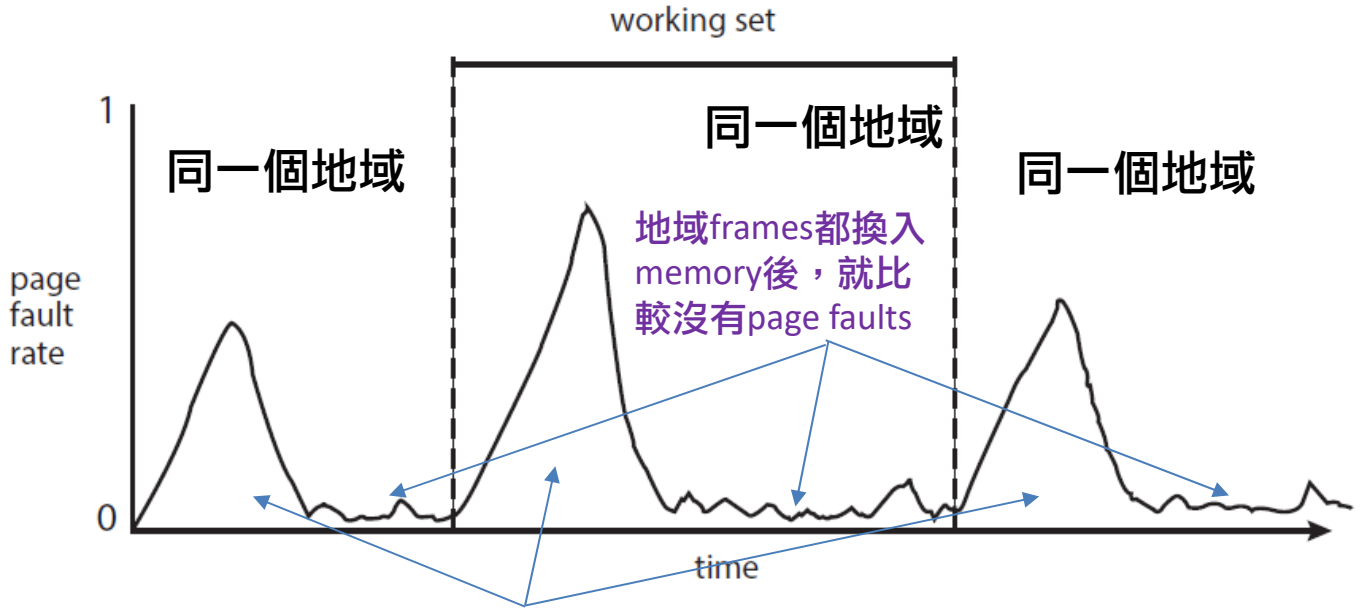
直覺意義: working set的size就是某一段時間內，process所需要的frames

Available frames不足以應付Pi所需

Case: Windows 10

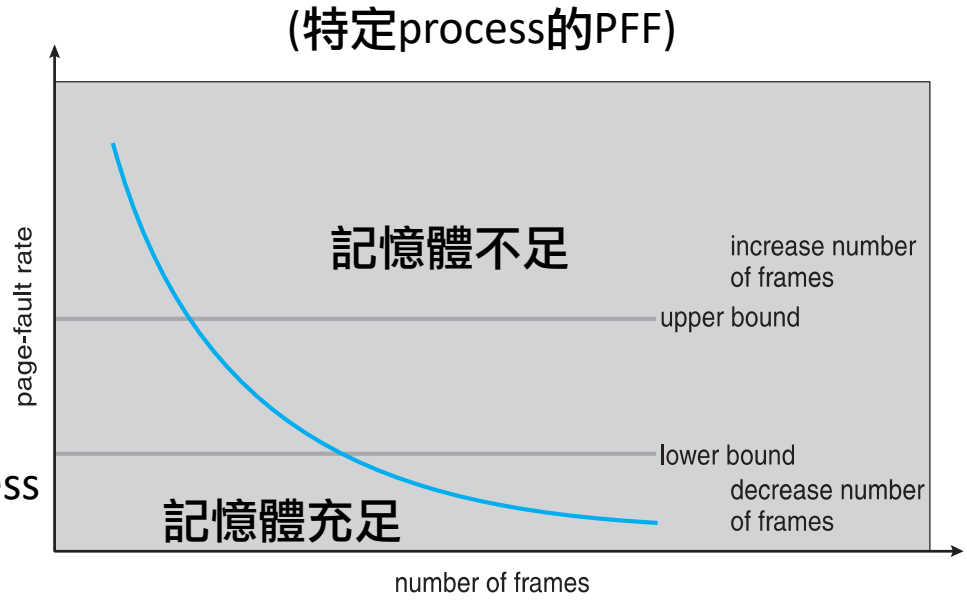
- When a process is created, it is assigned
  - Working set minimum = 50 pages
  - Working set maximum = 345 pages
- When the amount of memory is insufficient
  - Use a global replacement strategy called Automatic working-set trimming
    - If a process has more pages than its working-set minimum, the virtual memory manager removes pages from the working set

Working Set and Page Fault Rate



Page Fault Frequency (PFF)

- 追蹤Working Set難度高，PFF是可趨近且較簡單方法
  - 直覺意義: PFF與Thrashing可能性成正比
- 策略
  - 直接量測Process的PFF
  - 訂出PFF的上下限，採取因應措施
- 方法
  - If PFF exceeds the upper limit
    - allocate another frame to the process
  - If PFF falls below the lower limit
    - remove a frame from the process



Q & A