Chapter 9: Virtual-Memory Management

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Chapter 9: Virtual Memory

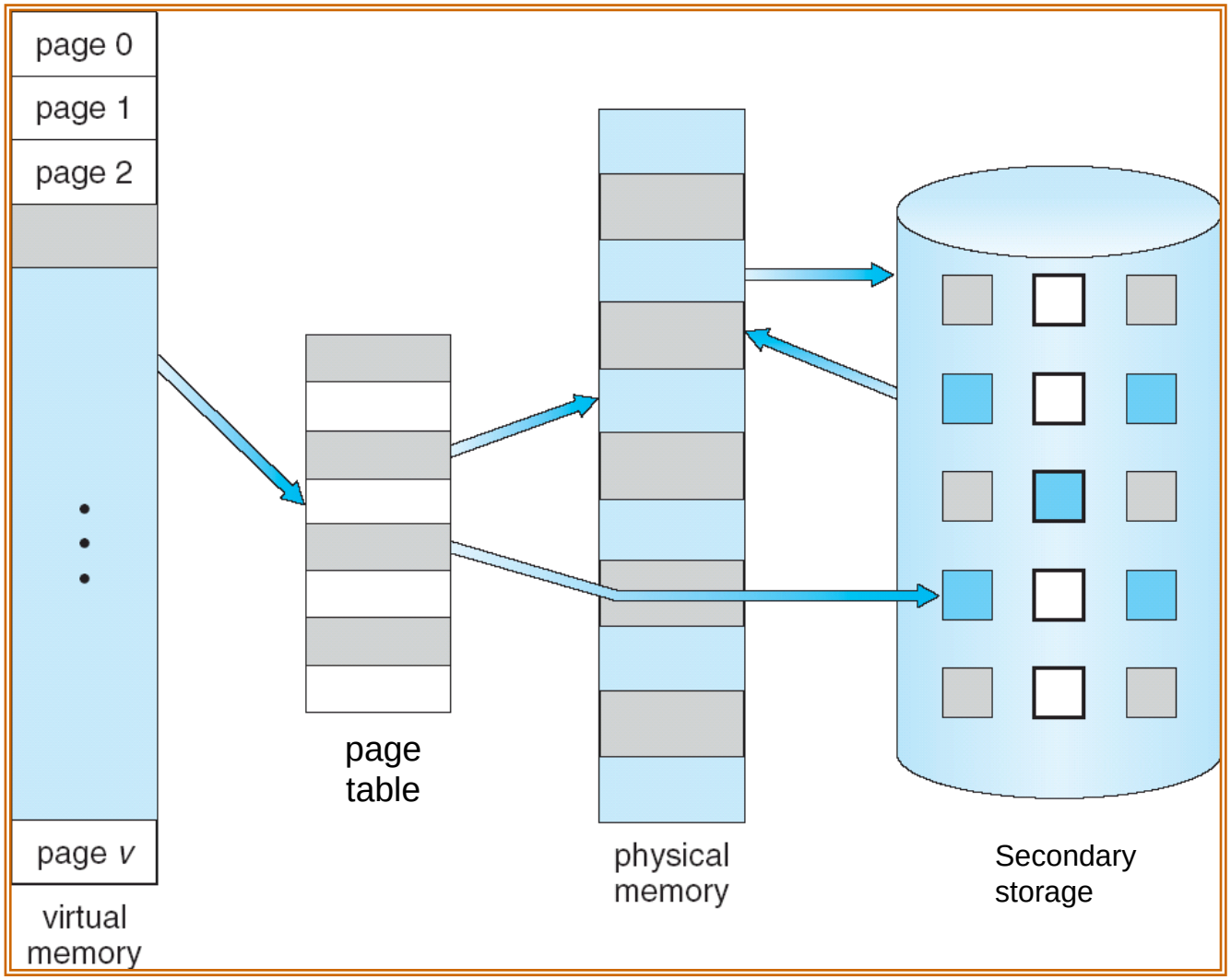
- Demand Paging
- Page Replacement
- OS features based on virtual memory
- Performance Issues
- Operating System Examples

DEMAND PAGING

Virtual Memory based on Demand Paging

- Recap: Virtual memory – separation of user logical memory from physical memory
- Virtual memory, based on demand paging, enables the following features
  - Only part of the program (subset of all pages) needs to be in memory for execution
  - Logical address space can therefore be much larger than physical address space
  - Allows for more efficient process creation
  - Improves the degree of multiprogramming
  - Allows address spaces to be shared by several processes

Virtual Memory That is Larger Than Physical Memory

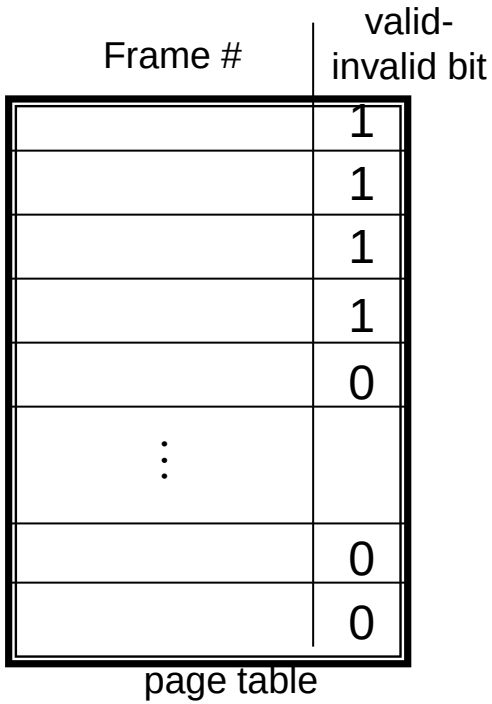


Demand Paging

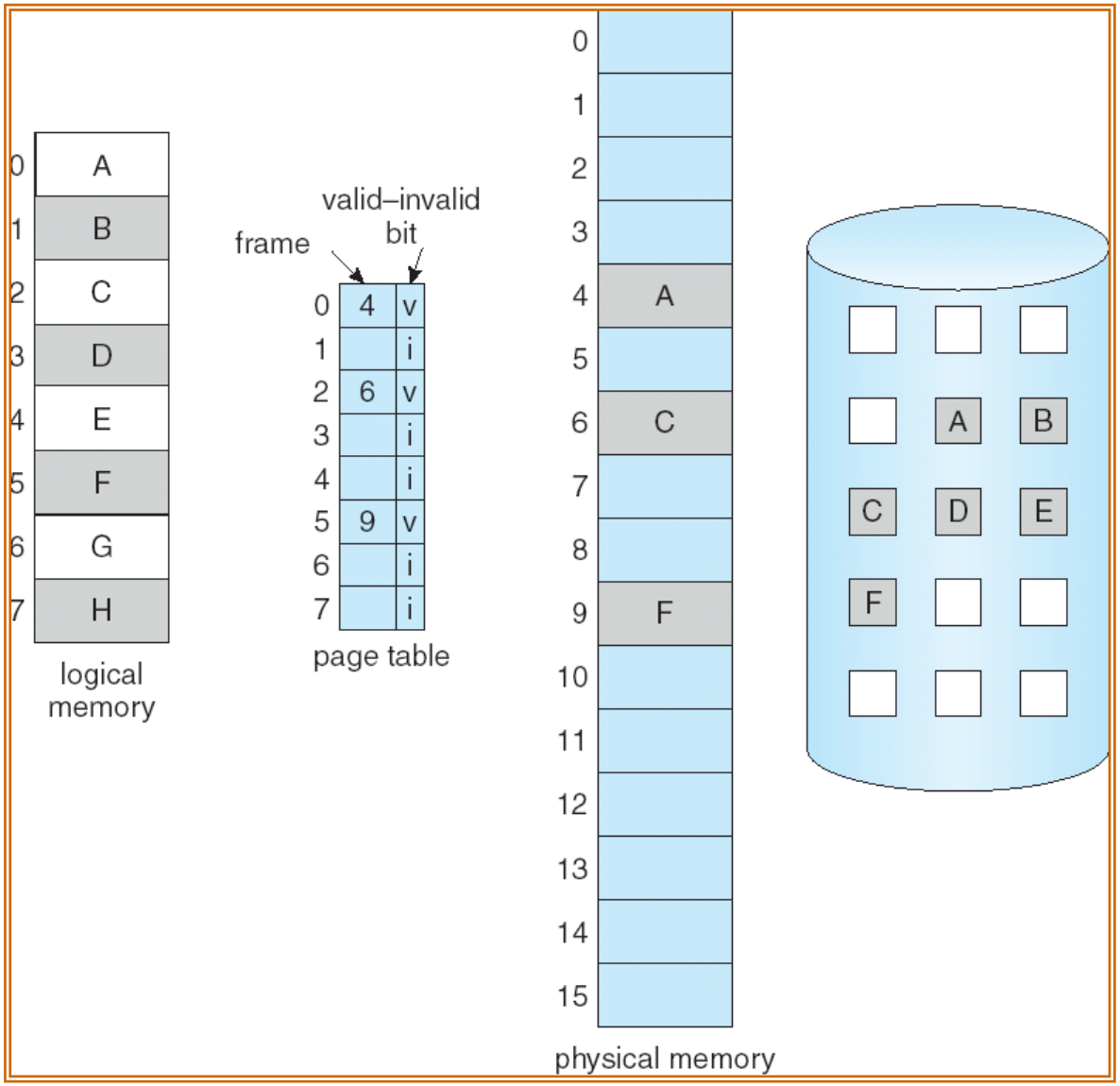
- An essential mechanism to implement virtual memory; requiring a (large) secondary storage as the backup of memory pages
- Bringing a page to memory only when it is needed
  - Less memory needed
  - Faster response
  - More users/processes
  - Less I/O needed
- Page is needed $\Rightarrow$ reference to it (load or store)
  - In-memory $\Rightarrow$ normal reference
  - not-in-memory $\Rightarrow$ bring to memory

Valid-Invalid Bit of Page Table Entry

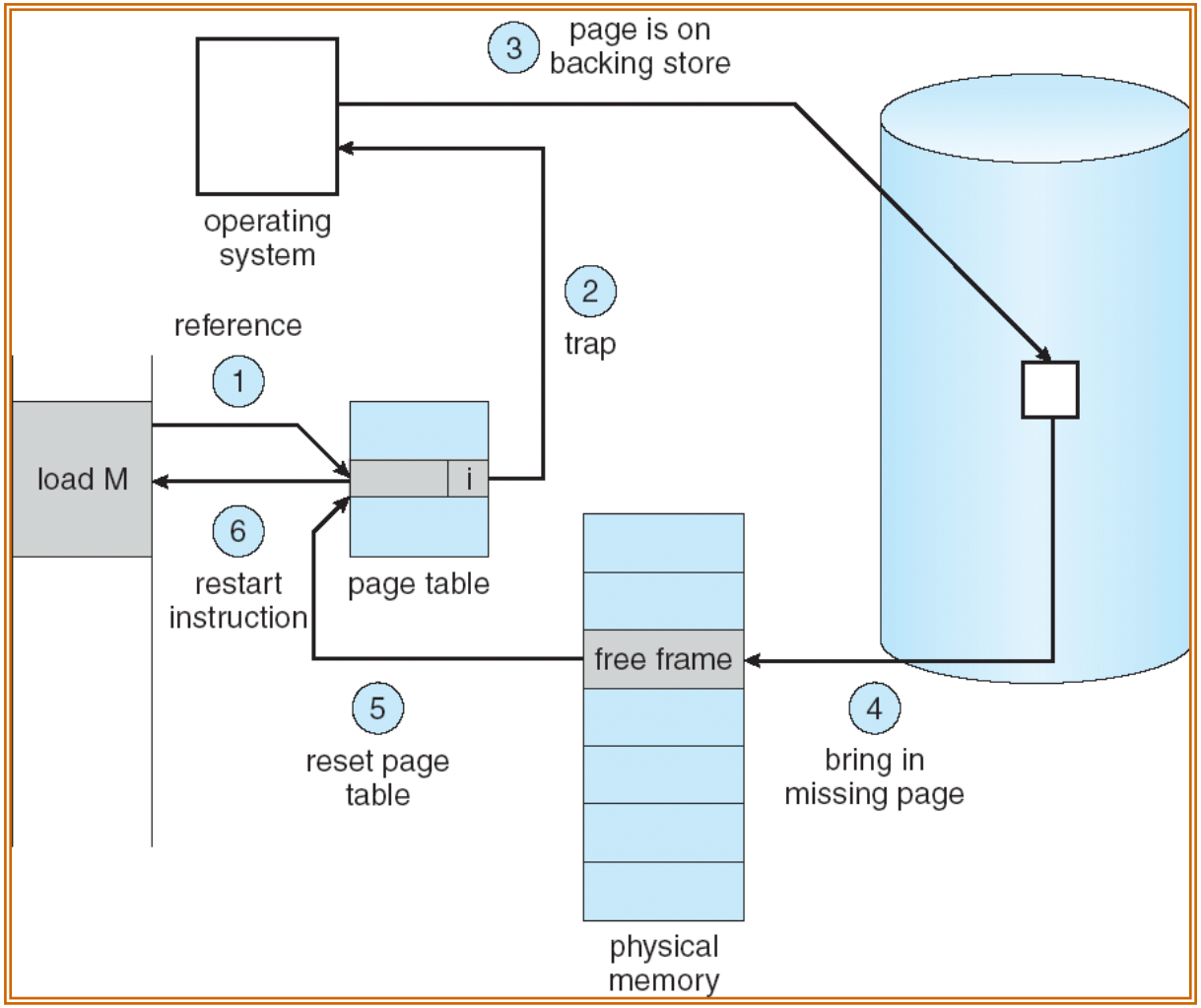
- With each page table entry a valid–invalid bit is associated
  (1 ⇒ in-memory, 0 ⇒ not-in-memory)
- Initially, valid–invalid bit is set to 0 on all entries
- During address translation, if valid–invalid bit in page table entry is 0 ⇒ page fault



Page Table When Some Pages Are Not in Main Memory



Steps of Handling a Page Fault



Detailed Procedure

1. Trap to the operating system.
2. Save the user registers and process state.
3. Determine that the interrupt was a page fault.
4. Check that the page reference was legal and determine the location of the page on the disk.
5. Issue a read from the disk to a free frame:
   a) Wait in a queue for this device until the read request is serviced.
   b) Wait for the device seek and/or latency time.
   c) Begin the transfer of the page to a free frame.
6. While waiting, allocate the CPU to some other user (CPU scheduling, optional).
7. Receive an interrupt from the disk t/0 subsystem. (I/O completed).
8. Save the registers and process state for the other user (if step 6 is executed).
9. Determine that the interrupt was from the disk.
10. Correct the page table and other tables to show that the desired page is now in memory.
11. Wait for the CPU to be allocated to this process again.
12. Restore the user registers, process state, and new page table, and then resume the interrupted instruction.

- Up to how many page faults that the following instruction can cause? Assume data and instructions are page-aligned

```
MOV       EAX, DWORD PTR [EDX]
```

- 1) The instruction itself once and 2) the access of memory location [EDX] the other one

Performance of Demand Paging

- Page Fault Rate $0 \leq p \leq 1.0$
  - if p = 0 no page faults
  - if p = 1, every reference is a fault

- Effective Access Time (EAT)

EAT = (1 – p) x memory access
+ p (page fault overhead
+ [swap page out]
+ swap page in
+ restart overhead)

Suppose that the page-fault service time is 8 ms, including disk I/O and all necessary memory access

A memory access takes 200ns (TLB hit+TLBmiss)

The page-fault ratio is p

The EAT is

(1-p)*200+p*8ms
=200+7999800p

The RHS term dominates the EAT! p should be as low as possible!!

If p=1/1000, EAT = 200+7999~8.2us, 40 times slower!!

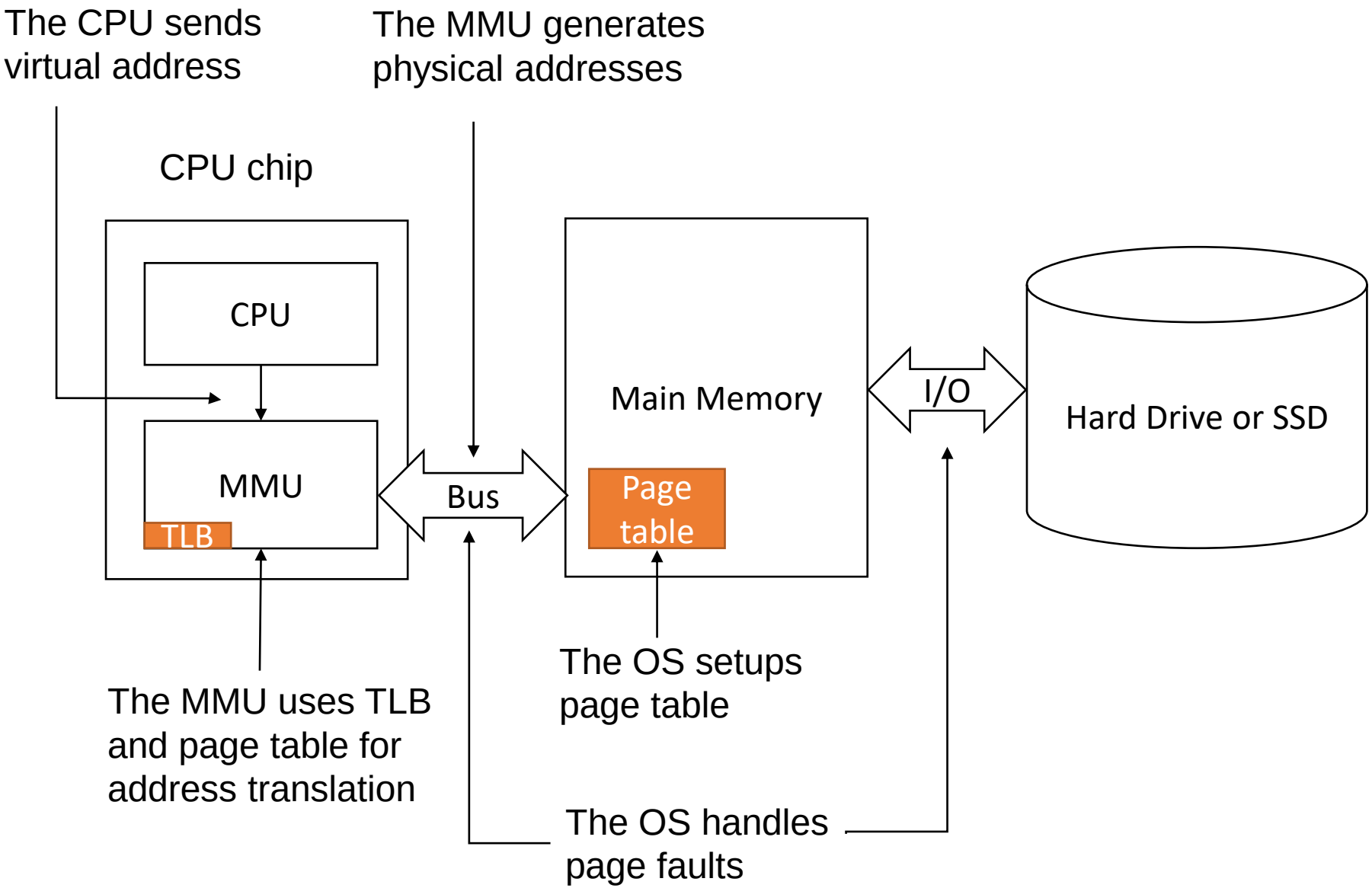
If the expected slowdown is no larger than 10% compared to 200ns, then

220>=200+7999800p
20>=7999800p
P<=0.0000025 in other words, no more than 1 page fault should happen out of 399,990 memory access.

**Consider a demand-paging system with a paging disk that has an average access and transfer time of 10 milliseconds. Addresses are translated through a page table in main memory, with an access time of 4 microsecond per memory access. Thus, each memory reference through the page table takes two accesses. To improve this time, we have added an associative memory that reduces access time to one memory reference, if the page-table entry is in the associative memory.

Assume that 87.5% of the accesses are in the associative memory and that, 20% of the remain 12.5% cause page faults. What is the effective memory access time?

- If TLB hit
  - won’t be a page fault
  - TLB access
- If TLB miss
  - If not a page fault
    - TLB access + page table access + TLB update
  - If a page fault
    - The page is not in memory
    - TLB access + page table access + page fault handling + TLB update

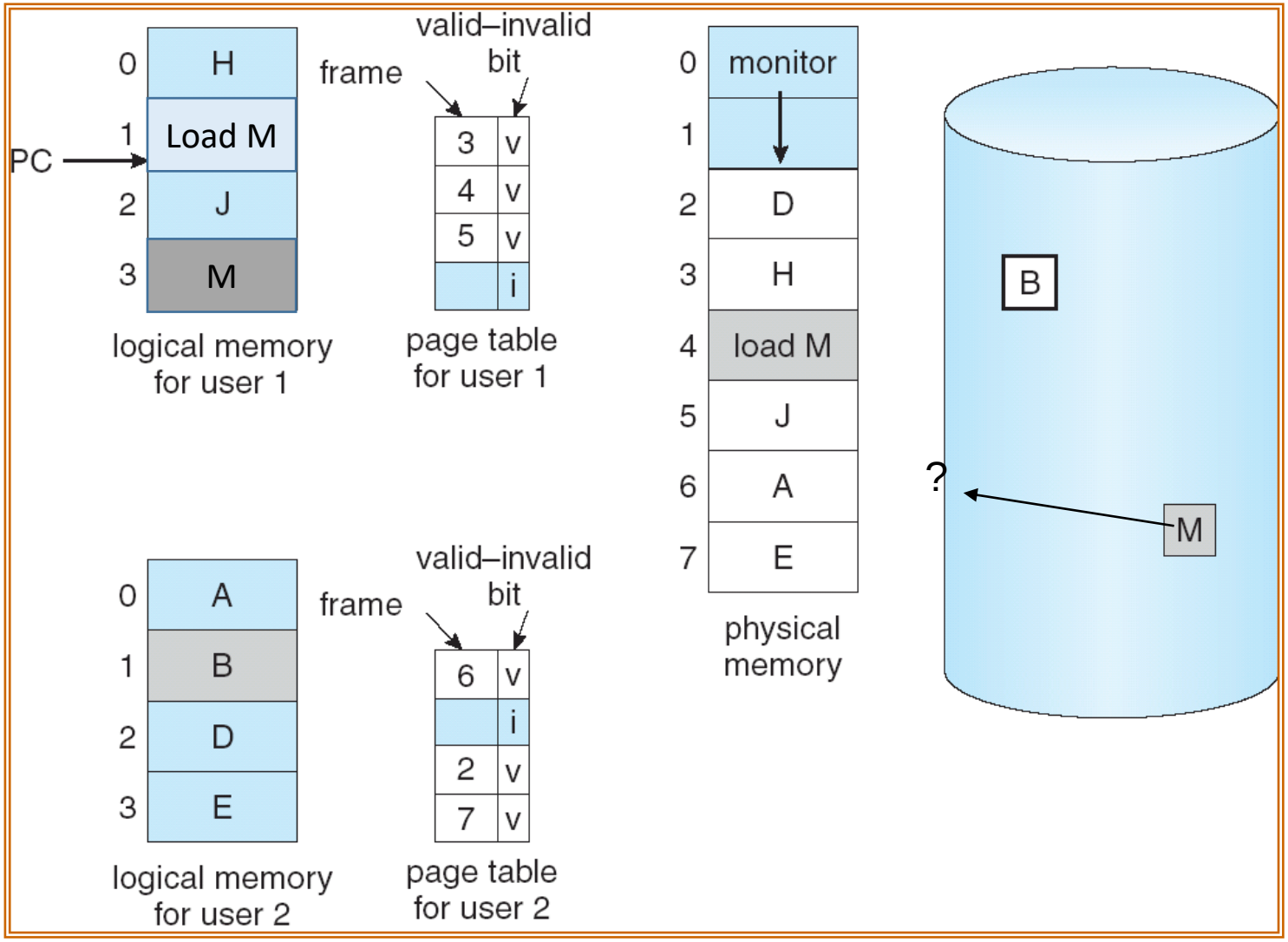

The CPU sends virtual address
The MMU generates physical addresses
CPU chip
CPU
MMU
TLB
Bus
Main Memory
Page table
I/O
Hard Drive or SSD
The MMU uses TLB and page table for address translation
The OS setups page table
The OS handles page faults

PAGE REPLACEMENT

Page Replacement

- Prevent over-allocation of memory by modifying page-fault service routine to include page replacement
- Page replacement completes separation between logical memory and physical memory – large virtual memory can be provided on a smaller physical memory

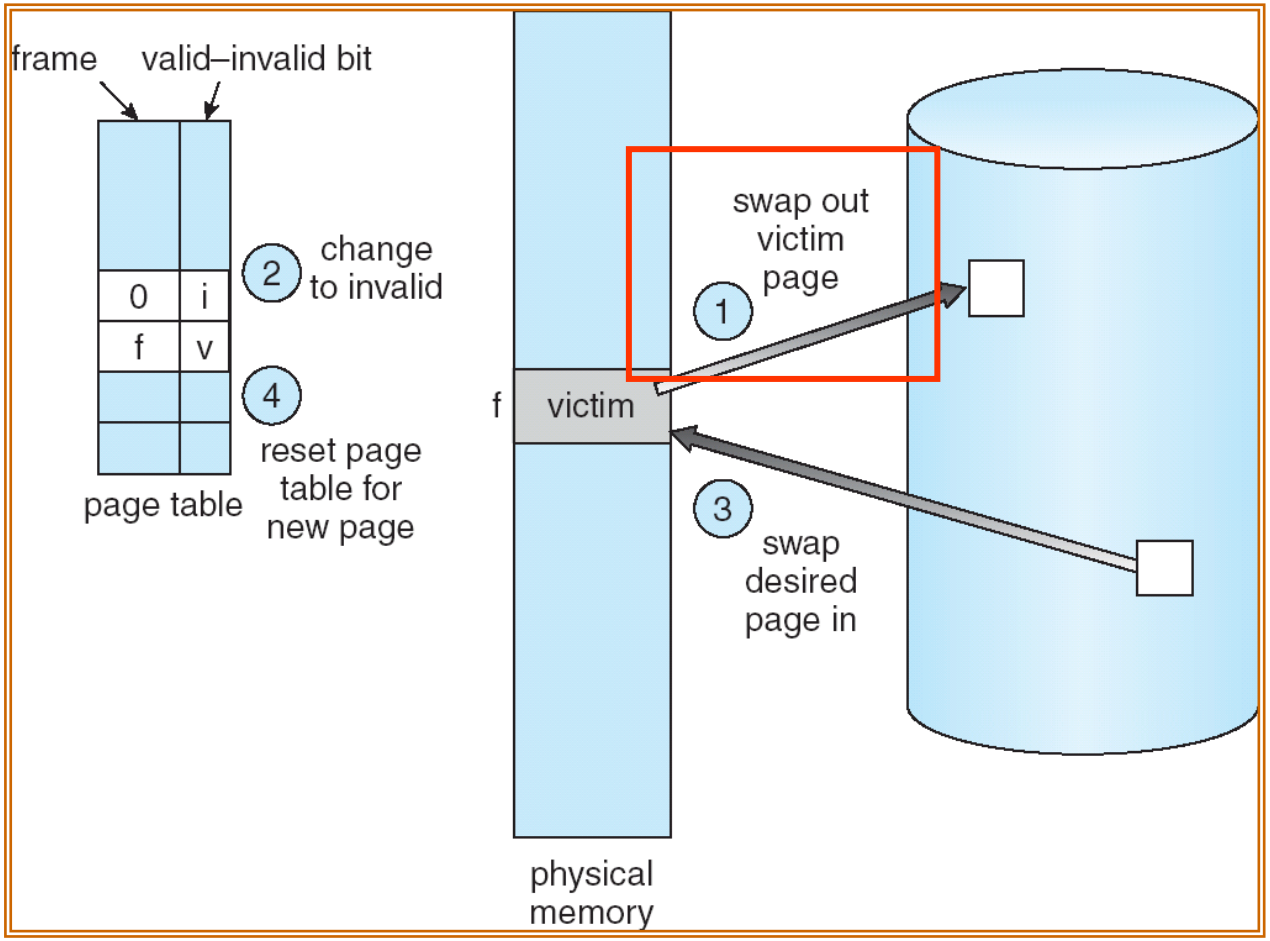
Need For Page Replacement



Basic Page Replacement

- Find the location of the desired page on disk
- Find a free frame:
  - If there is a free frame, use it
  - If there is no free frame, use a page replacement algorithm to select a victim frame
- Read the desired page into the free frame
- Update the page and frame tables
- Restart the process

Page Replacement



Page Replacement

- To replace a page, the victim page must be written back to the backing store. It may double the time of page-fault handling
- Use modify (dirty) bit to reduce overhead of page transfers – only modified pages are written to disk

Page Replacement Policy

- Replace a page that is unlikely to be used in the near future to reduce the overhead of reading a page from disk

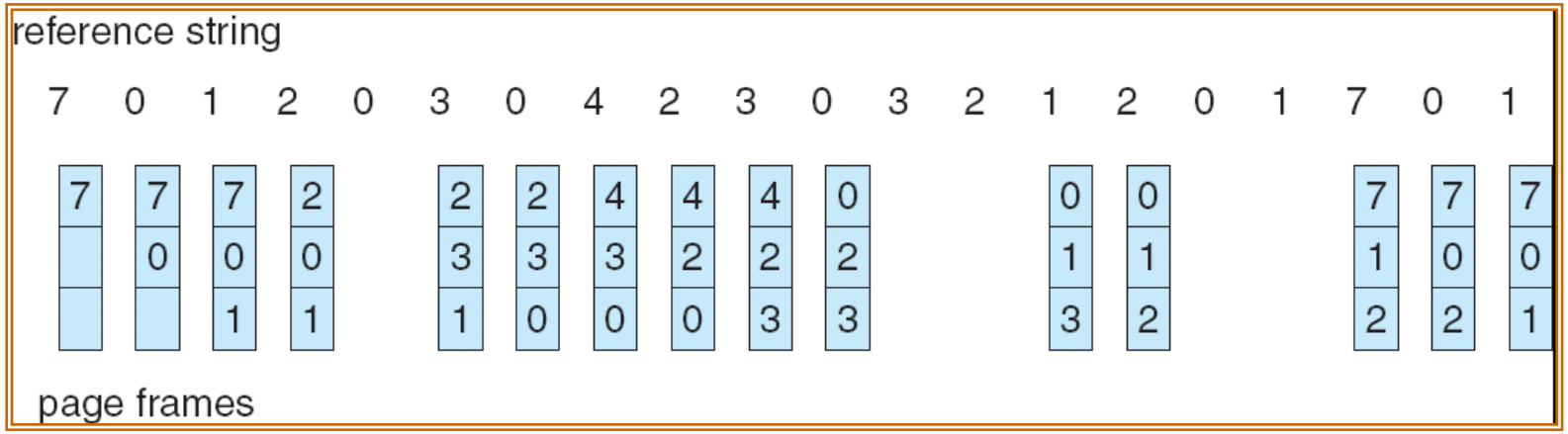
Reference string

0100, 0432, 0101, 0612, 0102, 0103, 0104, 0101, 0611, 0102, 0103,
0104, 0101, 0610, 0102, 0103, 0104, 0101, 0609, 0102, 0105

Page size=100B

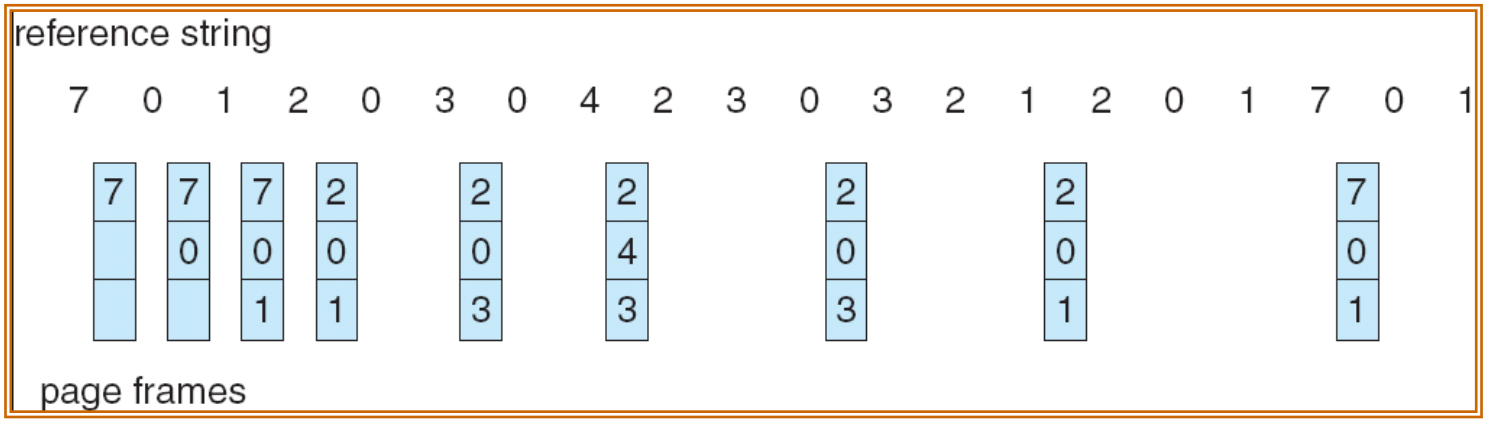
1, 4, 1, 6, 1, 6, 1, 6, 1, 6, 1

FIFO Page Replacement



15 page faults

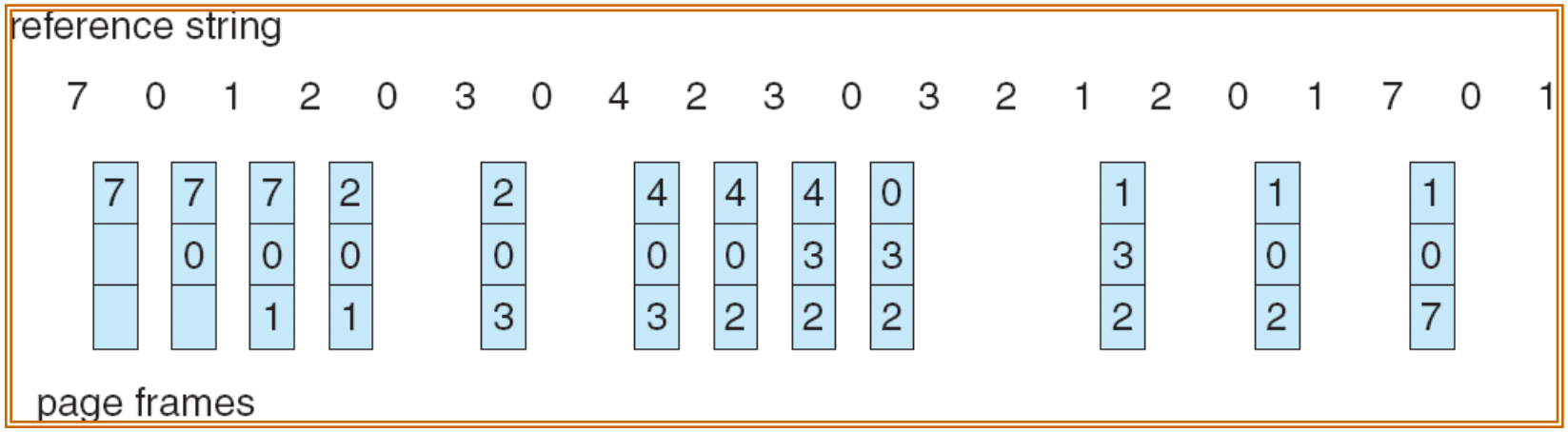
Optimal Page Replacement (OPT)



9 page faults.

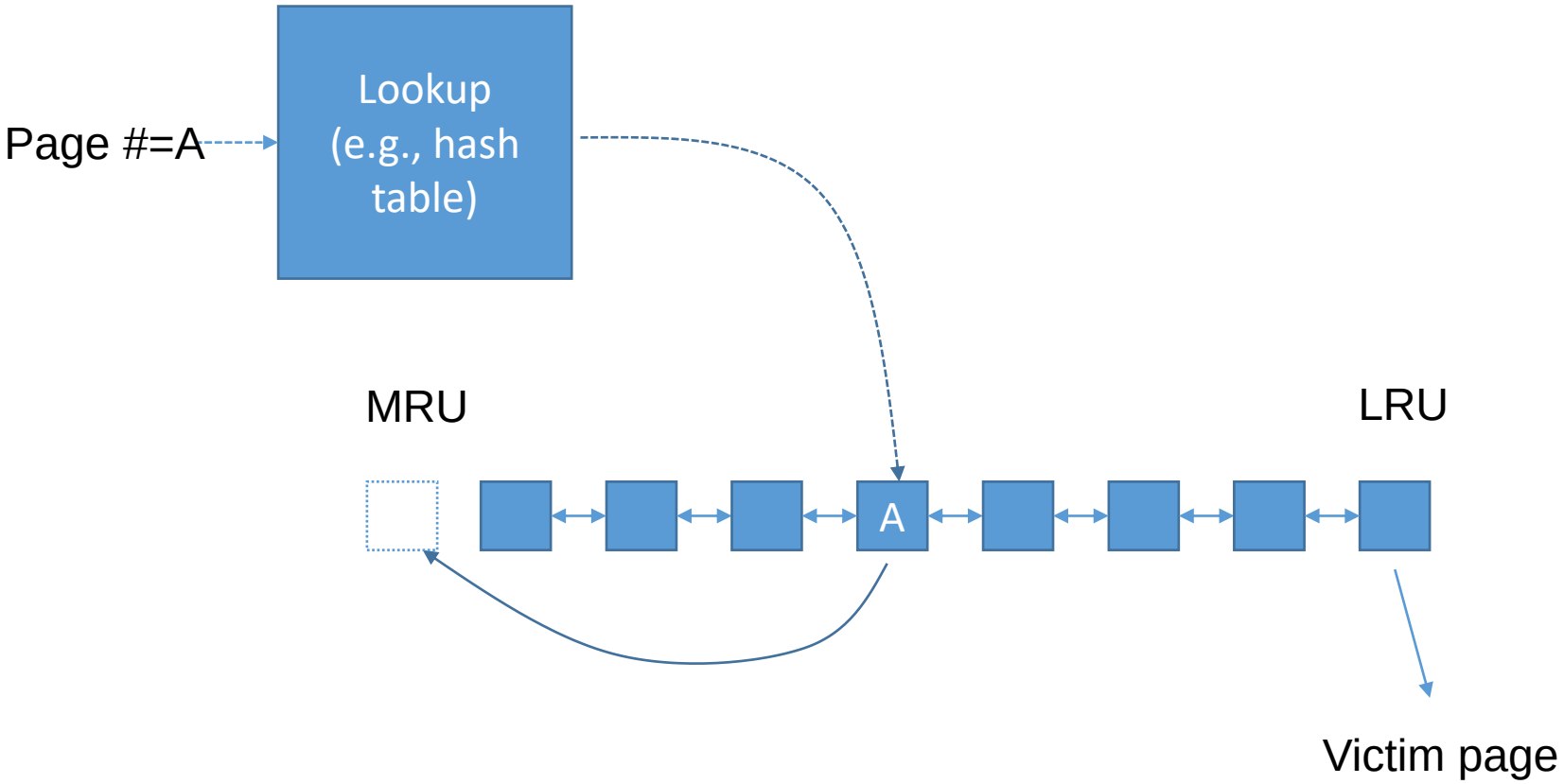
OPT is not applicable to real systems, however.

Least-Recently Used (LRU)

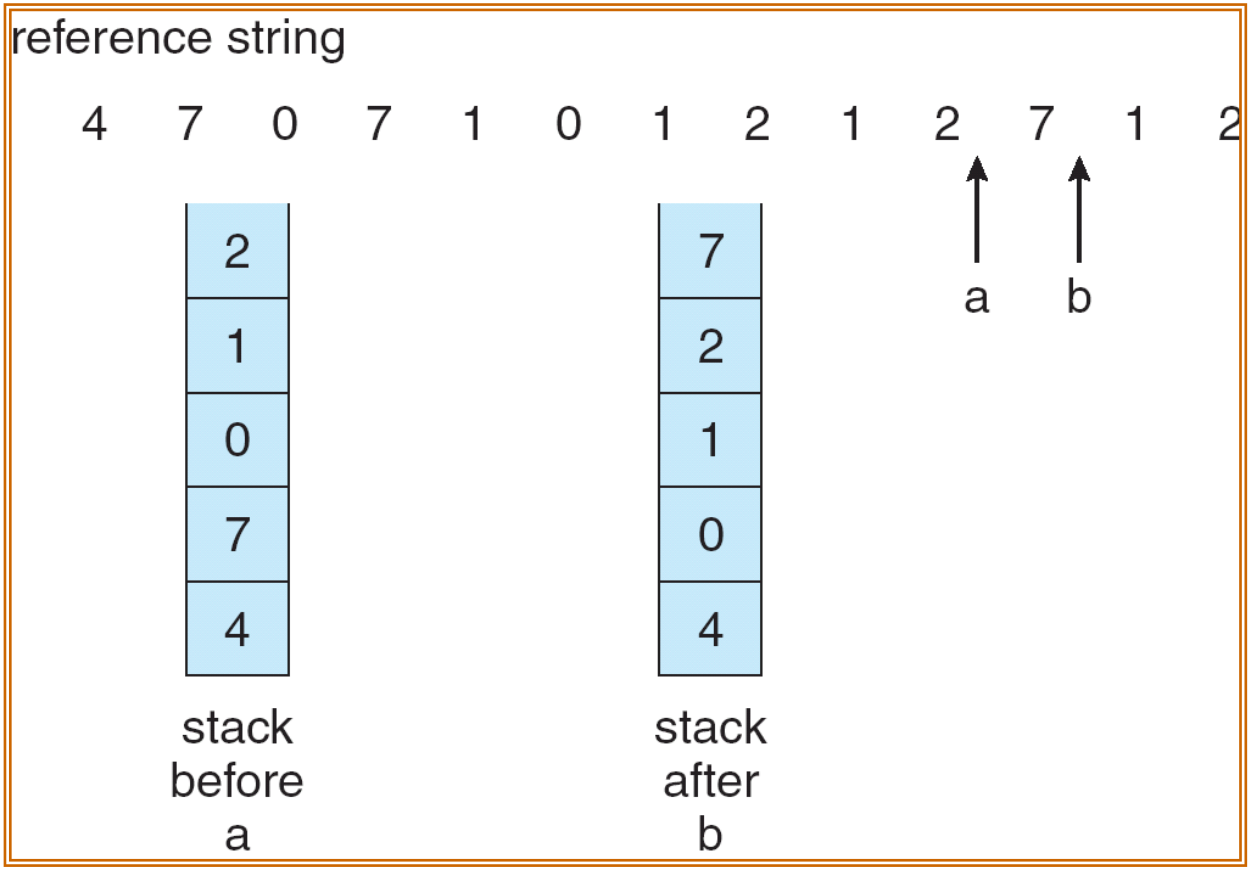


12 page faults.

An LRU Implementation



The “Stack” Property of LRU

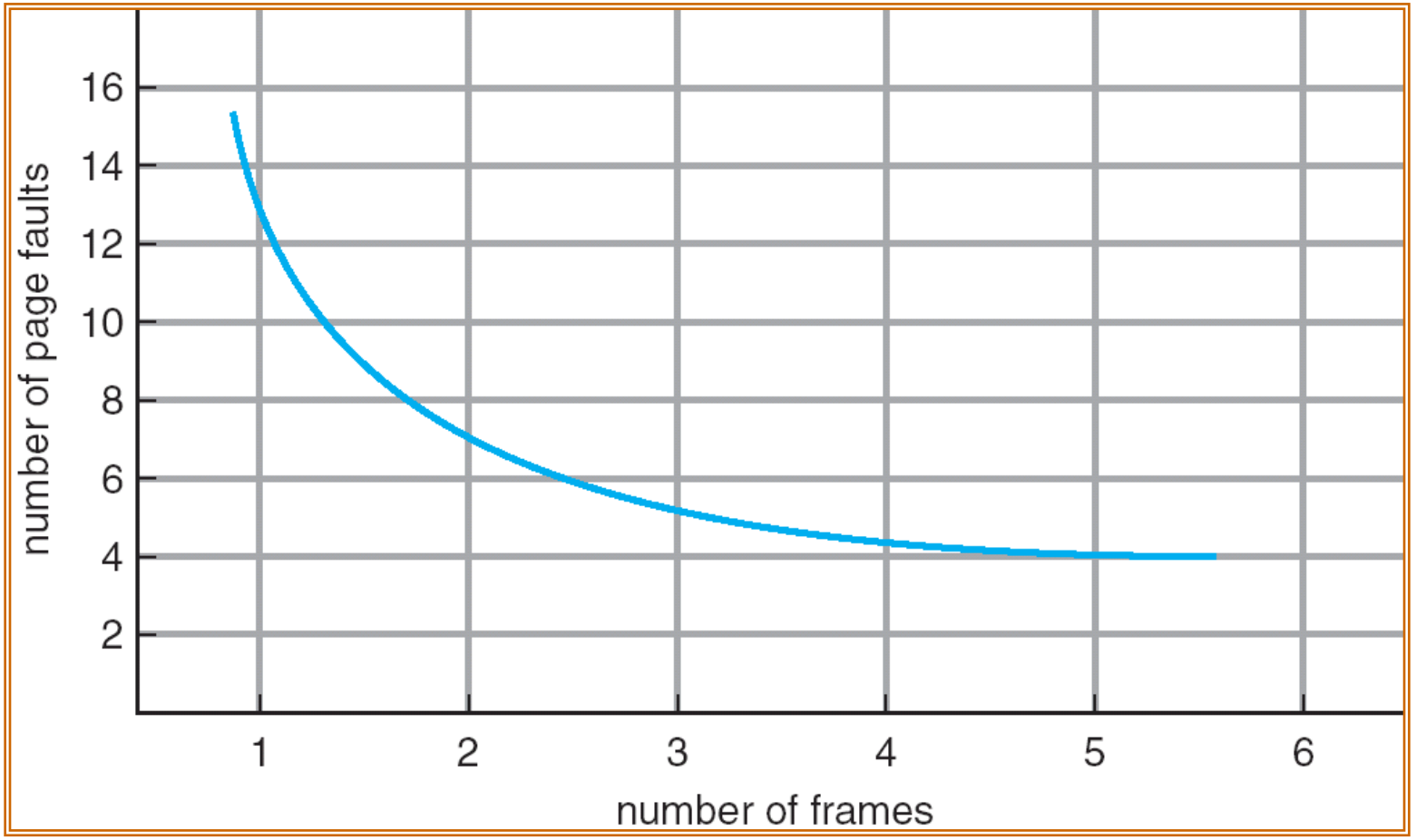


See what happens if there are four frames only.

The “Stack” Property of LRU

- The page set of LRU with K pages is a superset of that of LRU with K-1 pages; can be proved by math. induction
- This property suggests that LRU performance is always better as more frames are available
- Also useful in cache simulation. Simulating K pages get results of K, K-1, K-2….

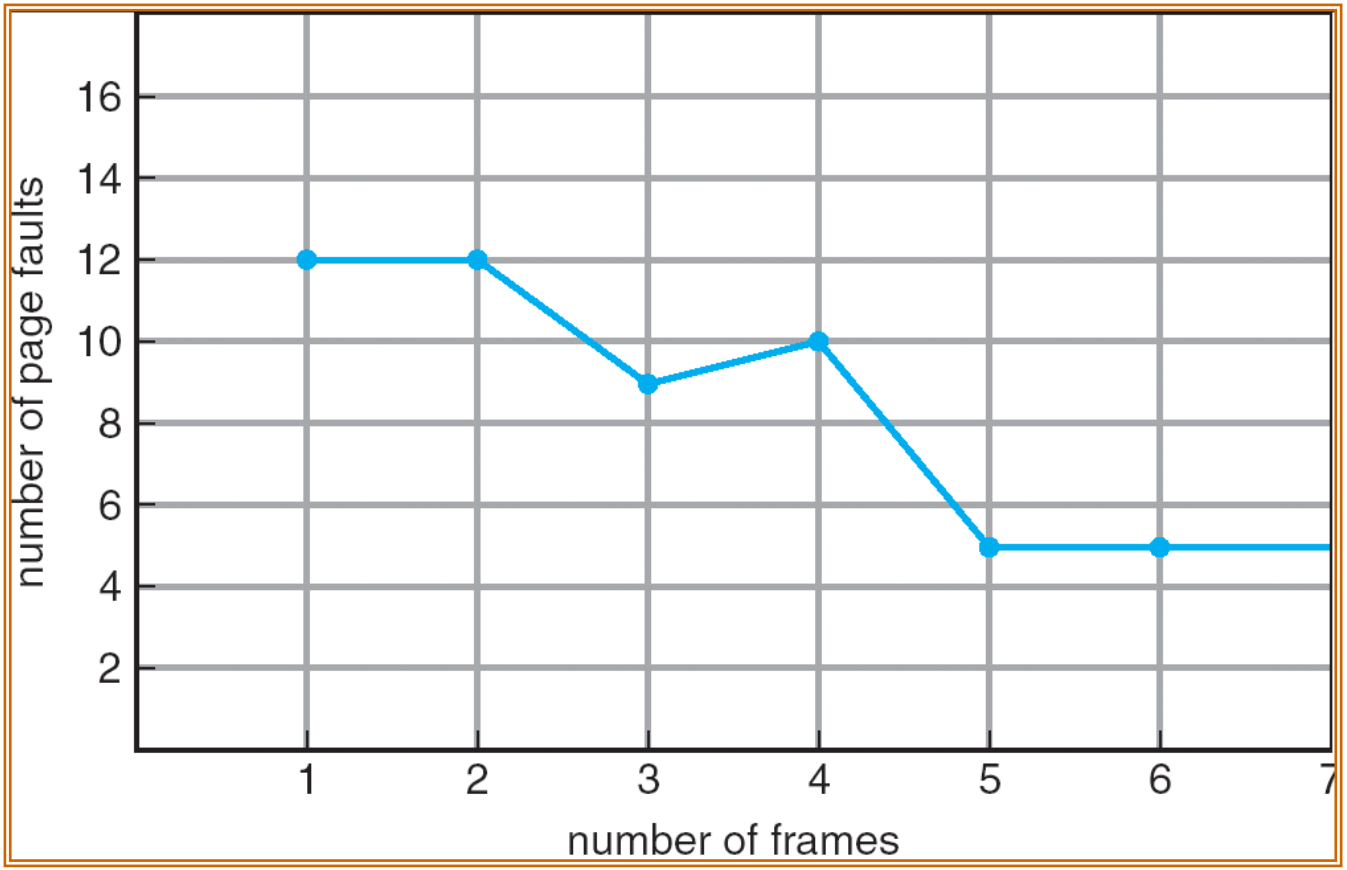
Trends of Page Fault # vs. Frame



The margin quickly saturates beyond a sweet spot
(working set/locality has been cached in memory)

Belady's Anomaly of FIFO

1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5



FIFO does not have the stack property

Adding more frames unexpectedly defragds the performance

Reproducing Belady's Anomaly

$$1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5$$

Belady's Anomaly

- FIFO suffers from Belady's anomaly
- LRU and OPT do not
- LRU and OPT are "stack algorithms", i.e., the page set with n frames is a subset of that with n+1 frames

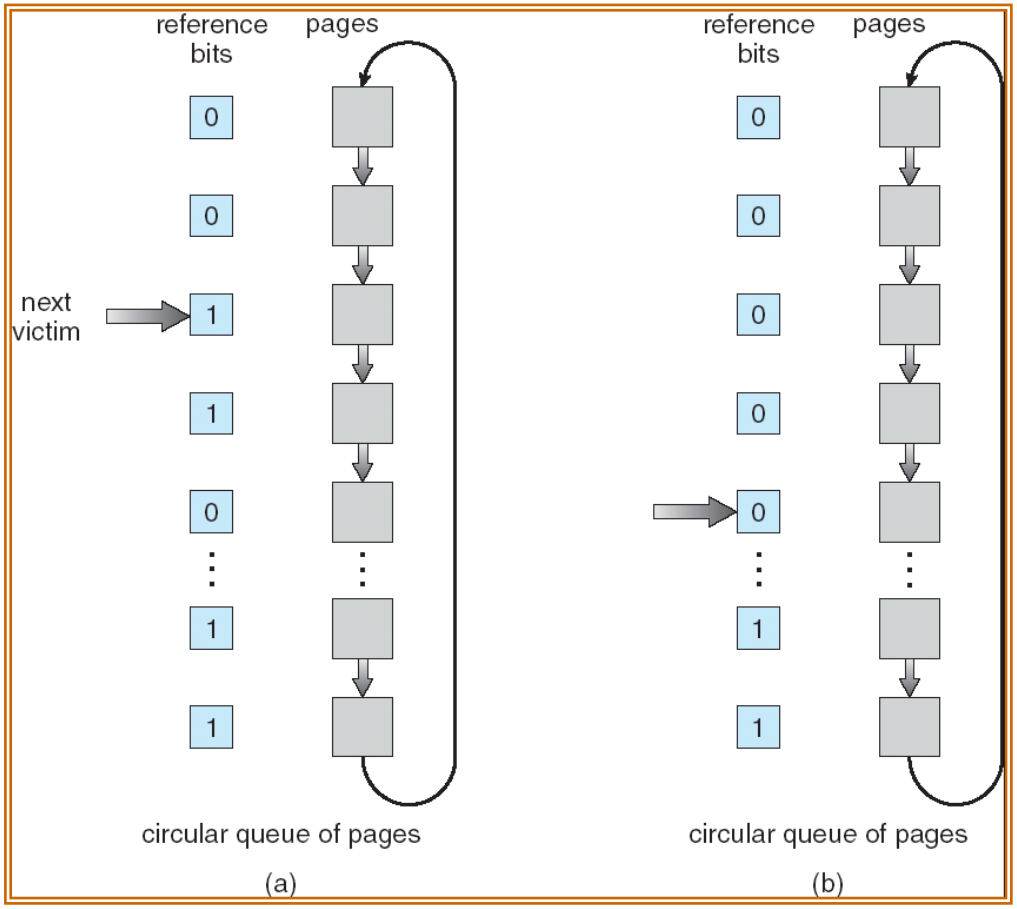
LRU Approximation Algorithms

- Efficient implementation of LRU for virtual memory management is difficult
  - Impractical to capture every load/store (page reference) and to adjust the list on every page reference
  - Hardware-assisted LRU approximation is necessary
- Reference bit
  - With each page associate a bit, initially = 0
  - When page is referenced bit set to 1
  - Replace the one which is 0 (if one exists). We do not know the order, however
- *Remark*: the "original" LRU is still a good practice to caching of I/O-based systems, e.g., file systems and databases, but not for virtual memory

LRU Approximation Algorithms

- Second chance algorithm
  - Need reference bit
  - Clock replacement
- If page to be replaced (in clock order) has reference bit = 1 then:
  - Set reference bit 0,
  - leave page in memory (i.e., give a second chance), and
  - replace next page (in clock order), subject to same rules

Second-Chance (clock) Page-Replacement Algorithm



Enhanced Second-Chance Algorithm

(ref, dirty)

1. (0, 0) neither recently used nor modified—best page to replace
2. (0, 1) not recently used but modified—not quite as good, because the page will need to be written out before replacement
3. (1, 0) recently used but clean—probably will be used again soon
4. (1, 1) recently used and modified—probably will be used again soon, and the page will be need to be written out to disk before it can be replaced

- The first page encountered at the lowest nonempty class is replaced
- This method considers to reduce I/O costs.

Counting Algorithms

- Keep a counter of the number of references that have been made to each page
- LFU (Least Frequently Used) Algorithm: replaces page with smallest count

- Once-popular pages may stay in the memory forever
  - Solution: periodically shifting of counter bits (aging)

Recency vs. Frequency

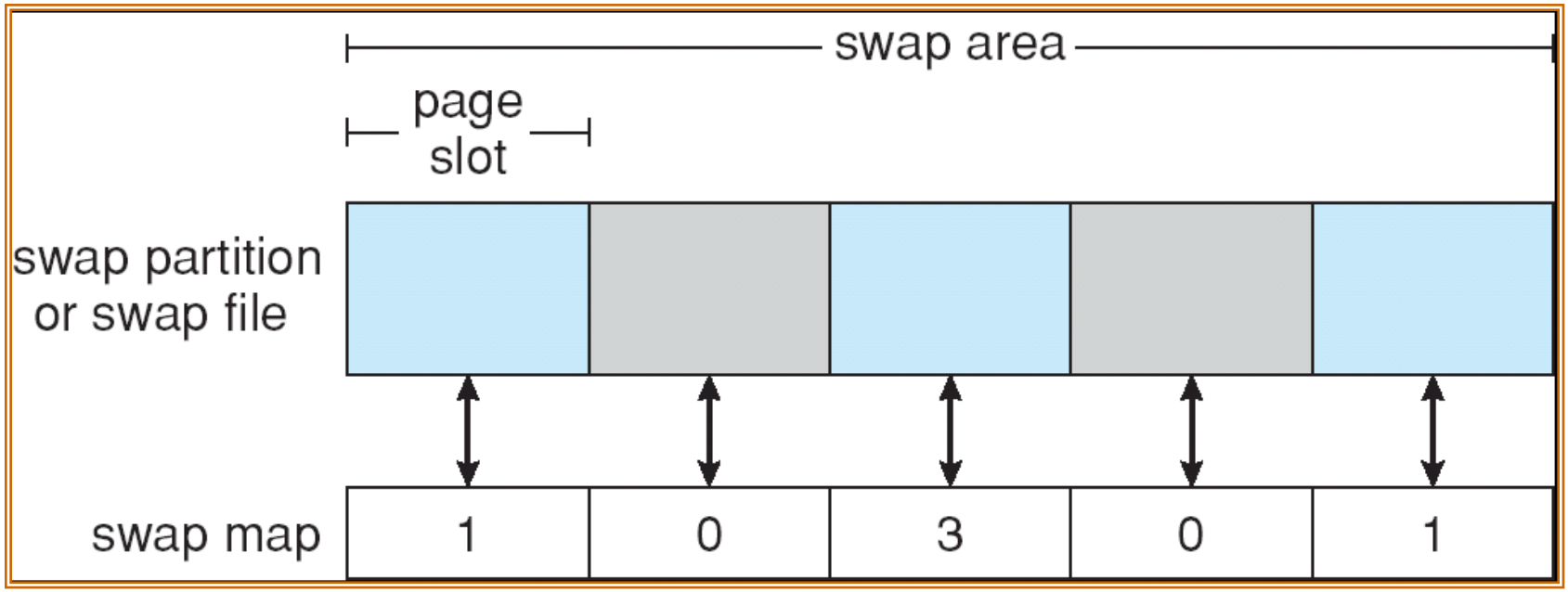
- LRU
  - Replace the least recently used page
  - Fast response to locality change
  - Sequential reference will wash away all cached pages
- LFU
  - Replace the least frequently used page
  - Resistant to sequential reference
  - Need time to warm up and cool down a page

Swap Space Management

Swap-Space Management

- Swap-space — Virtual memory uses disk space as an extension of main memory
- Swap-space can be carved out of the normal file system (Windows/Linux) or can be in a separate disk partition (Linux)
- Swap-space management
  - Kernel uses swap maps to track swap-space use
  - 4.3BSD allocates swap space when process starts; holds text segment (the program) and data segment
  - Solaris 2 allocates swap space only when a page is forced out of physical memory, not when the virtual memory page is first created

The Data Structures for Swapping on Linux Systems



Why there are entries > 1?

OS Features Based on Demand Paging

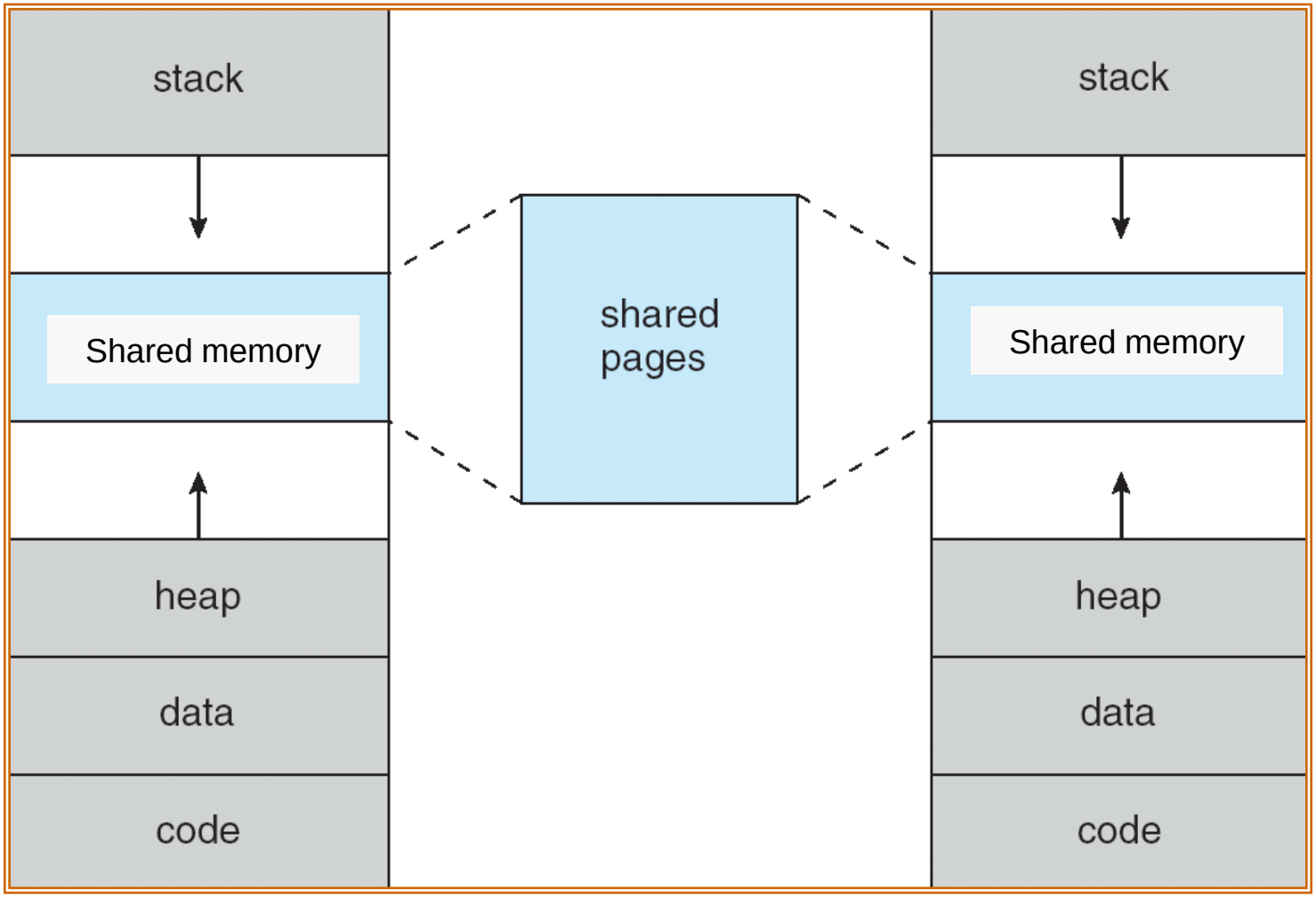
OS Features Based on Demand Paging

- Page Sharing
  - Two processes share a memory region
  - Shared memory can be mapped to a file
- Copy-on-write
  - A fast implementation of memory duplication between processes, e.g., fast fork()
  - Pages are shared until being modified
- Memory-mapped file
  - Memory region backed by a regular file, not the swap space

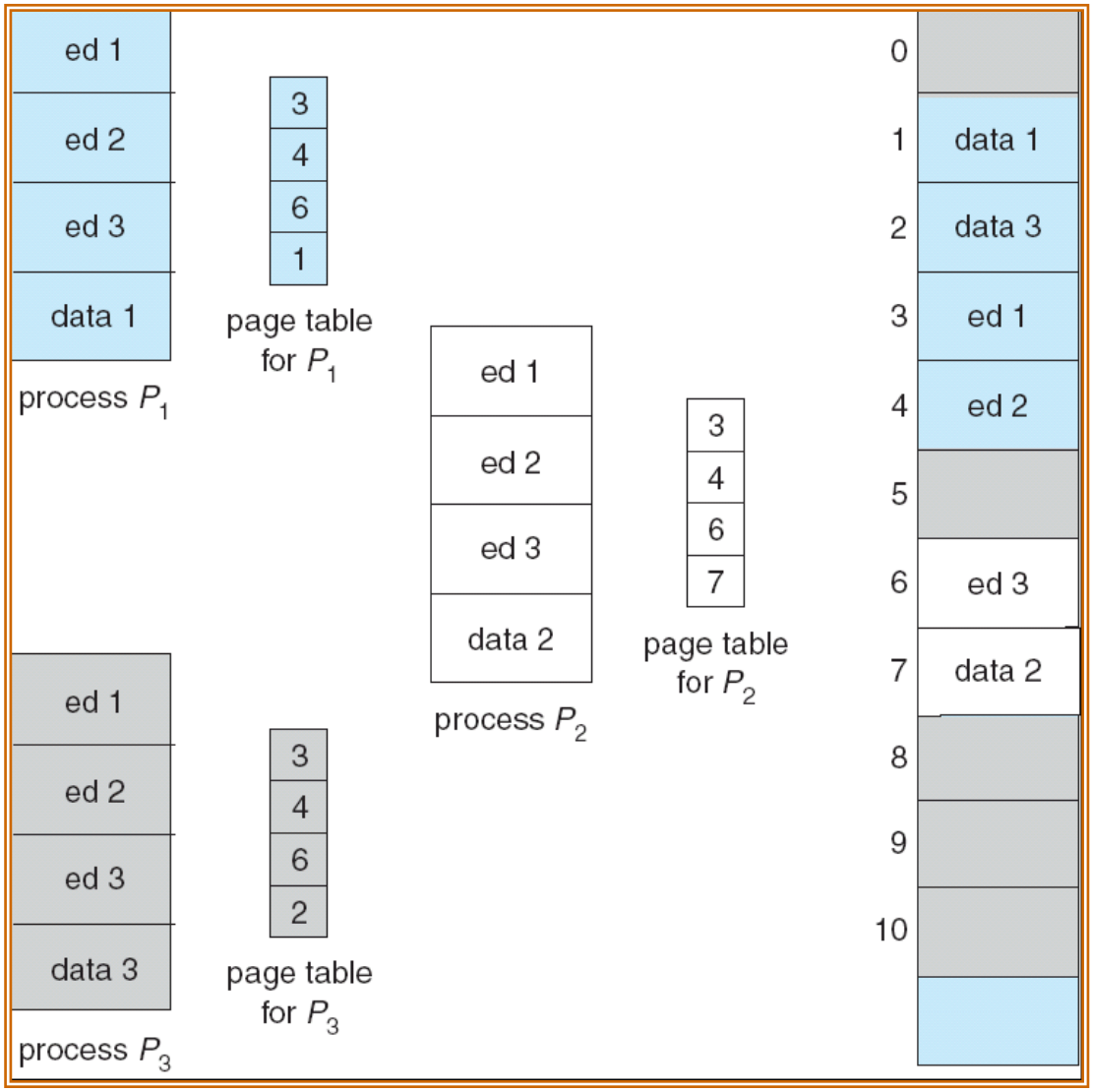
Page sharing

- Shared code
  - Dynamic linking-loading libraries (e.g., libc)
  - Kernel code
  - Handled by OS
- Shared memory
  - Creating a piece of shared memory: shmget()
  - Mapping a piece of shared memory to process address space: shmat()

Shared Memory

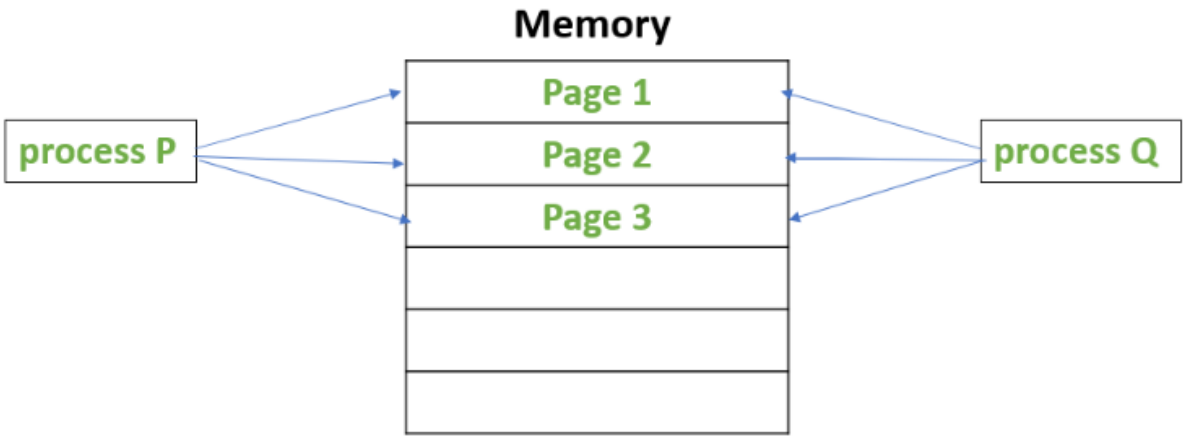


Shared Code

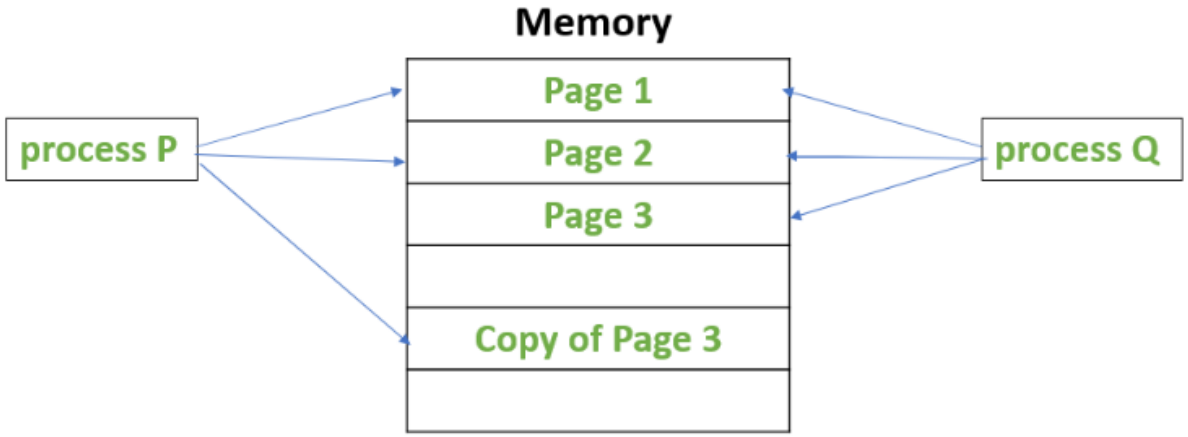

ed 1
ed 2
ed 3
data 1
process P_1
3
4
6
1
page table for P_1
ed 1
ed 2
ed 3
data 2
process P_2
3
4
6
7
page table for P_2
ed 1
ed 2
ed 3
data 3
process P_3
3
4
6
2
page table for P_3
0
1
data 1
2
data 3
3
ed 1
4
ed 2
5
6
ed 3
7
data 2
8
9
10

Copy-on-Write

- An extension to shared page; for fast duplication of memory
- Copy-on-Write (COW) allows both parent and child processes to initially share the same pages in memory
  - If either process modifies a shared page, a copy of the page is then created
- A RO/RW bit for each page is necessary to trap writes to shared page; write to the page cause an exception/trap
- COW allows more efficient process creation as only modified pages are copied



Before process P modifies Page 3



After process P modifies Page 3

https://www.geeksforgeeks.org/copy-on-write/

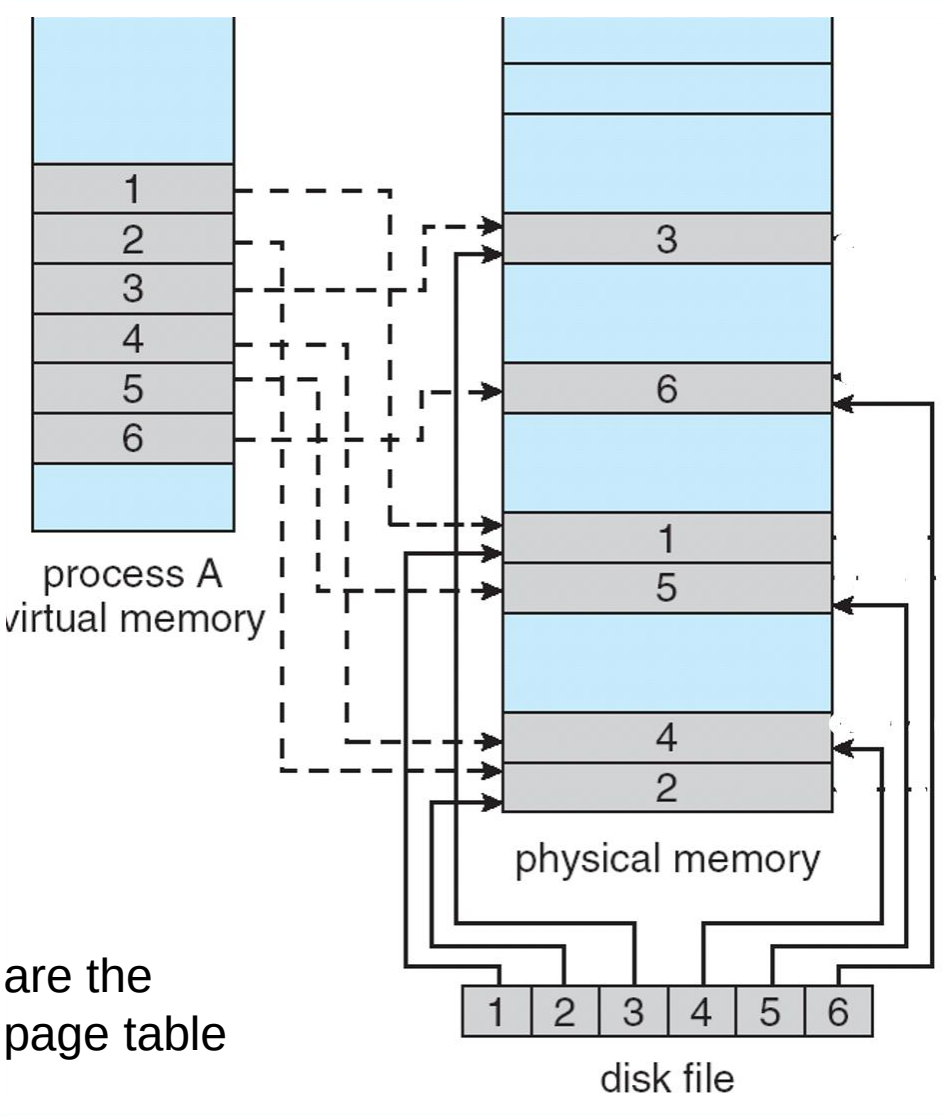
fork() and COW

- fork() uses copy-on-write
- vfork() does not use copy-on-write. It suspends the parent process and let the child process use the memory pages of the parent
  - The child uses on top of the parent's stack
  - The child is supposed to call exec() immediately
  - Child's leftovers on the stack is cleaned up upon exec()
- vfork() is for CPUs without a MMU. Otherwise, fork() with COW is efficient enough

Memory-Mapped Files

- A segment of virtual memory that is linearly mapped to a disk file
- Reading the memory segment triggers page faults, which brings a page-sized portion of the file through demand paging
- Writing the memory regions makes pages dirty; dirty pages are flushed to disk file in background or explicitly

Memory Mapped Files



The dotted lines are the mappings of the page table

Memory-Mapped Files

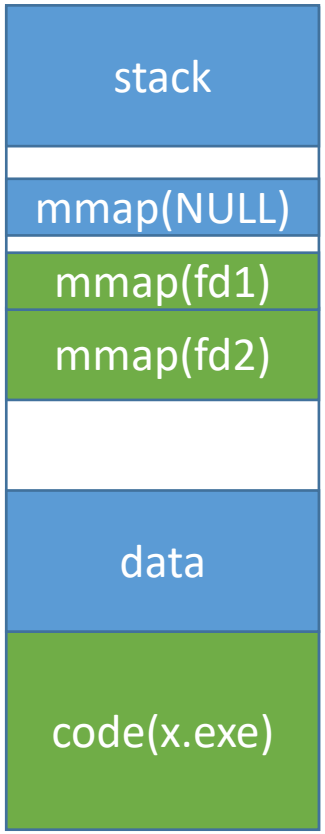
- Available to user program through the mmap() system call
- Simplifies file access by treating file I/O through memory rather than read() write() system calls
  - Simple byte-level memory reference
  - No need to enter the kernel
- If the mapped file is null, pages go to the swap space
  - mmap(…, -1, …) as you did in the programming assignment

Shared Memory by mmap()

- POSIX shared memory through mmap()
  - Similar but different from System V shmget()&shmat()
- mmap(fd)
  - fd can be a regular file (I/O involved)
  - fd can also be a temporary object (under /dev/shm), no actual I/O involved, created through shm_open()
  - Common for SHM between independent processes, open by object name
- mmap(-1)
  - Common for parent-child IPC

Mapping of Pages: File and Anonymous

- Anonymous pages belong to memory segments of processes, such as data, stack, and mmap(null) regions
- File pages belong to memory regions that are mapped to a (named) file
- Anonymous pages are backed by the swap device; file pages are backed by files
- They share the same mechanism for paging in and paging out but with different swap-out destinations



- For pages associated with the following memory regions, what are their page type?

- Memory of executable binary
- Process stacks
- Process heaps
- Memory created by mmap(fd), fd is regular file
- Memory created by mmap(fd=-1)

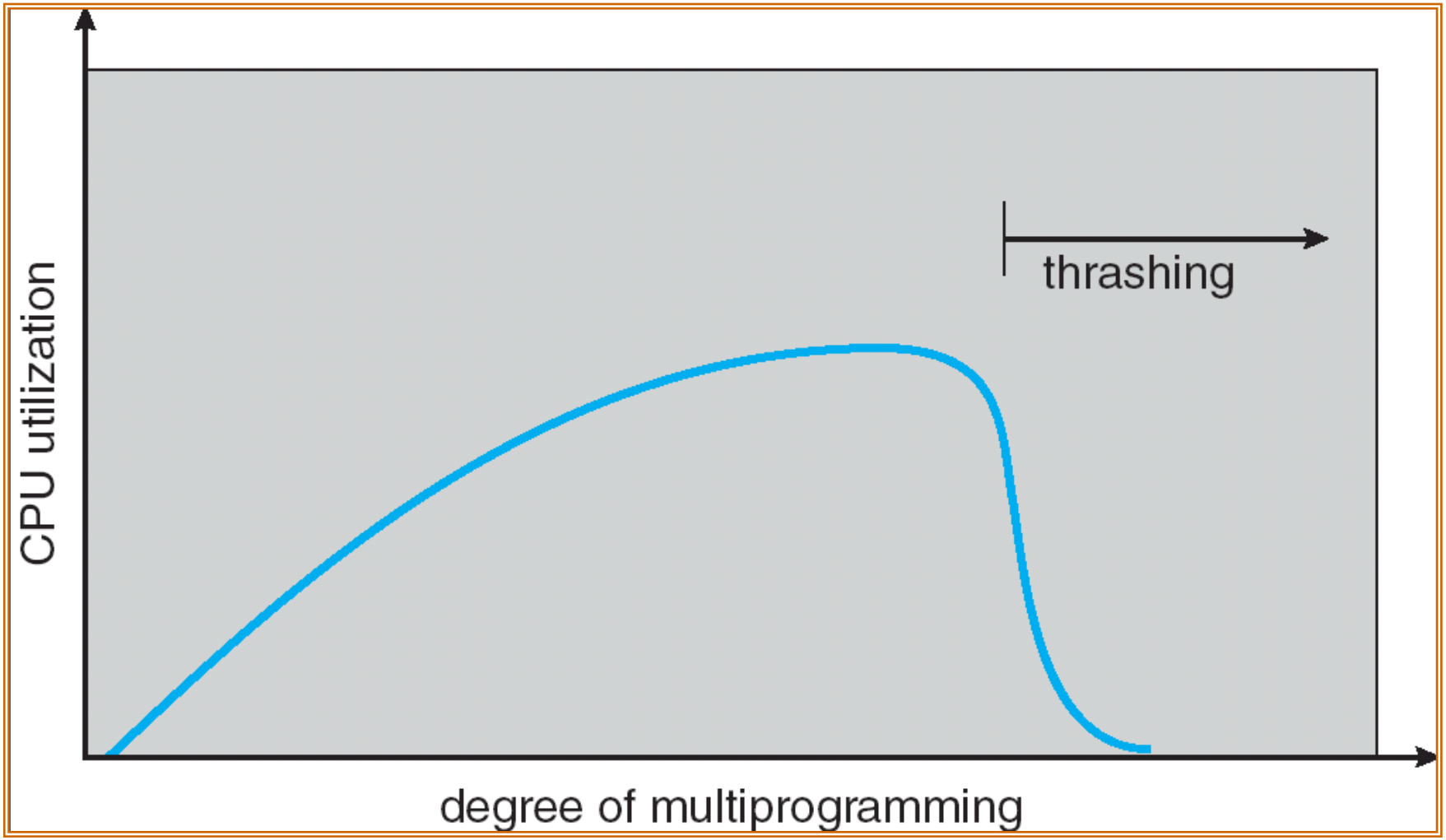
PERFORMANCE ISSUES

Thrashing

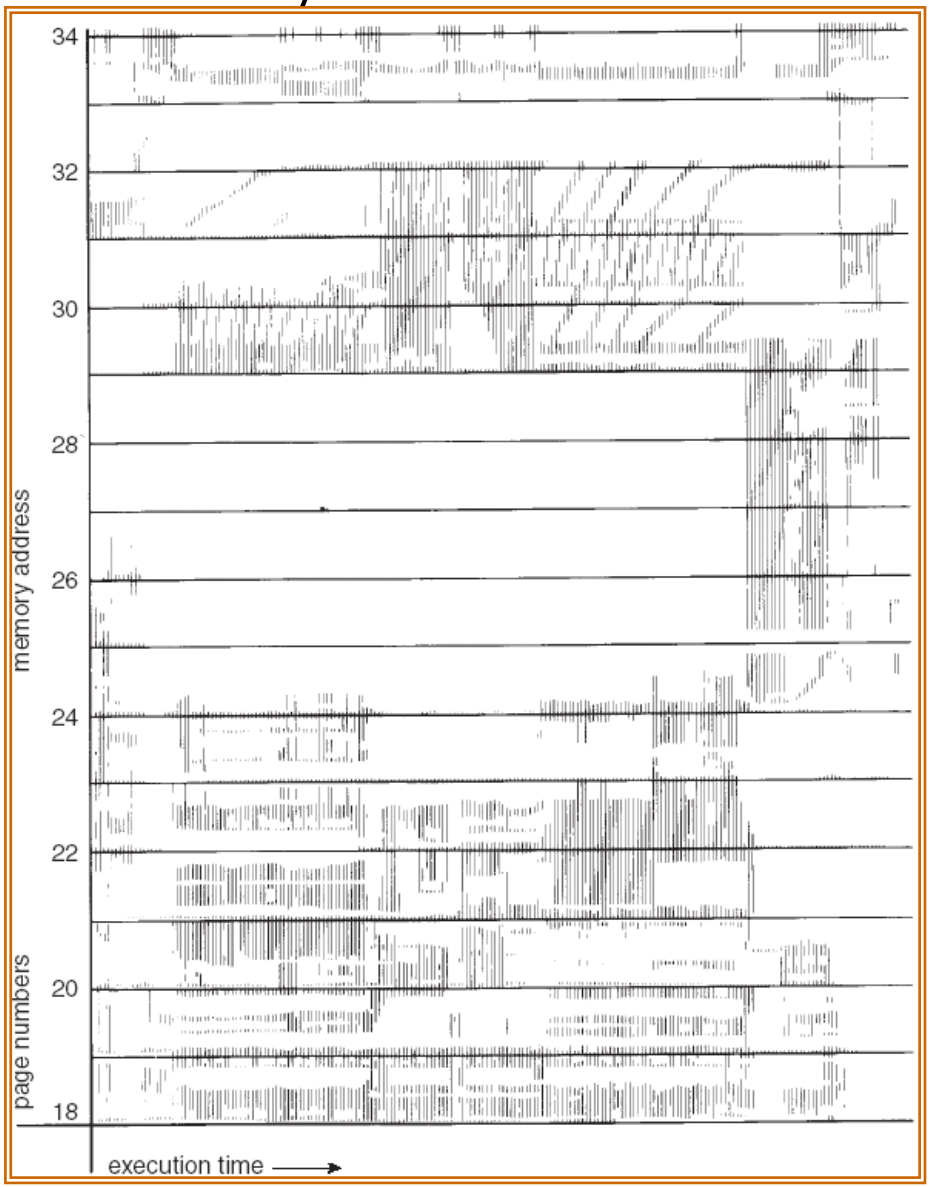
- If a process does not have “enough” pages, the page-fault rate will be very high. This leads to:
  - a low CPU utilization
  - operating system thinks that it needs to increase the degree of multiprogramming
  - another process is added to the system

- Thrashing ≡ a state that the kernel is busy swapping pages in and out

Thrashing (Cont.)



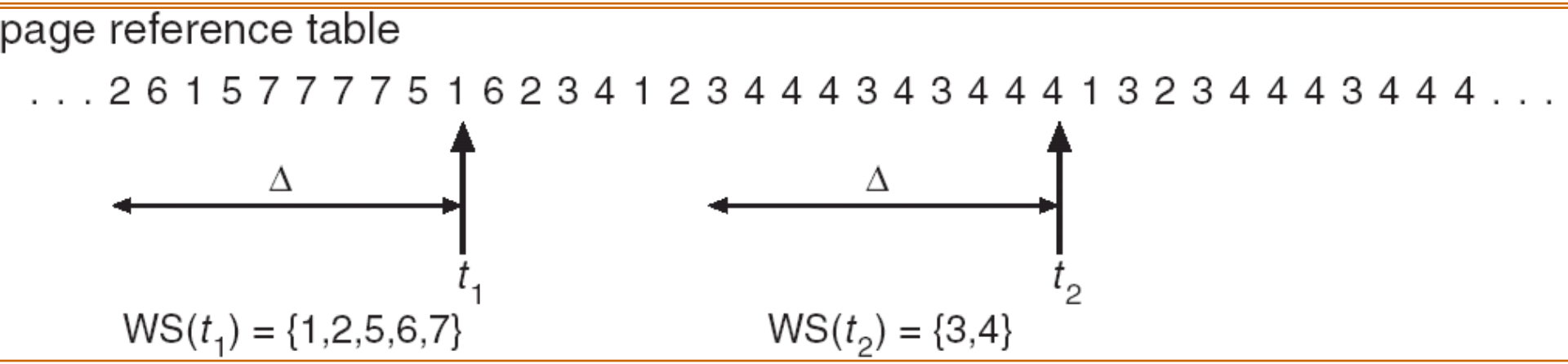
Locality In A Memory-Reference Pattern



Working-Set Model

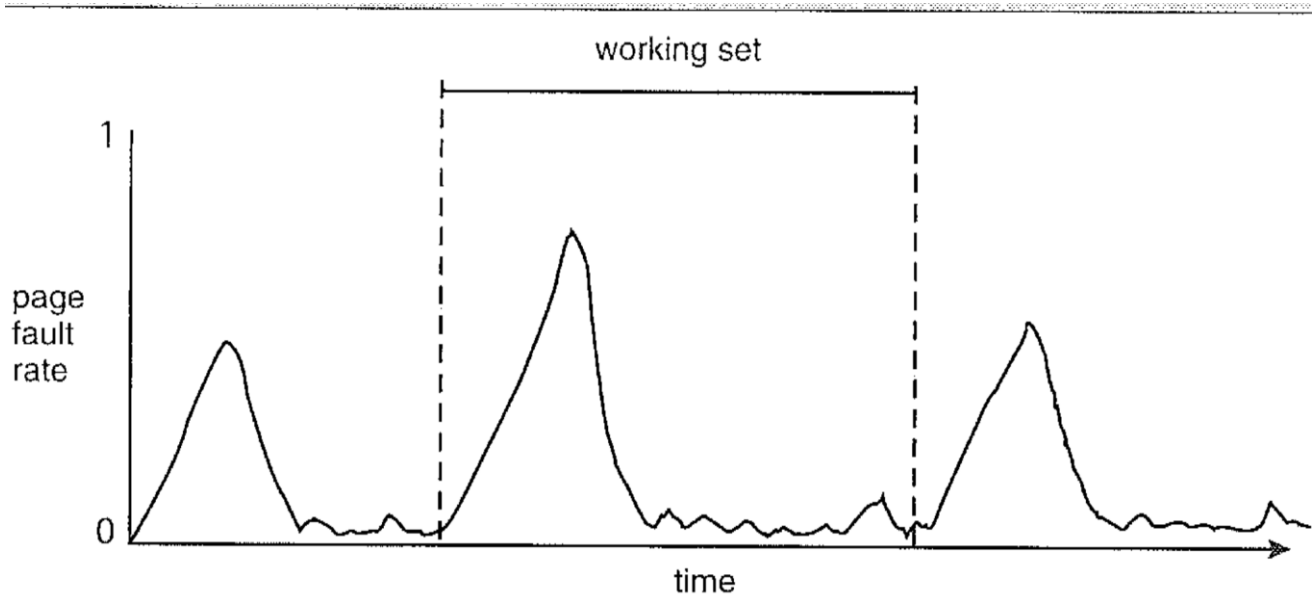
- $\Delta \equiv$ working-set window $\equiv$ a fixed number of page references. Example: 10,000 references
- WSSi (working set of Process Pi) = a set of pages referenced in the most recent Δ
  - if Δ too small will not encompass the entire locality
  - if Δ too large will unnecessarily encompass old localities
- D = Σ WSSi $\equiv$ total demand frames; m is the total number of frames
- if D > m $\Rightarrow$ Thrashing

Working-set model



Remark: Migration of Working Sets

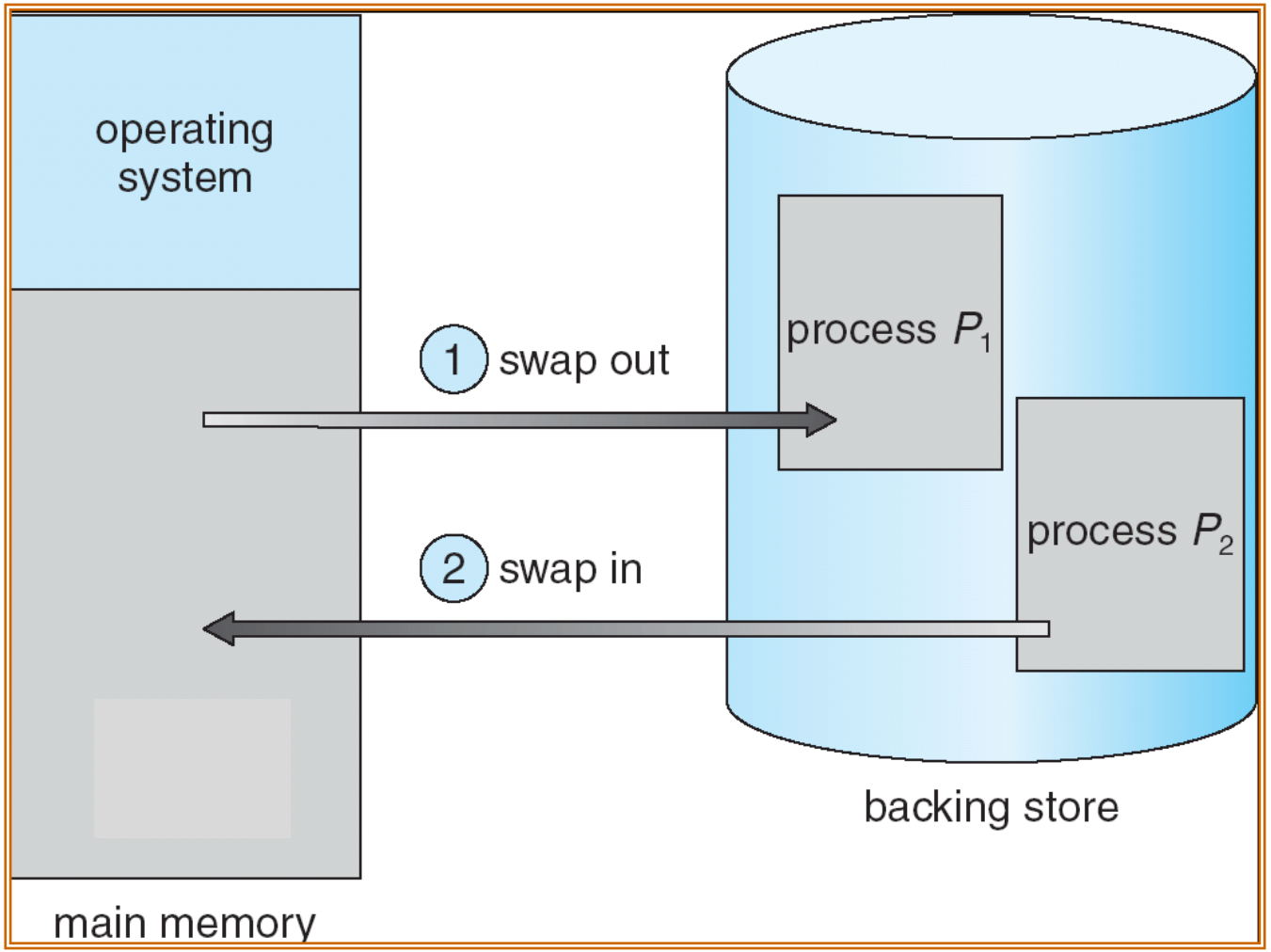
- Working set is a time-variant, when a process migrates from a working set to another, the page fault rate also increases (but not thrashing)



Thrashing Management

- Swapper
  - AKA Midterm scheduler; process-based swapping
  - A process can be swapped temporarily out of memory to a backing store, and then brought back into memory for continued execution
  - Memory of a swapped-out process are released; useful to thrashing management

Schematic View of Process Swapping



Thrashing Management

- Modern UNIX OSes, however, do not implement process swapping and use finer-granularity page swapping instead
- The kernel cannot reclaim free pages quickly enough when the system is under thrashing
- Process termination: Linux uses Out-of-Memory (OOM) Killer as the last resort

Background Dirty Page Flushing

- Reclaiming a clean page is very fast (just discard it), but reclaiming a dirty page involves a slow I/O (page write back)
- The OS flushes dirty pages in background
  - Making dirty pages clean
  - Removing page writing-back from the critical path
- Related Linux kernel threads
  - Flush threads: flush dirty pages to storage devices (pdflush vs. bdi_writeback)
  - Kswapd (background) & DirectReclaim (blocking): scans and reclaims memory pages

Pre-paging (Pre-fetching)

- On a page fault, read multiple pages ahead to exploit spatial locality
- Pros 1: Less disk head movement
  - Sequential disk access is highly efficient
- Pros 2: Fewer page faults
  - 1 big I/O for many small I/Os
  - 128 KB=32 pages in Linux
- Cons: If pre-prtched pages are not used, I/Os and memory are wasted

Program Structure

- Program structure
  - Int[128,128] data;
  - Each row is stored in one page
  - Program 1

```
for (j = 0; j <128; j++)
    for (i = 0; i < 128; i++)
        data[i,j] = 0;
```

128 x 128 = 16,384 page faults

  - Program 2

```
for (i = 0; i < 128; i++)
    for (j = 0; j < 128; j++)
        data[i,j] = 0;
```

128 page faults

Page size=128 integers

Suppose that we have < 128 frames…

TLB Reach & Large Pages

- TLB Reach = (TLB Size) X (Page Size)
  - The amount of memory accessible without page table lookup
- Ideally, the working set of each process is stored in the TLB. Otherwise there is a high degree of TLB miss
- Solution 1: increase the TLB size
  - Less practical: too expensive
- Solution 2: Increase the Page Size
  - May have negative performance impacts: internal fragmentation, more I/O traffic, etc.
- Provide Multiple Page Sizes
  - For a good balance between I/O traffic volume and TLB hit ratio
  - IA-64 supports 4 KB and 4 MB pages

Page Size Tradeoff

- Large pages
  - Small page table (good)
  - Large TLB reach (good)
  - May bring unused data into memory (bad)
- Small pages
  - Large page table (bad)
  - Small TLB reach (bad)
  - Less unused data in memory (good)

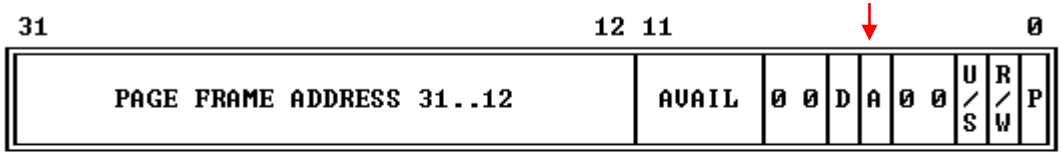
Operating System Examples

Status Bits Associated with a Page (x86)

- Valid (Present) bit: does the page present in main memory?
- RW bit: is the page read-only or read-write?
- Reference bit: is the page referenced?
- Dirty bit: is a page modified?

Figure 5-10. Format of a Page Table Entry

A: referenced



P - PRESENT
R/W - READ/WRITE
U/S - USER/SUPERVISOR
D - DIRTY
AVAIL - AVAILABLE FOR SYSTEMS PROGRAMMER USE

NOTE: 0 INDICATES INTEL RESERVED. DO NOT DEFINE.

https://pdos.csail.mit.edu/6.828/2007/readings/i386/s05_02.htm#fig5-10

Linux Page Reclaiming

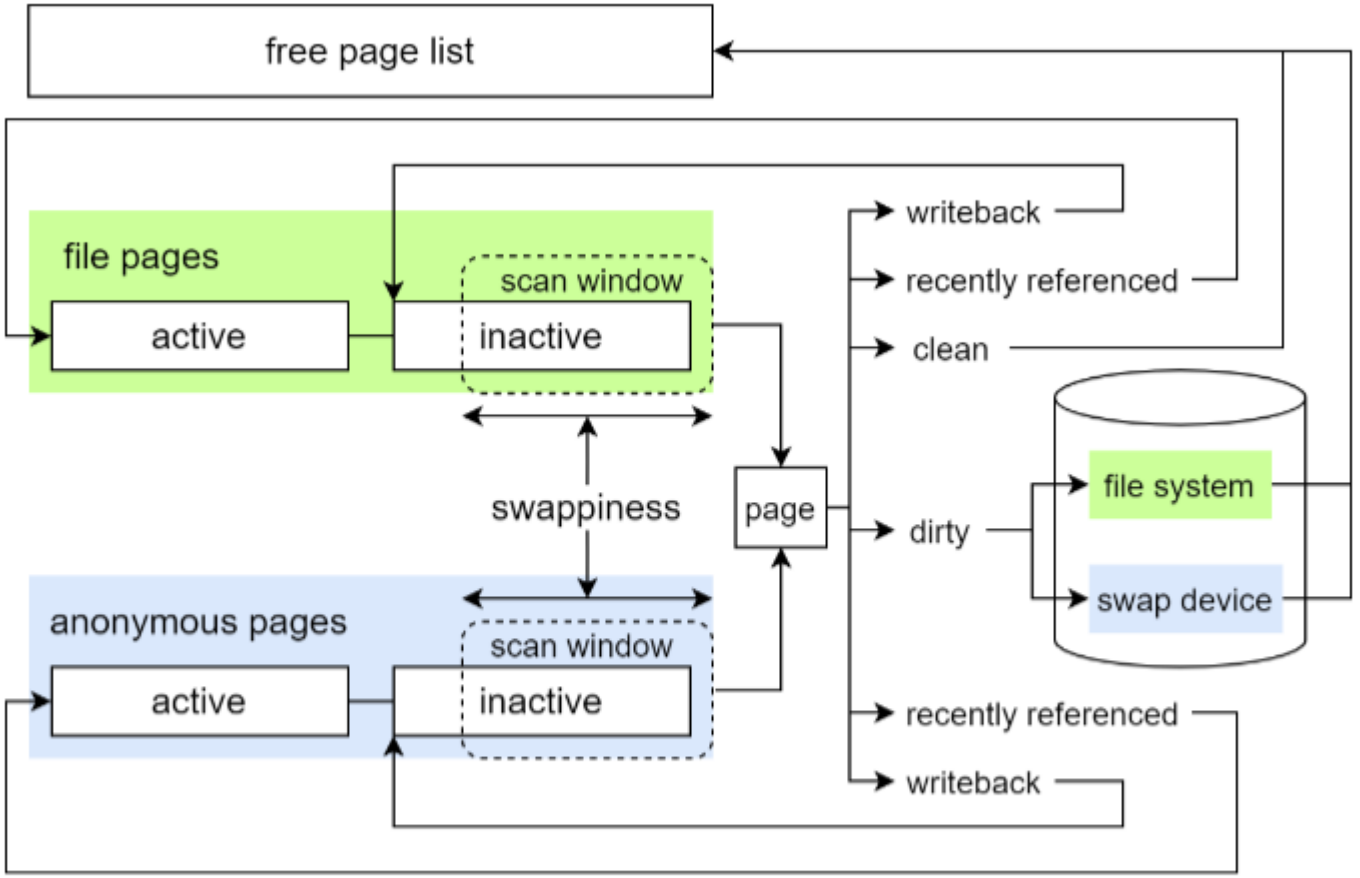
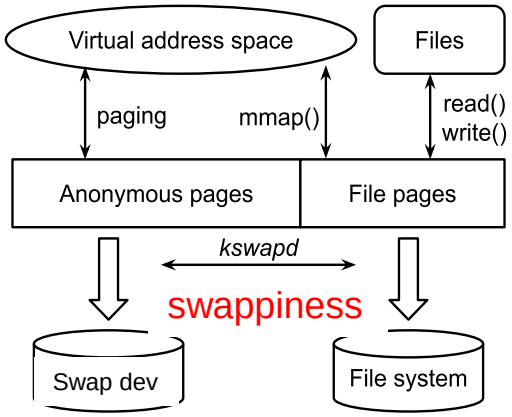


Figure A.1: An overview of page scanning for reclaiming free memory.

-王詠萱、蔡宗軒、張立平 Yong-Xuan Wang, Chung-Hsuan Tsai and Li-Pin Chang, “Killing Processes or Killing Flash? Escaping from the Dilemma Using Lightweight, Compression-Aware Swap for Mobile Devices,” International Conference on Embedded Software (EMSOFT 2021)

Linux Swappiness



- The costs of faulting in anon pages and that of faulting in file pages are very different
  - Swap I/Os are more expensive (slower): they are small and random compared with file I/Os
  - File I/Os are large and sequential (prefetching)
- Swappiness: a tunable kernel knob

  (file) 0 |----------[]----------| 200 (anon)
- Swappiness is set to 60 for historical reasons as on hard drives, random (swap) access is slower than sequential (file) access

Linux Swappiness

(file) 0 |----------[]----------| 200 (anon)

- Legacy swappiness is broken for fast swap devices
- Time costs of anon page fault vs. file page fault
  - 5 vs. 1 flash swap vs. flash file system
  - 0.03 vs. 1 zRAM swap vs. flash file system
  - Android devices swap on zRAM rather than flash
- Swappiness >= 100 improves the overall page fault cost for Android devices or computers with SSDs

周益全、沈林緯、張立平 Yi-Quan Chou, Lin-Wei Shen, and Li-Pin Chang, "Rectifying Skewed Kernel Page Reclamation in Mobile Devices for Improving User-Perceivable Latency, " International Conference on Embedded Software (EMSOFT'23), 2023.

Check file pages and anon pages of process

- Run “ps” to find out the ID of a process of yours
- cat /proc/[pid]/status | grep Rss

```
[lpchang@linux1 3253000]$ ps
    PID TTY          TIME CMD
3253000 pts/52   00:00:00 tcsh
3255286 pts/52   00:00:00 ps
[lpchang@linux1 3253000]$ cat /proc/3253000/status |grep Rss
RssAnon:               960 kB
RssFile:              3172 kB
RssShmem:                0 kB
[lpchang@linux1 3253000]$
```

Swapping on Mobile Systems

- Typically not enabled (flash swap, UFS/eMMC)
  - Limited number of flash write cycles
  - Android uses zRAM instead of flash swap, effectively compressing unused memory
- Instead use other methods to free memory if low
  - iOS ***asks*** apps to voluntarily relinquish allocated memory
  - Android terminates apps if low free memory

End of Chapter 9

Review Questions

1. Redo the question for effective access time calculation.
2. What are the pros and cons of LRU? and of LFU?
3. Read this article. How the *simplified 2Q* protects LRU against sequential scan?
4. Why the original LRU cannot be implemented in demand paging (so we use an approximation instead)?
5. Discuss the purposes of the various page bits that we mentioned, including valid bit, dirty bit, reference bit, and rw bit
6. Can thrashing be resolved using a faster swap device, e.g., replacing hard drives with SSDs?
7. Modern CPUs support multiple page sizes. Discuss the pros and cons of using large pages and using small pages
8. Compare System V shared memory vs. POSIX shared memory
9. What are the purposes of madvise() and msync()?
10. Use pmap() to show the process memory layout and try to interpret the results
11. What is rss (resident set size) of a process?