Operating System

Ch10: Virtual memory

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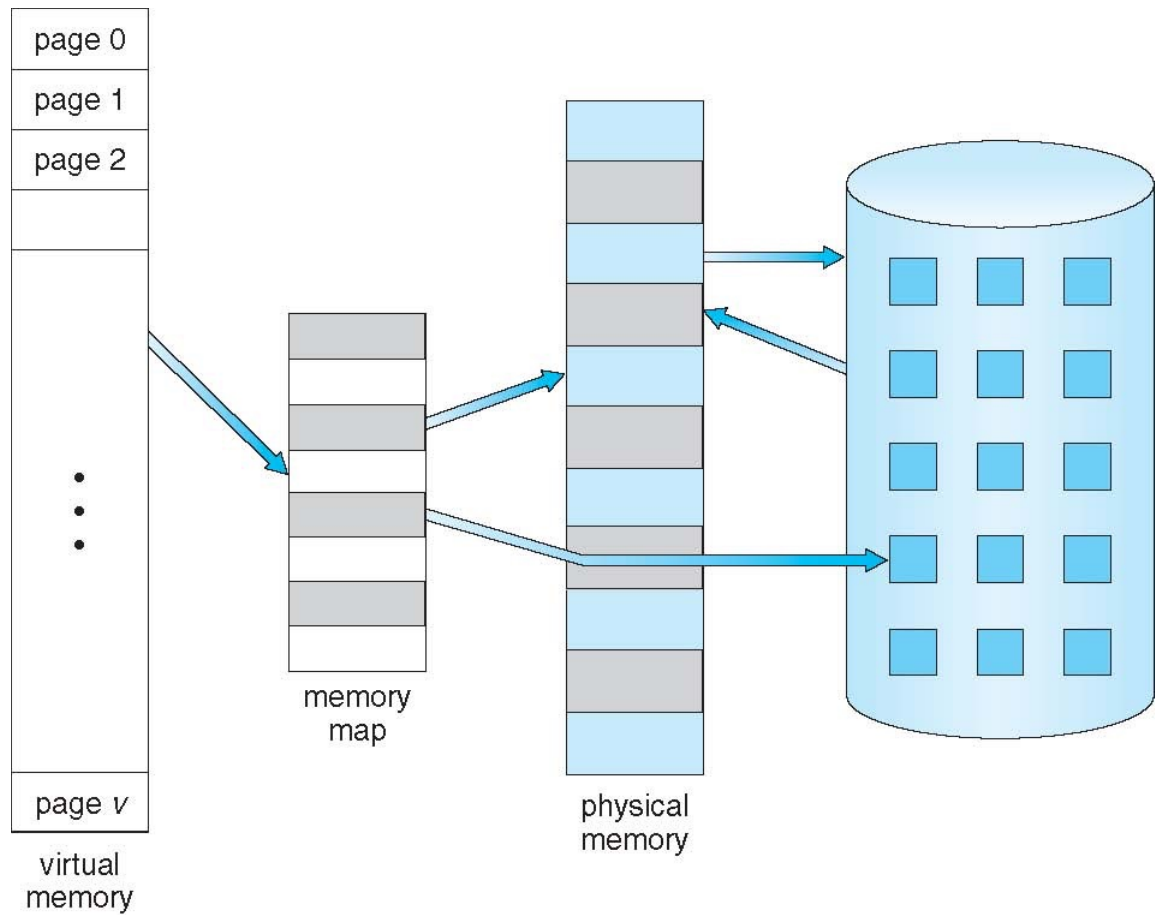
Virtual Memory That is Larger Than Physical Memory



Demand Paging

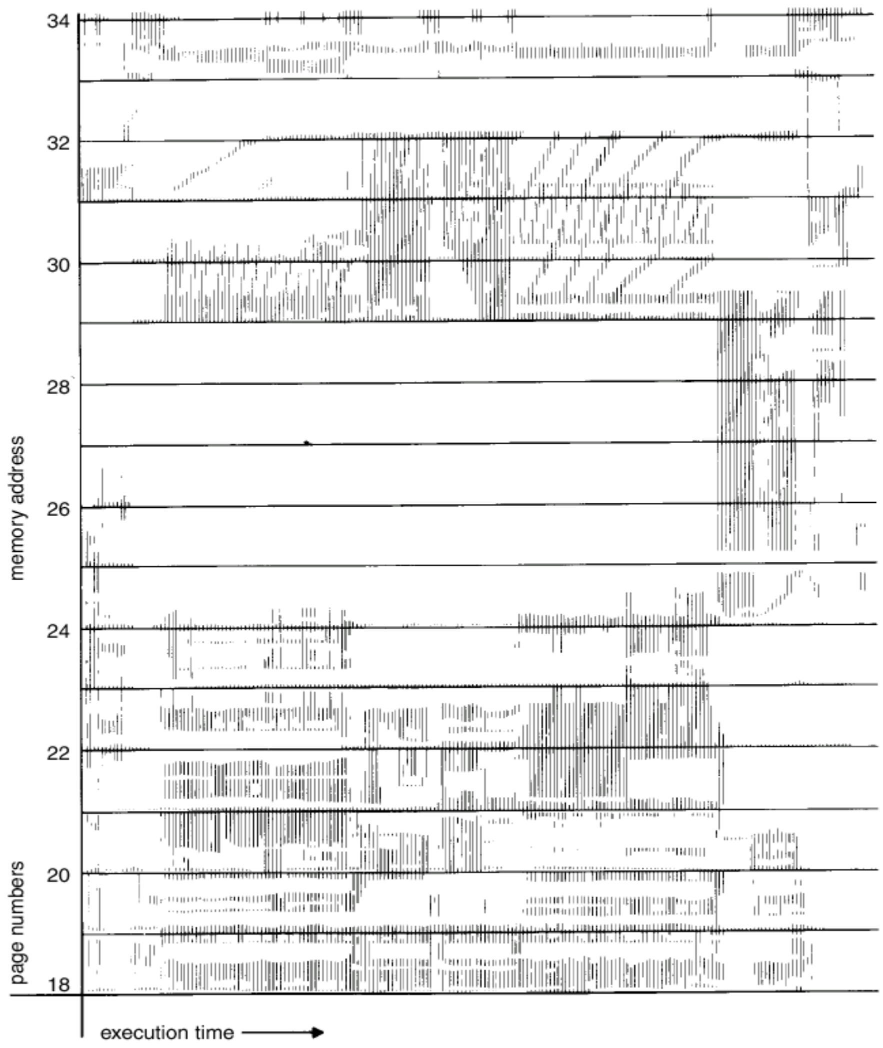
- A paging system with (page-level) swapping
- Bring a page into memory only when it is needed
  - ✓ Cf) swapping: entire process is moved
- OS uses main memory as a (page) cache of all of the data allocated by processes in the system
  - ✓ Initially, pages are allocated from physical memory frames
  - ✓ When physical memory fills up, allocating a page requires some other page to be evicted from its physical memory frame
- Evicted pages go to disk (only need to write if they are dirty)
  - ✓ To a swap file
  - ✓ Movement of pages between memory/disks is done by the OS
  - ✓ Transparent to the application

Demand Paging

- Why does this work? → Locality
  - ✓ Temporal locality: locations referenced recently tend to be referenced again soon
  - ✓ Spatial locality: locations near recently referenced locations are likely to be referenced soon

- Locality means paging can be infrequent
  - ✓ Once you've paged something in, it will be used many times
  - ✓ On average, you use things that are paged in
  - ✓ But this depends on many things:
    - ➢ Degree of locality in application
    - ➢ Page replacement policy
    - ➢ Amount of physical memory
    - ➢ Application's reference pattern and memory footprint

Locality in a Memory-Reference Pattern

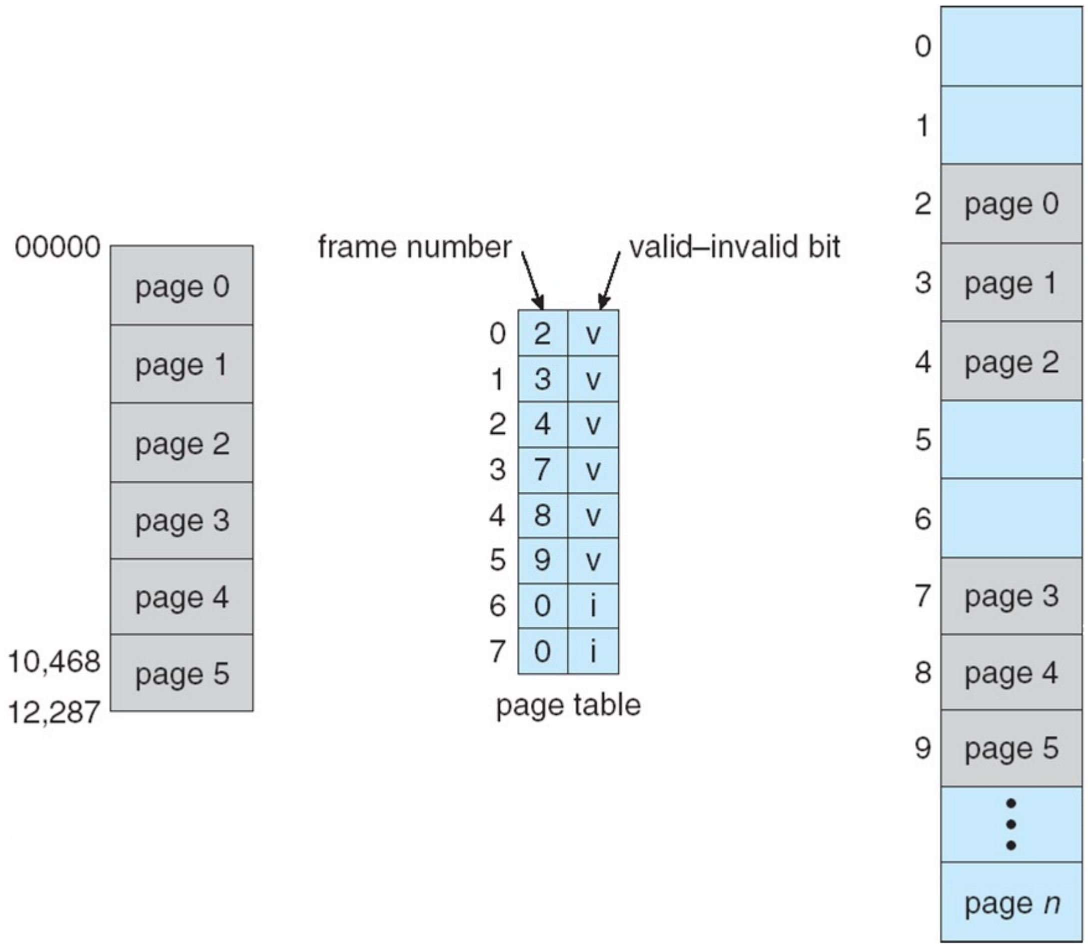


Demand Paging

- Why is this "demand" paging?
  - ✓ When a process first starts up, it has a brand new page table, with all PTE valid bits "false"
    - ➢ No pages are yet mapped to physical memory
  - ✓ When the process starts executing:
    - ➢ Instructions immediately fault on both code and data pages
    - ➢ Faults stop when all necessary code/data pages are in memory
    - ➢ Only the code/data that is needed (demanded!!) by process needs to be loaded
    - ➢ What is needed changes over time, of course…

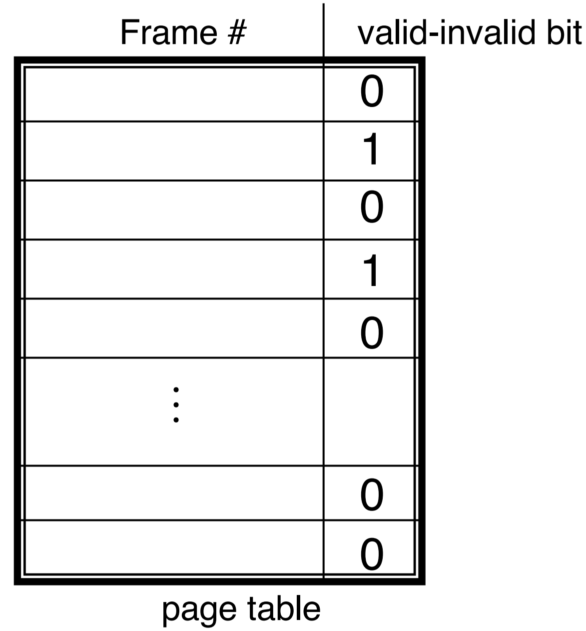
Revisited: Memory Protection in Paging

- if valid-invalid bit == i
  - ✓ Protection fault



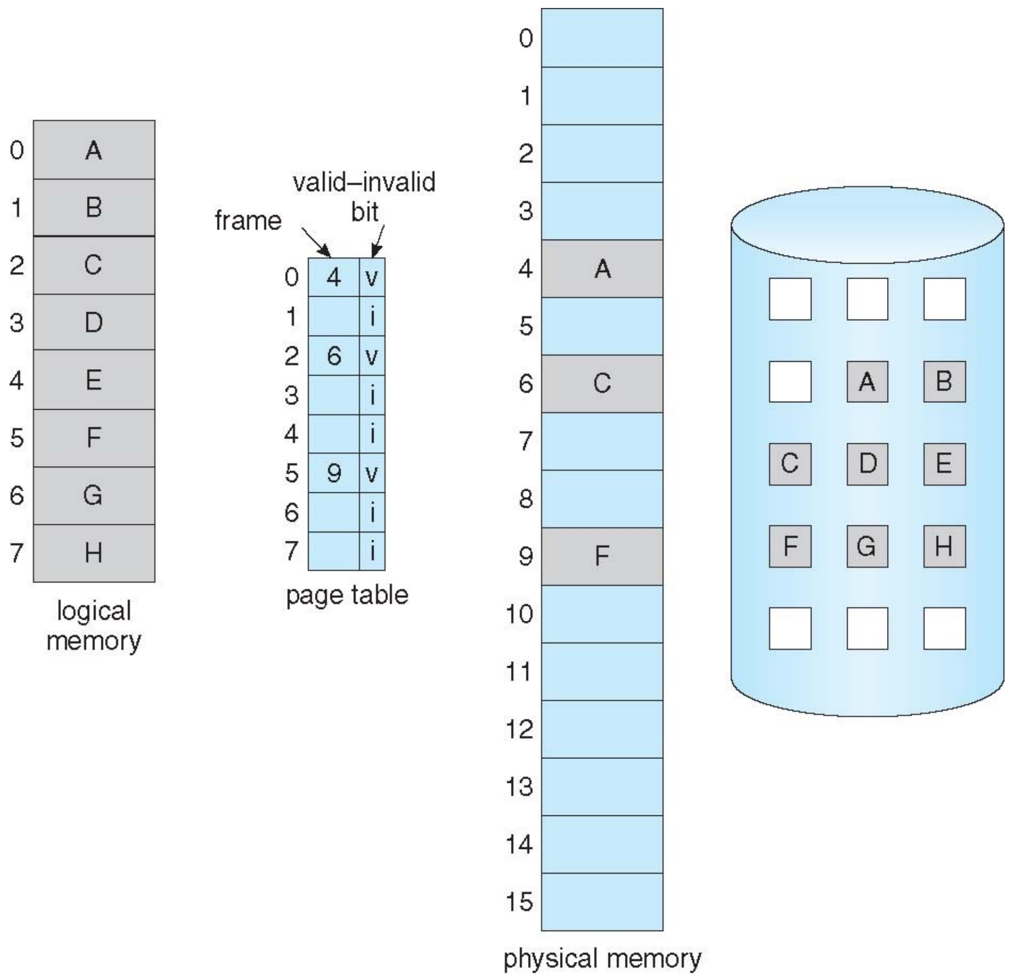
Valid-Invalid Bit in Demand Paging

- if valid-invalid bit == v
  - ✓ in-memory
- if valid-invalid bit == i
  - ✓ not-in-memory
  - ✓ Page fault
- Example of a page table snapshot



- Initially, valid–invalid bits are set to invalid on all entries
  - ✓ Demand paging

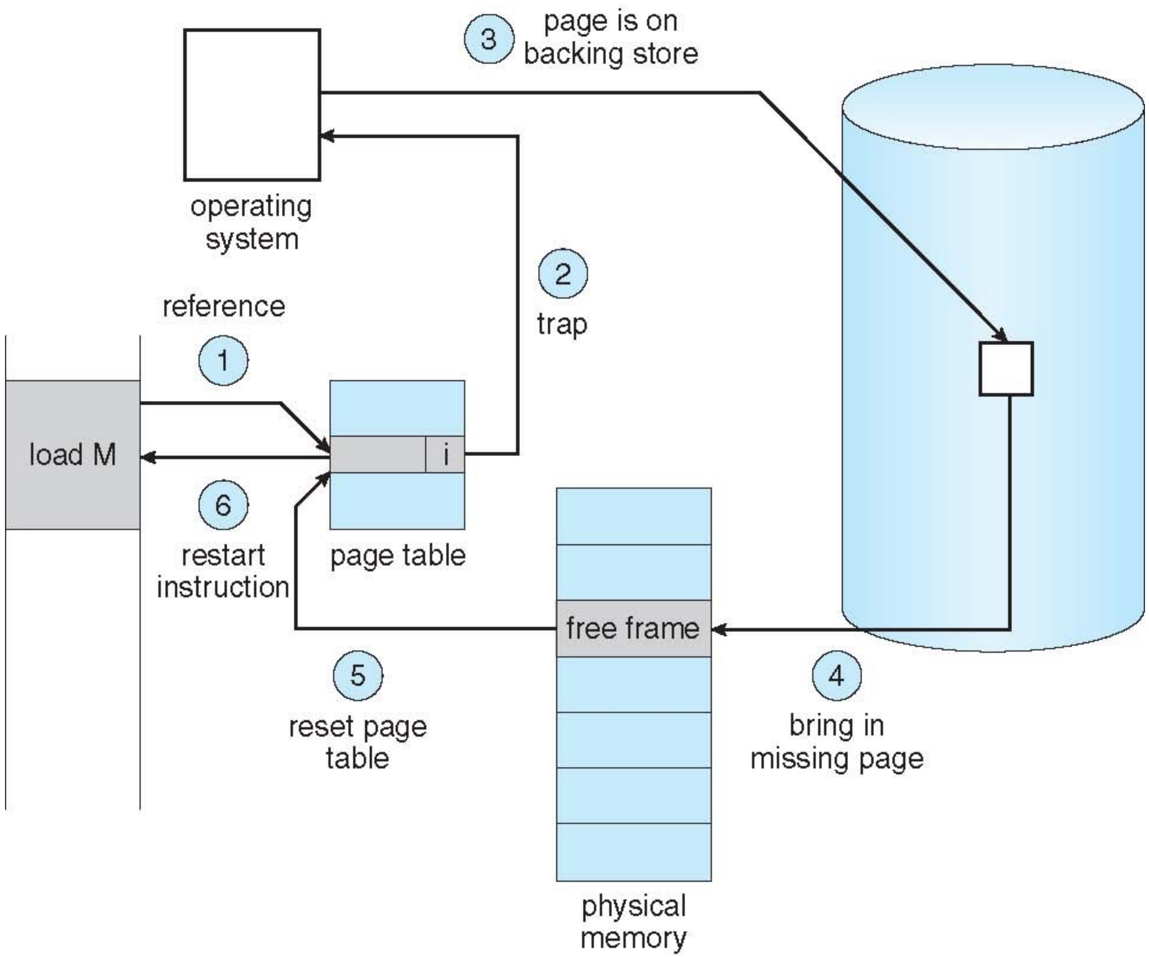
Valid-Invalid Bit in Demand Paging



Page Fault

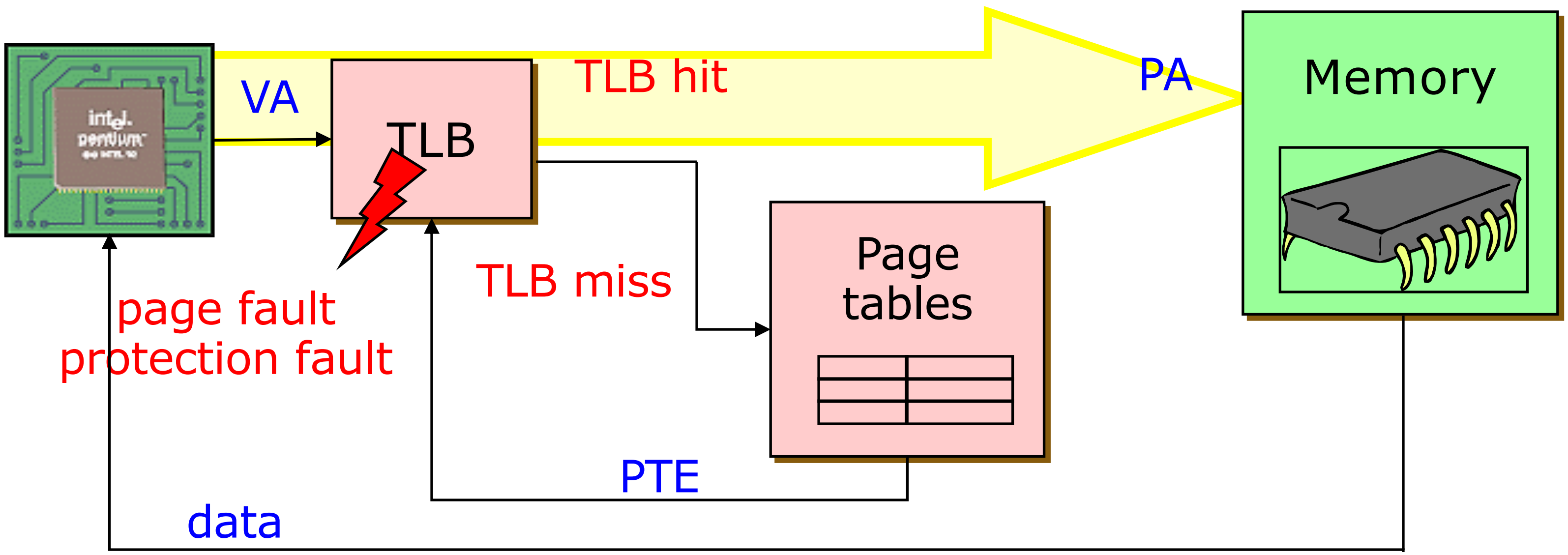
- What happens to a process that references a virtual address in a page that has been evicted?
  - ✓ When the page was evicted, the OS sets the PTE as invalid and stores (in PTE) the location of the page in the swap file
  - ✓ When a process accesses the page, the invalid PTE will cause an exception to be thrown
- The OS will run the page fault handler in response
  - ✓ Handler uses invalid PTE to locate page in swap file
  - ✓ Handler reads page into a physical frame, updates PTE to point to it and to be valid
  - ✓ Handler restarts the faulted process
- Where does the page that's read in go?
  - ✓ Have to evict something else (page replacement algorithm)
  - ✓ OS typically tries to keep a pool of free pages around so that allocations don't inevitably cause evictions

Steps in Handling a Page Fault



Memory Reference

- Situation
  - ✓ Process is executing on the CPU, and it issues a read to a (virtual) address



Memory Reference

- The common case
  - ✓ The read goes to the TLB in the MMU
  - ✓ TLB does a lookup using the page number of the address
  - ✓ The page number matches, returning a PTE
  - ✓ TLB validates that the PTE protection allows reads
  - ✓ PTE specifies which physical frame holds the page
  - ✓ MMU combines the physical frame and offset into a physical address
  - ✓ MMU then reads from that physical address, returns value to CPU

Memory Reference

- TLB misses: two possibilities
  - ✓ (1) MMU loads PTE from page table in memory
    - ➢ Hardware managed TLB, OS not involved in this step
    - ➢ OS has already set up the page tables so that the hardware can access it directly
  - ✓ (2) Trap to the OS
    - ➢ Software managed TLB, OS intervenes at this point
    - ➢ OS does lookup in page tables, loads PTE into TLB
    - ➢ OS returns from exception, TLB continues

  - ✓ At this point, there is a valid PTE for the address in the TLB

Memory Reference

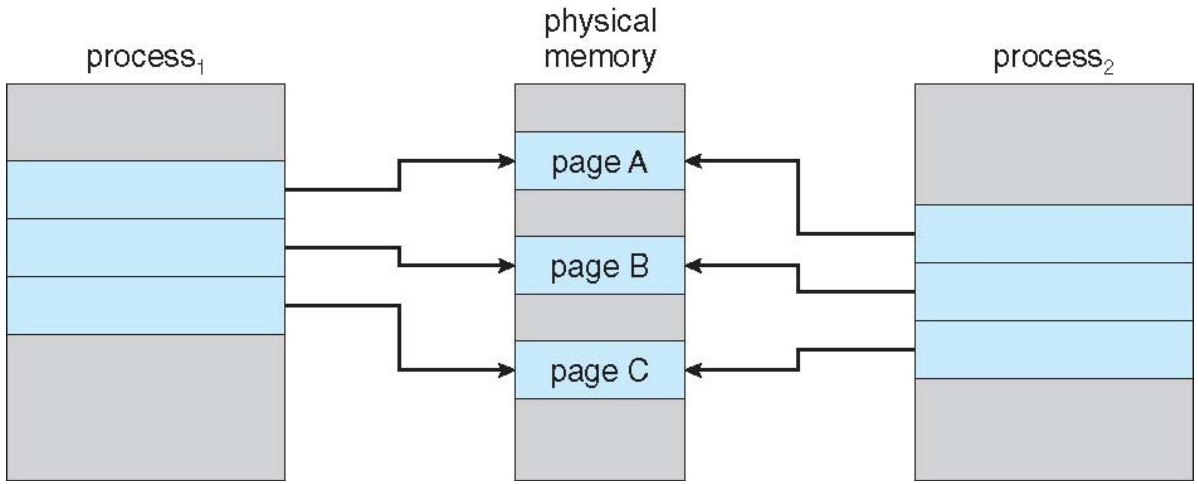
- TLB misses
  - ✓ Page table lookup (by HW or OS) can cause a recursive fault if page table is paged out
    - ➢ Assuming page tables are in OS virtual address space
    - ➢ Not a problem if tables are in physical memory
  - ✓ When TLB has PTE, it restarts translation
    - ➢ Common case is that the PTE refers to a valid page in memory
    - ➢ Uncommon case is that TLB faults again on PTE because of PTE protection bits (e.g., page is invalid)

Memory Reference

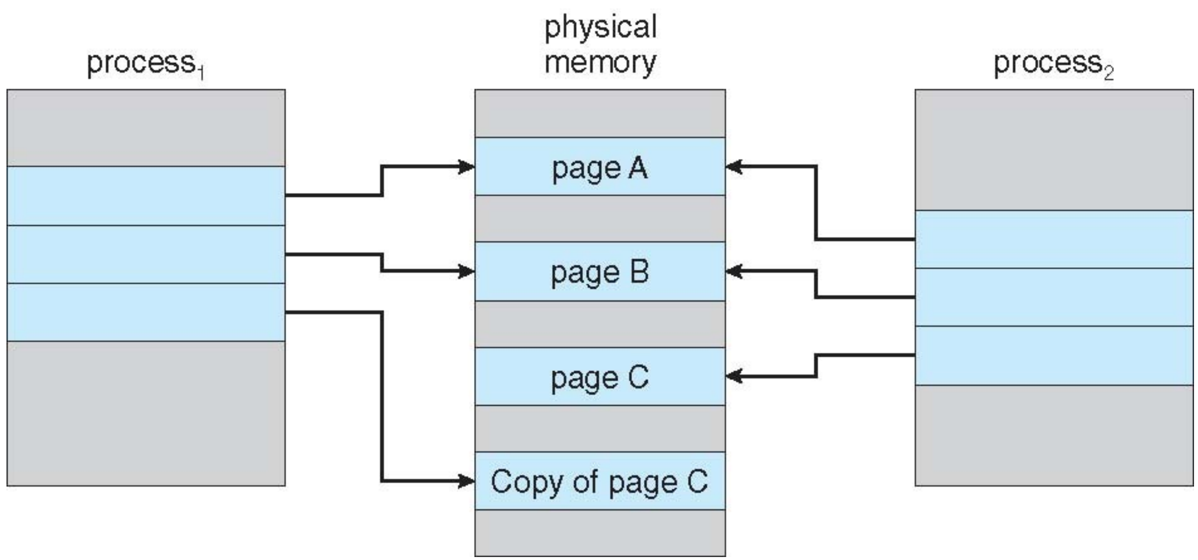
- Page faults
  - PTE can indicate a protection fault
    - Read/Write/Execute – operation not permitted on page
    - Invalid – virtual page not allocated, or page not in physical memory
  - TLB traps to the OS (software takes over)
    - Read/Write/Execute – OS usually will send fault back to the process, or might be playing tricks (e.g., copy on write, mapped files)
    - Invalid (Not allocated) – OS sends fault to the process (e.g., segmentation fault)
    - Invalid (Not in physical memory) – OS allocates a frame, reads from disk, and maps PTE to physical frame

Copy-on-Write

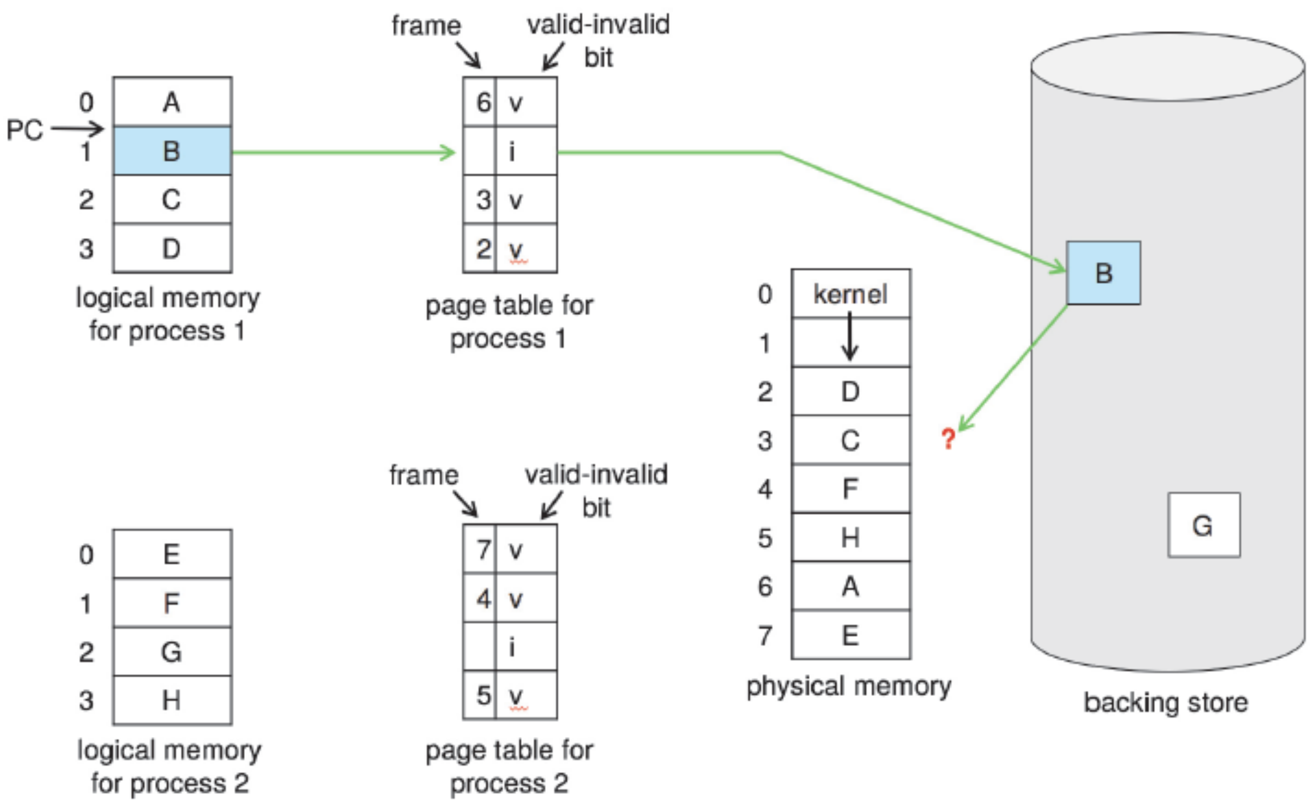
- Right after fork( )



- When process 1 modifies page C



What happens if there is no free frame?



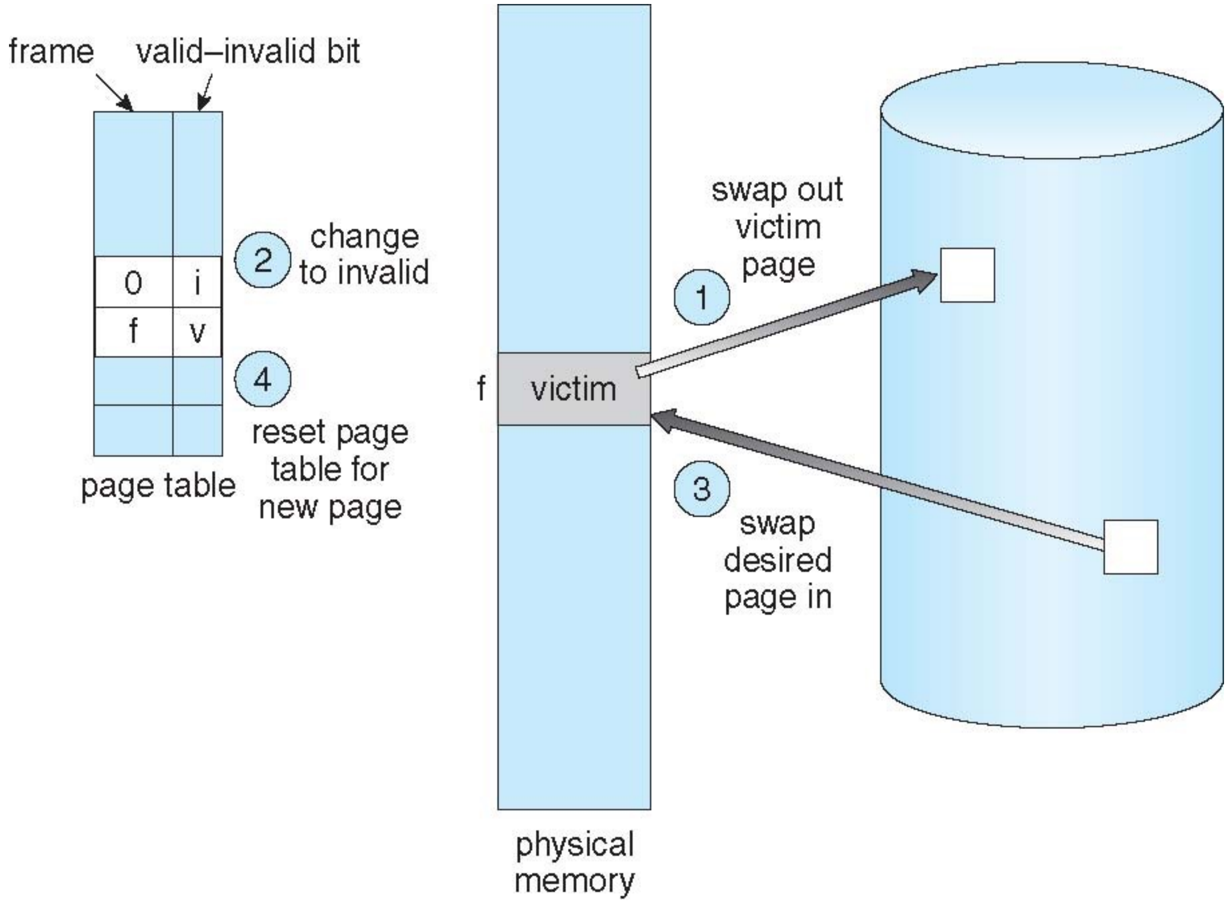
Page Replacement

- When a page fault occurs, the OS loads the faulted page from disk into a page frame of memory
- At some point, the process has used all of the page frames it is allowed to use
- When this happens, the OS must replace a page for each page faulted in
  - ✓ It must evict a page to free up a page frame
- The page replacement algorithm determines how this is done

Page Replacement

- Evicting the best page
  - ✓ The goal of the replacement algorithm is to reduce the fault rate by selecting the best victim page to remove
  - ✓ The best page to evict is the one never touched again
    - ➢ as process will never again fault on it
  - ✓ "Never" is a long time, so picking the page closest to "never" is the next best thing
    - ➢ Belady's proof: Evicting the page that won't be used for the longest period of time minimizes the number of page faults

Page Replacement



Performance of Demand Paging

- Page Fault Rate p, $0 \le p \le 1$

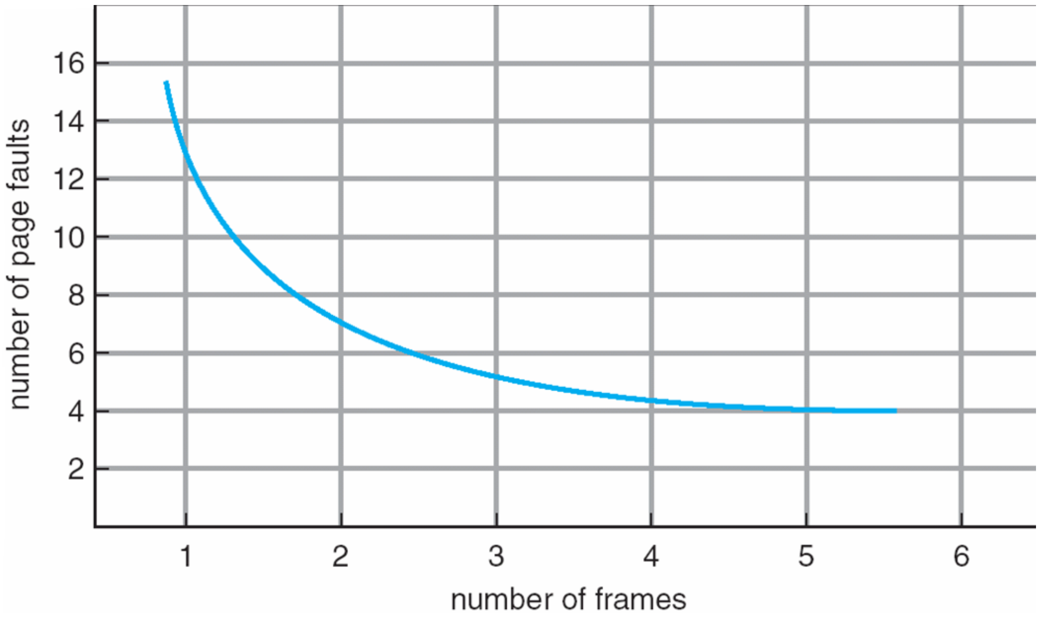
- Effective Access Time (EAT)

$$
\begin{aligned}
\text{EAT} = (1 - p) \times \text{memory access} \\
+ p \times (\text{page fault overhead} \\
+ [\text{swap page out}] \\
+ \text{swap page in} \\
+ \text{restart overhead})
\end{aligned}
$$

Page Replacement Algorithms

- Goal: lowest page-fault rate
  - ✓ Evaluate algorithm by running it on a particular string of memory references (reference string) and computing the number of page faults on that string
  - ✓ In all our examples, the reference string is "1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5"

- Page faults vs. Number of frames

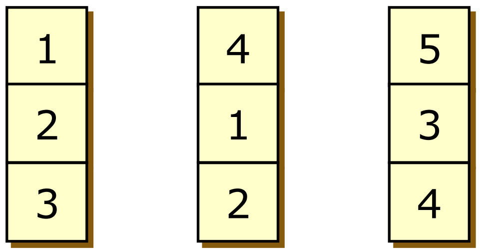


FIFO

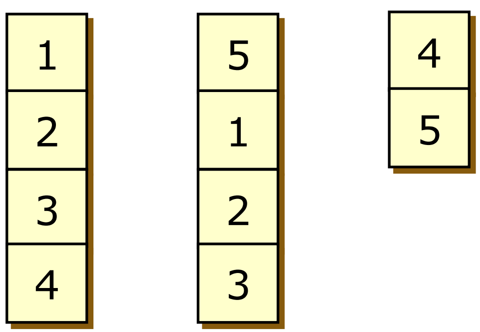
- Obvious and simple to implement
  - ✓ Maintain a list of pages in order they were paged in
  - ✓ On replacement, evict the one brought in longest time ago
- Why might this be good?
  - ✓ Maybe the one brought in the longest ago is not being used
- Why might this be bad?
  - ✓ Maybe, it's not the case
  - ✓ We don't have any information either way
- FIFO suffers from "Belady's Anomaly"
  - ✓ The fault rate might increase when the algorithm is given more memory

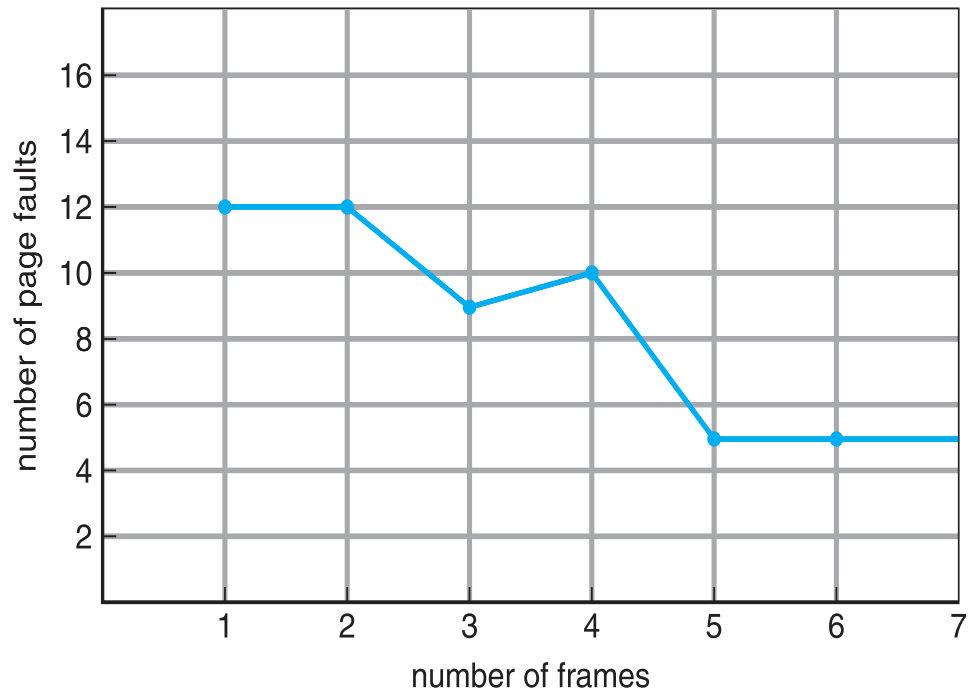
FIFO

- Example: Belady's anomaly
  - ✓ Reference string: 1,2,3,4,1,2,5,1,2,3,4,5
  - ✓ 3 frames: 9 faults



  - ✓ 4 frames: 10 faults





Optimal Algorithm

- Replace page that will not be used for longest period of time

- 4 frames example

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

1	4
2	
3	
4	5

6 page faults

- How do you know this?

- Used for measuring how well your algorithm performs

Least Recently Used (LRU) Algorithm

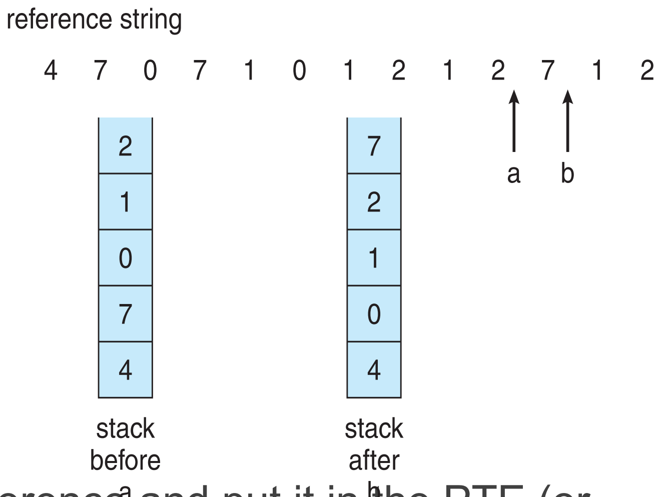
- LRU uses reference information to make a more informed replacement decision
  - ✓ Idea: past experience gives us a guess of future behavior
  - ✓ On replacement, evict the page that has not been used for the longest time in the past
  - ✓ LRU looks at the past, Belady’s wants to look at future

- Reference string: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

1	5	
2		
3	5	4
4	3	

Implementation of LRU Algorithm

- Timestamp implementation
  - ✓ Every page entry has a counter
  - ✓ Every time page is referenced through this entry, copy the clock into the counter
  - ✓ When a page needs to be changed, look at the counters to determine which are to change
- Stack implementation
  - ✓ Keep a stack of page numbers
  - ✓ Page referenced:
    - ➢ move it to the top
    - ➢ requires 6 pointers to be changed
  - ✓ No search for replacement



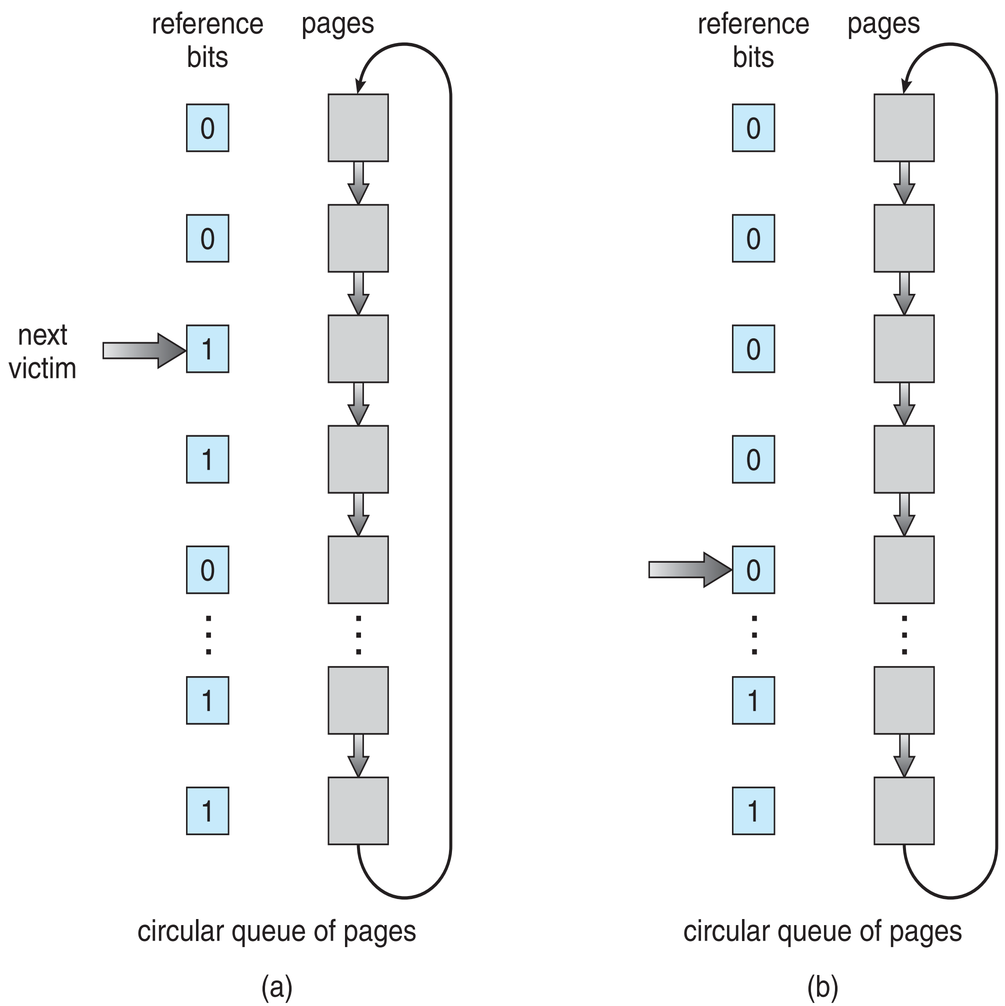
- Approximation
  - ✓ To be perfect, need to timestamp every reference and put it in the PTE (or maintain a stack) – too expensive
  - ✓ So, we need an approximation

LRU Approximation Algorithms

- 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

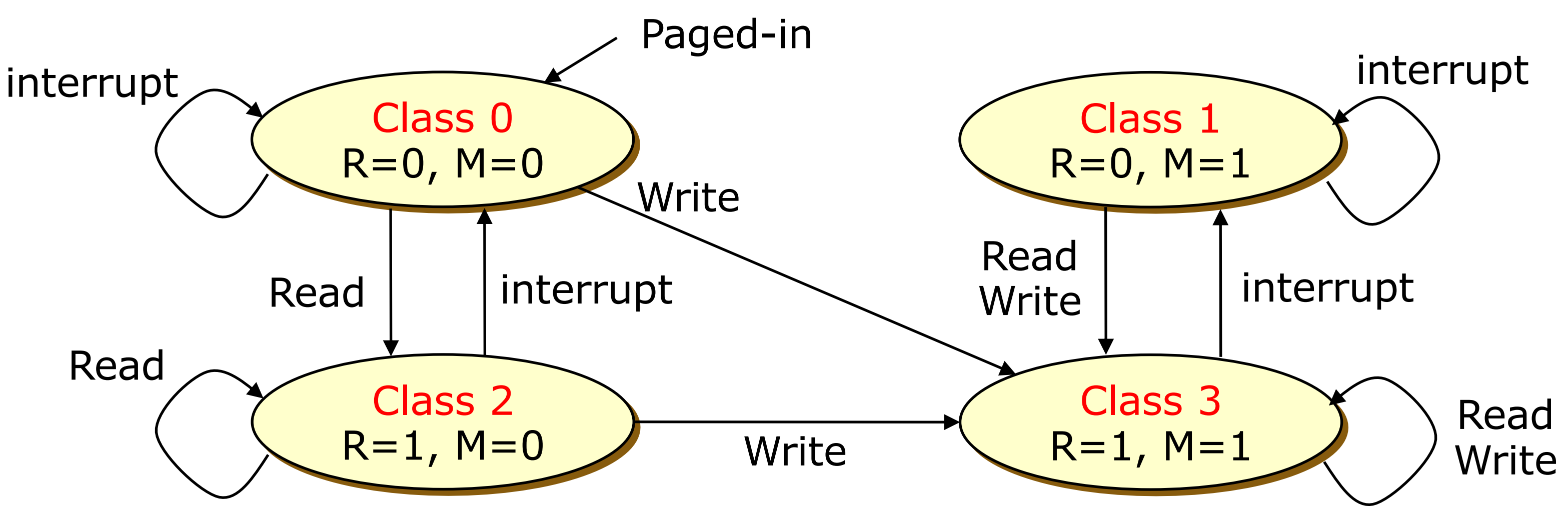
- Second chance (or LRU clock)
  - ✓ Need reference bit
  - ✓ Clock replacement
  - ✓ If page to be replaced (in clock order) has reference bit = 1, then:
    - ➢ set reference bit 0
    - ➢ leave page in memory
    - ➢ replace next page (in clock order), subject to same rules

Second Chance (LRU Clock)



Not Recently Used (NRU)

- NRU or enhanced second chance
  - ✓ Use R (reference) and M (modify) bits
    - ➢ Periodically, (e.g., on each clock interrupt), R is cleared, to distinguish pages that have not been referenced recently from those that have been



Not Recently Used

- Algorithm
  - ✓ Removes a page at random from the lowest numbered nonempty class
  - ✓ It is better to remove a modified page that has not been referenced in at least one clock tick than a clean page that is in heavy use

- Advantages
  - ✓ Easy to understand
  - ✓ Moderately efficient to implement
  - ✓ Gives a performance that, while certainly not optimal, may be adequate

Revisited: Page Table Entries (PTEs)

1	1	1	2	20
V	R	M	Prot	Frame Number (FN)

- Valid bit (V) says whether or not the PTE can be used
  - ✓ It is checked each time a virtual address is used
- Reference bit (R) says whether the page has been accessed
  - ✓ It is set when a read or write to the page occurs
- Modify bit (M) says whether or not the page is dirty
  - ✓ It is set when a write to the page occurs
- Protection bits (Prot) control which operations are allowed on the page
  - ✓ Read, Write, Execute, etc.
- Frame number (FN) determines physical page

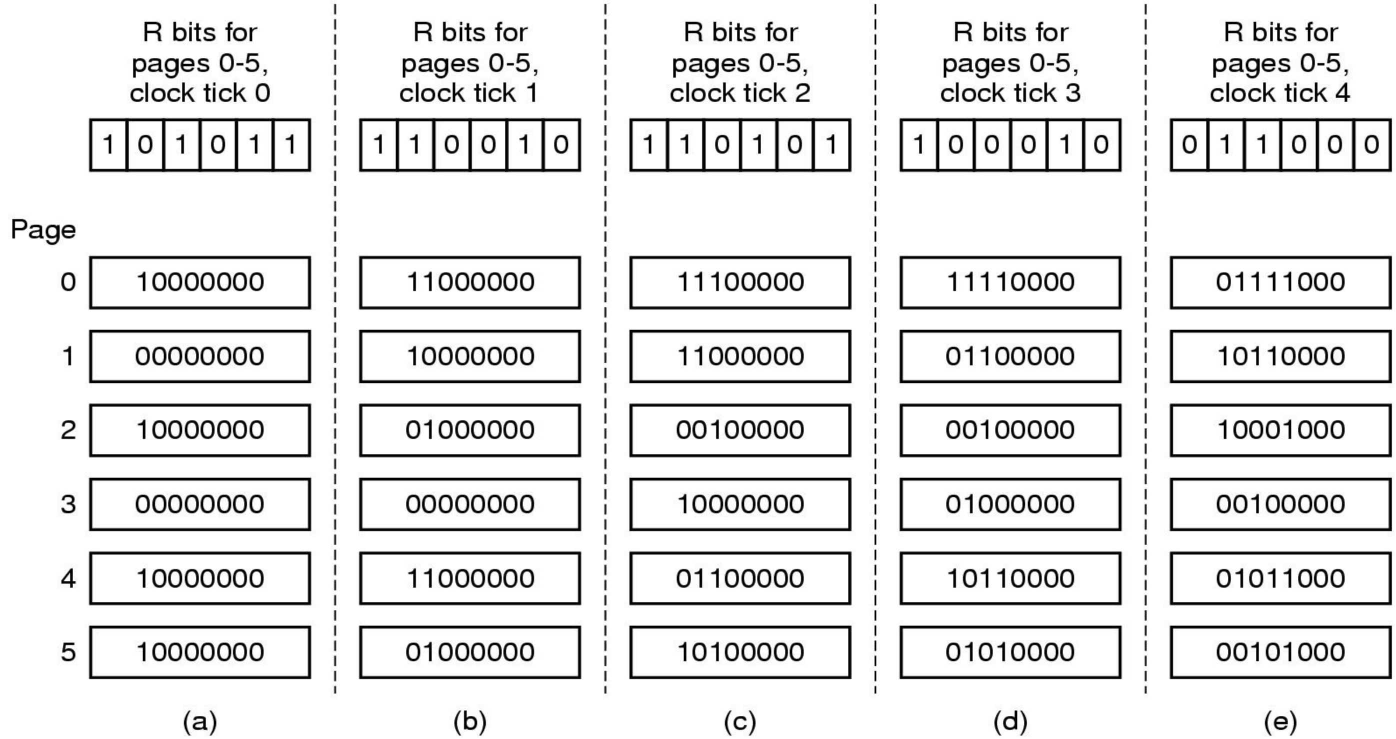
Least Frequently Used (LFU)

- Counting-based page replacement
  - ✓ A software counter is associated with each page
  - ✓ At each clock interrupt, for each page, the R bit is added to the counter
    - ➢ The counters denote how often each page has been referenced

- Least Frequently Used (LFU)
  - ✓ The page with the smallest count will be replaced
  - ✓ Cf) Most frequently used (MFU) page replacement
    - ➢ The page with the largest count will be replaced
    - ➢ Based on the argument that the page with the smallest count was probably just brought in and has yet to be used
  - ✓ It never forgets anything
    - ➢ A page may be heavily used during the initial phase of a process, but then is never used again

Least Frequently Used (LFU)

- Aging
  - ✓ The counters are shifted right by 1 bit before the R bit is added to the leftmost

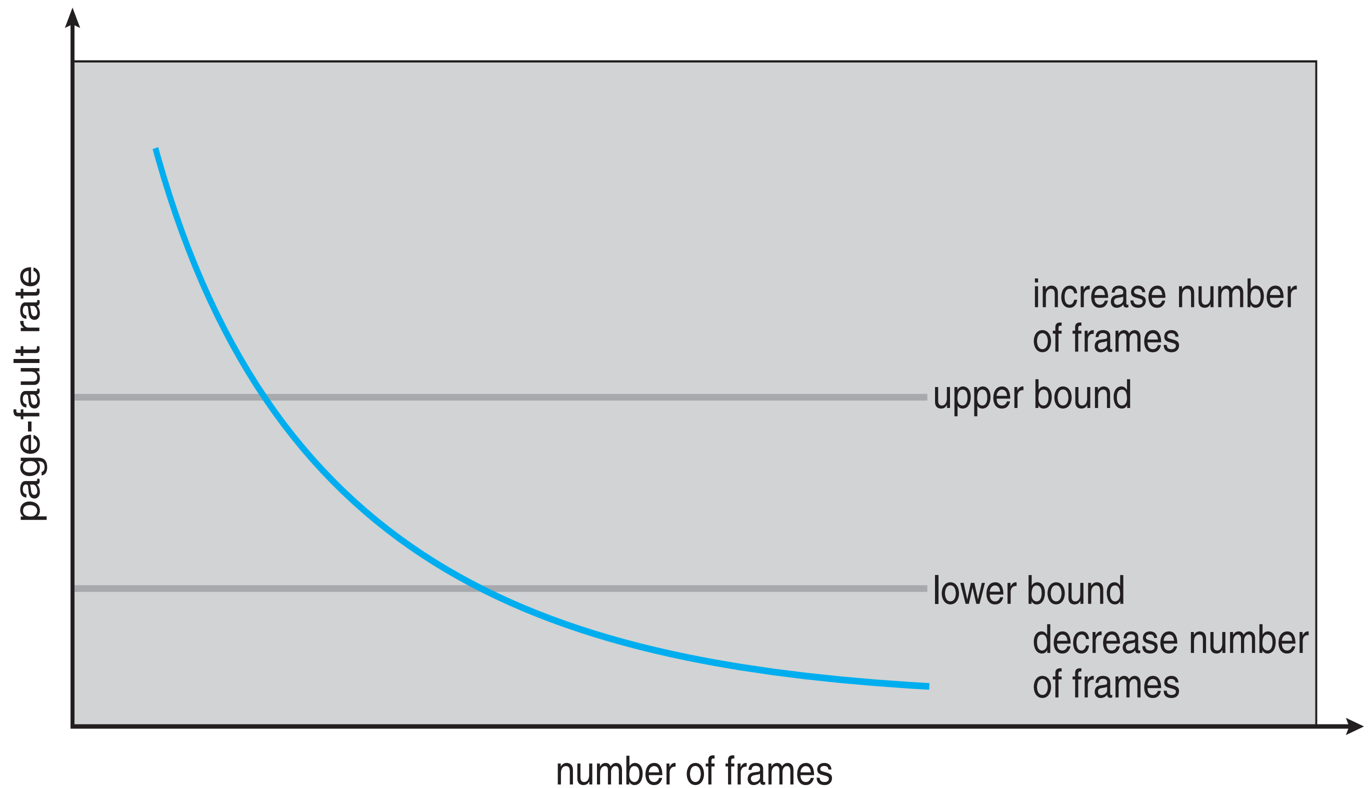


Allocation of Frames

- Allocation algorithms
  - ✓ Equal allocation
  - ✓ Proportional allocation
    - ➢ Allocate according to the size of process
  - ✓ Priority-based allocation

- Page replacement
  - ✓ Global replacement
  - ✓ Local replacement

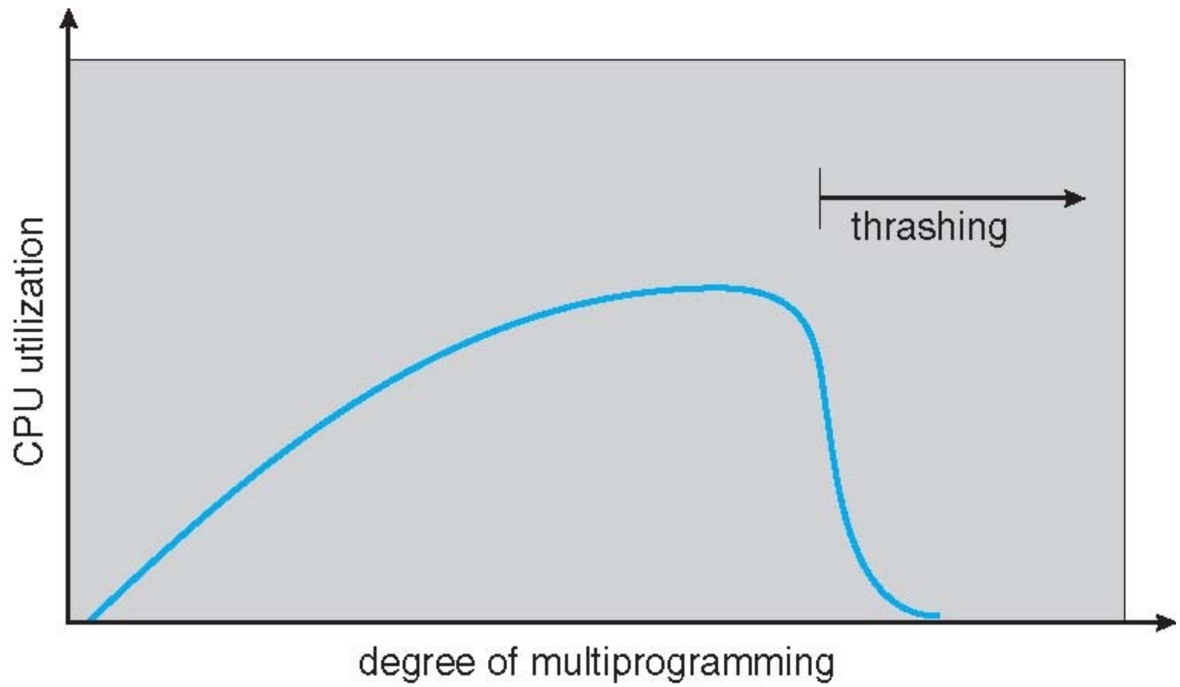
Page-Fault Frequency Scheme



- Establish "acceptable" page-fault rate
  - ✓ If actual rate too low, process loses frame
  - ✓ If actual rate too high, process gains frame

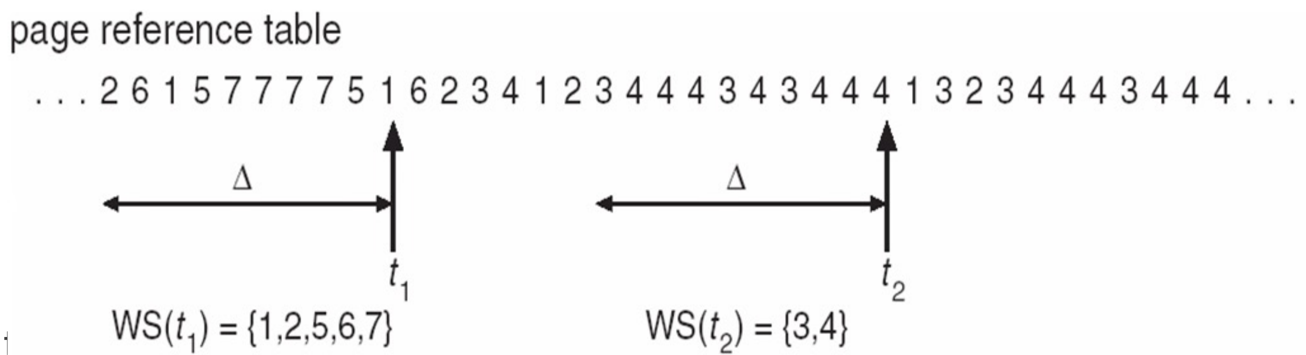
Thrashing

- **Thrashing** ≡ a process is busy swapping pages in and out
- Why does thrashing occur?
  - ✓ Σ size of locality > total memory size



Working-Set Model

- Locality $D = \Sigma\, WSS_i \equiv$ total demand frames
- WSS_i (Working Set Size of Process P_i) =
  total number of pages referenced in the most recent Δ (varies in time)
  - ✓ $\Delta \equiv$ working-set window $\equiv$ a fixed number of page references



  - ✓ if Δ too small will not encompass entire locality
  - ✓ if Δ too large will encompass several localities
  - ✓ if $\Delta = \infty \Rightarrow$ will encompass entire program
- if $D > m \Rightarrow$ Thrashing

Other Considerations

- Prepaging

- Page size selection
  - ✓ Fragmentation
  - ✓ Page table size
  - ✓ I/O overhead
  - ✓ Locality

- TLB Reach
  - ✓ The amount of memory accessible from the TLB
  - ✓ TLB Reach = (TLB Size) X (Page Size)
  - ✓ Ideally, the working set of each process is stored in the TLB
    - ➢ Otherwise there is a high degree of page faults
  - ✓ Increase TLB size or Multiple page size

Other Considerations

- Program structure
  - ✓ `int A[1024][1024];`
  - ✓ Each row is stored in one page
  - ✓ Program 1

```
for (j = 0; j < 1024; j++)
   for (i = 0; i < 1024; i++)
               A[i][j] = 0;
```

    1024 x 1024 page faults

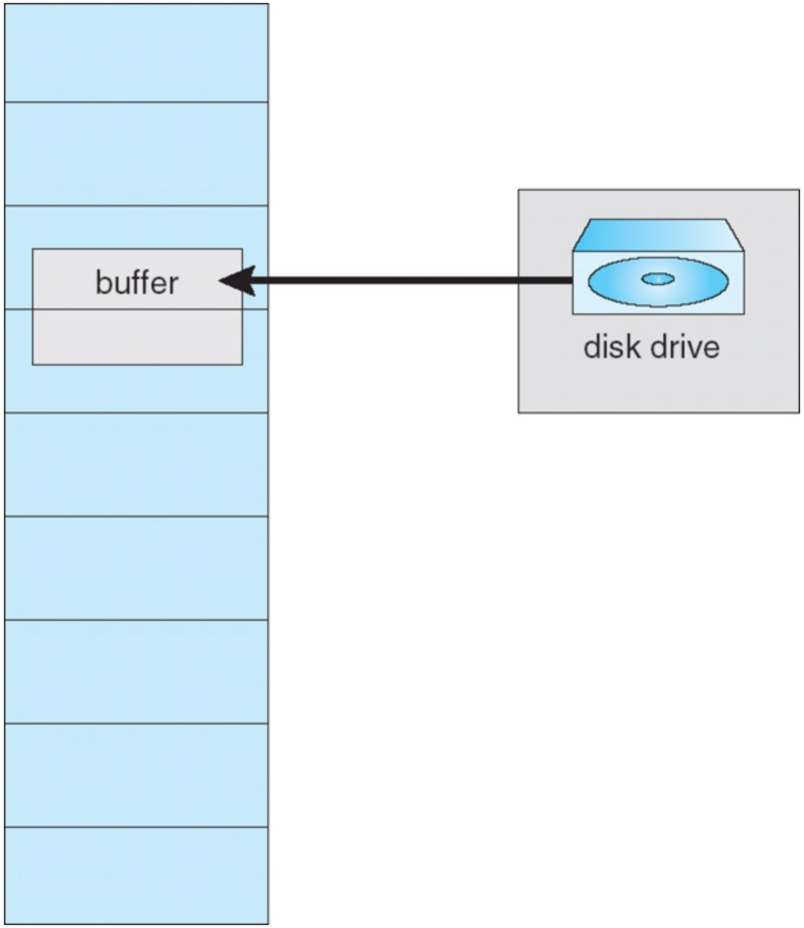
  - ✓ Program 2

```
for (i = 0; i < 1024; i++)
   for (j = 0; j < 1024; j++)
               A[i][j] = 0;
```

    1024 page faults

Other Considerations

- I/O Interlock
  - ✓ Pages must sometimes be locked into memory
- Consider I/O
  - ✓ Pages that are used for copying a file from a device must be locked from being selected for eviction by a page replacement algorithm



Thank You!
Q&A