Virtual Memory II

TLB Recap

- Fast associative cache of page table entries
  - Contains a subset of the page table
  - What happens if required entry for translation is not present (a *TLB miss*)?

TLB Recap

- TLB may or may not be under OS control
  - Hardware-loaded TLB
    - On miss, hardware performs PT lookup and reloads TLB
    - Example: Pentium
  - Software-loaded TLB
    - On miss, hardware generates a TLB miss exception, and exception handler reloads TLB
    - Example: MIPS

Demand Paging/Segmentation

- With VM, only parts of the program image need to be resident in memory for execution.
- Can swap presently unused pages/segments to disk
- Reload non-resident pages/segment *on demand*.
  - Reload is triggered by a page or segment fault
  - Faulting process is blocked and another scheduled
  - When page/segment is resident, faulting process is restarted
  - May require freeing up memory first
    - Replace current resident page/segment
    - How determine replacement “victim”?
  - If victim is unmodified (“clean”) can simply discard it
    - This is reason for maintaining a “dirty” bit in the PT

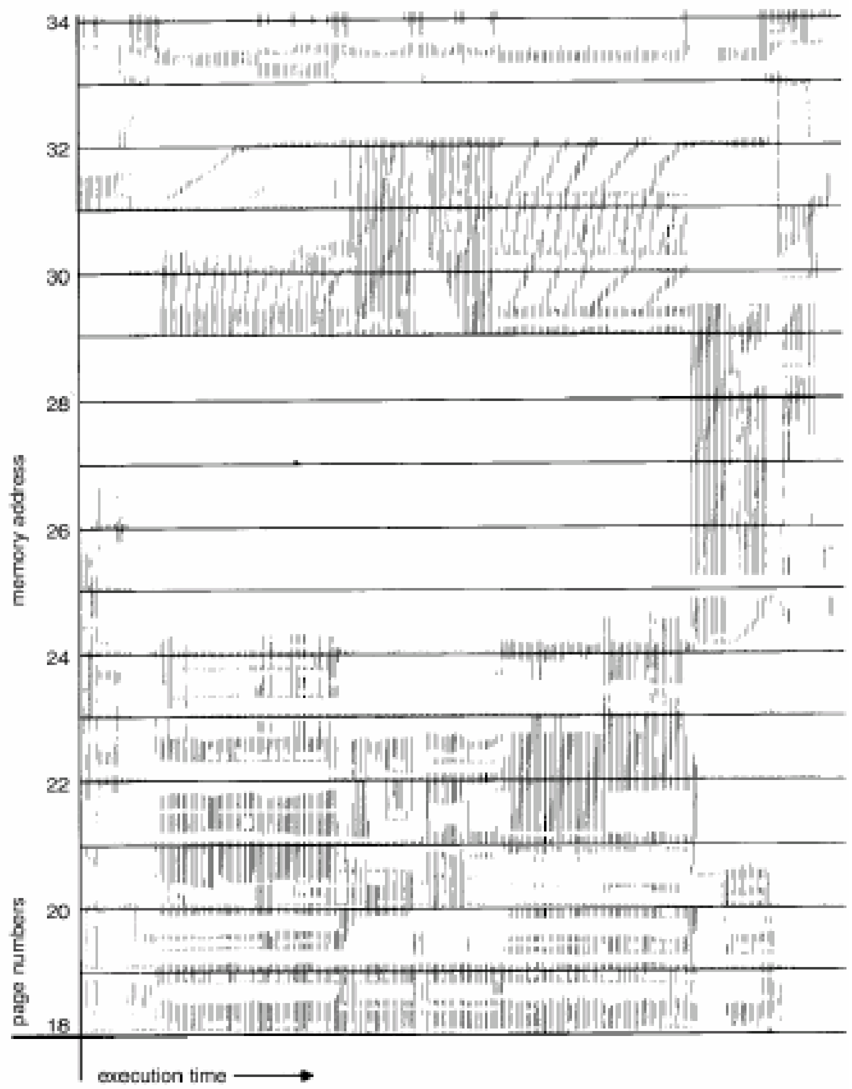
- Why does demand paging/segmentation work?
  - Program executes at full speed only when accessing the resident set.
  - TLB misses introduce delays of several microseconds
  - Page/segment faults introduce delays of several milliseconds
  - Why do it?
- Answer
  - Less physical memory required per process
    - Can fit more processes in memory
    - Improved chance of finding a runnable one
  - Principle of locality

Principle of Locality

- An important observation comes from empirical studies of the properties of programs.
  - Programs tend to reuse data and instructions they have used recently.
  - **90/10 rule**
    "A program spends 90% of its time in 10% of its code"
- We can exploit this *locality of references*
- An implication of locality is that we can reasonably predict what *instructions* and *data* a program will use in the near future based on its accesses in the recent past.

- **Two different types** of locality have been observed:
  - ***Temporal*** locality: states that recently accessed items are likely to be accessed in the near future.
  - ***Spatial*** locality: says that items whose addresses are near one another tend to be referenced close together in time.

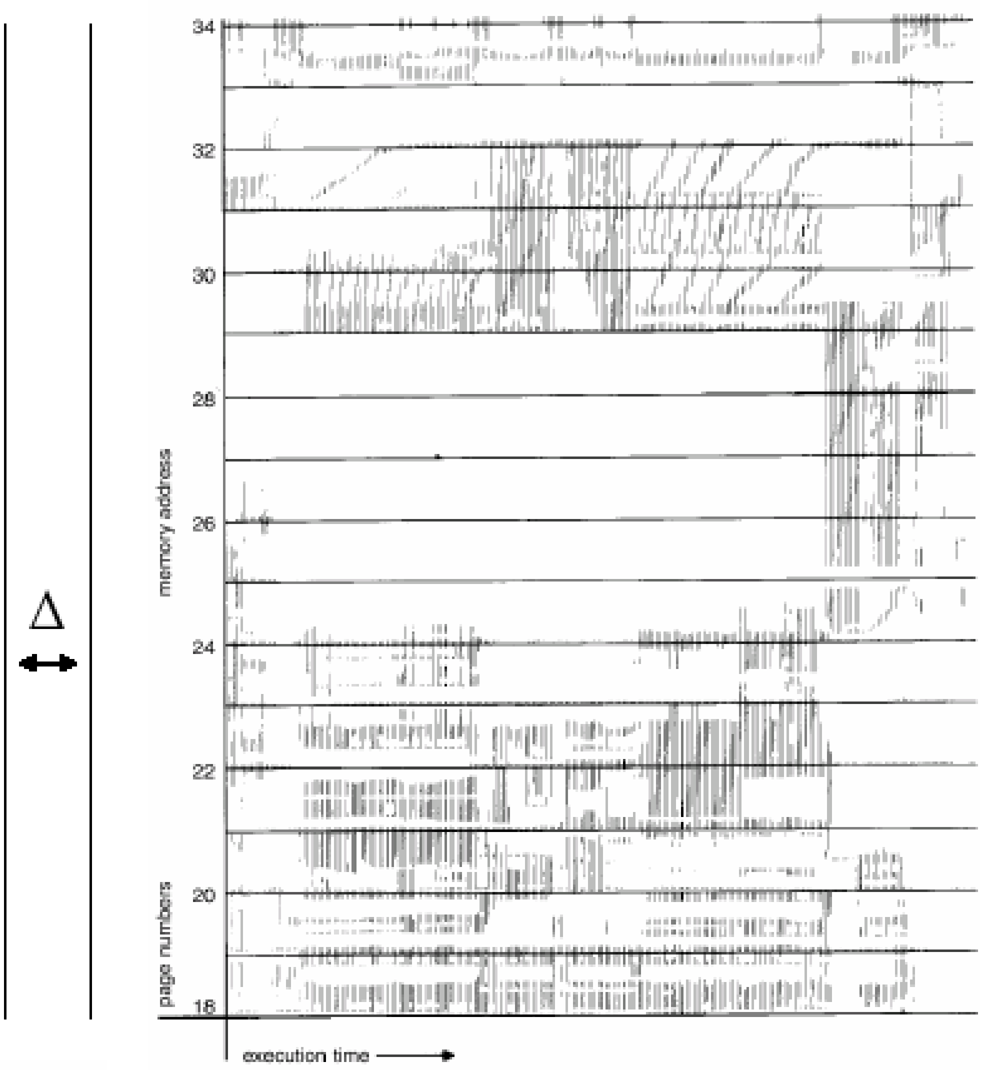
Locality In A Memory-Reference Pattern



Working Set

- The pages/segments required by an application in a time window (Δ)is called its memory ***working set***.
- Working set is an approximation of a programs' locality
  - 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.
  - Δ's size is an application specific tradeoff
- System should keep resident at least a process's working set
  - Process executes while it remains in its working set
- Working set tends to change gradually
    - Get only a few page/segment faults during a time window
    - Possible to make intelligent guesses about which pieces will be needed in the future
      - May be able to pre-fetch page/segments

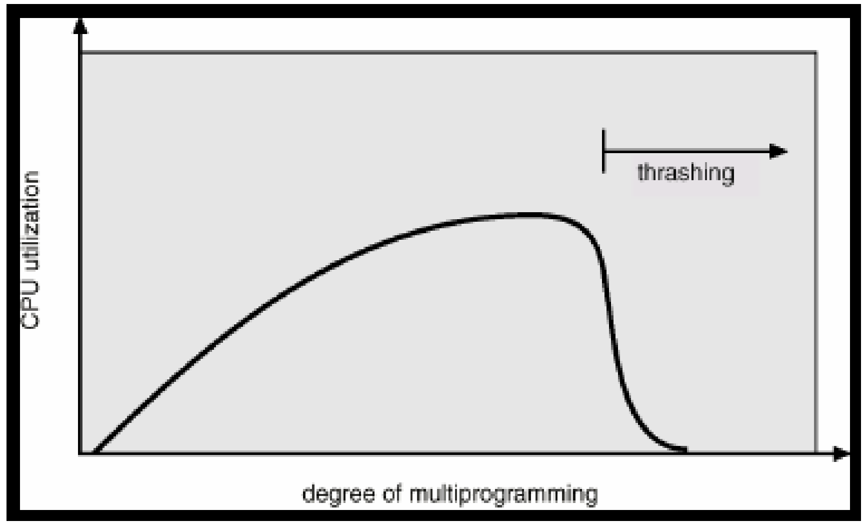
Working Set Model



Thrashing

- CPU utilisation tends to increase with the degree of multiprogramming
  - number of processes in system
- Higher degrees of multiprogramming – less memory available per process
- Some process's working sets may no longer fit in RAM
  - Implies an increasing page fault rate
- Eventually many processes have insufficient memory
  - Can't always find a runnable process
  - Decreasing CPU utilisation
  - System become I/O limited
- This is called ***thrashing***.

Thrashing



- Why does thrashing occur?

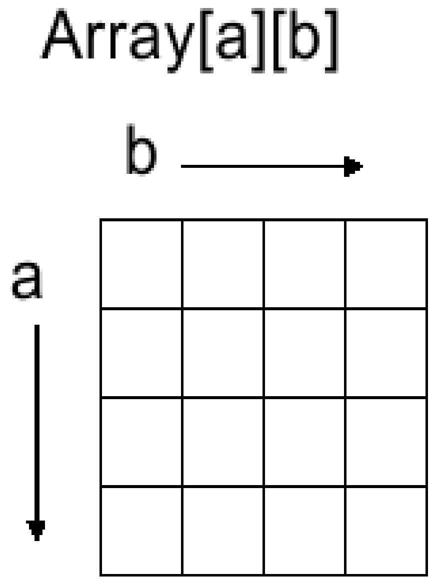
Σ working set sizes > total physical memory size

Recovery From Thrashing

- In the presence of increasing page fault frequency and decreasing CPU utilisation
  - Suspend a few processes to reduce degree of multiprogramming
  - Resident pages of suspended processes will migrate to backing store
  - More physical memory becomes available
    - Less faults, faster progress for runnable processes
  - Resume suspended processes later when memory pressure eases

What is the difference?

```
/* reset array */
int array[10000][10000];
int i,j;
for (i = 0; i < 10000; i++) {
   for (j = 0; j < 10000;j ++) {
        array[i][j] = 0;
        /* array[j][i] = 0 */
   }
}
```



VM Management Policies

- Operation and performance of VM system is dependent on a number of policies:
  - Page table format (my be dictated by hardware)
    - Multi-level
    - Hashed
  - Page size (may be dictated by hardware)
  - Fetch Policy
  - Replacement policy
  - Resident set size
    - Minimum allocation
    - Local versus global allocation
  - Page cleaning policy
  - Degree of multiprogramming

Page Size

Increasing page size

- ✗ Increases internal fragmentation
  - reduces adaptability to working set size
- ✓ Decreases number of pages
  - Reduces size of page tables
- ✓ Increases TLB coverage
  - Reduces number of TLB misses
- ✗ Increases page fault latency
  - Need to read more from disk before restarting process
- ✓ Increases swapping I/O throughput
  - Small I/O are dominated by seek/rotation delays
- Optimal page size is a (work-load dependent) trade-off.

Atlas	512 words (48-bit)
Honeywell/Multics	1K words (36-bit)
IBM 370/XA	4K bytes
DEC VAX	512 bytes
IBM AS/400	512 bytes
Intel Pentium	4K and 4M bytes
ARM	4K and 64K bytes
MIPS R4000	4k – 16M bytes in powers of 4
DEC Alpha	8K - 4M bytes in powers of 8
UltraSPARC	8K – 4M bytes in powers of 8
PowerPC	4K bytes + “blocks”
Intel IA-64	4K – 256M bytes in powers of 4

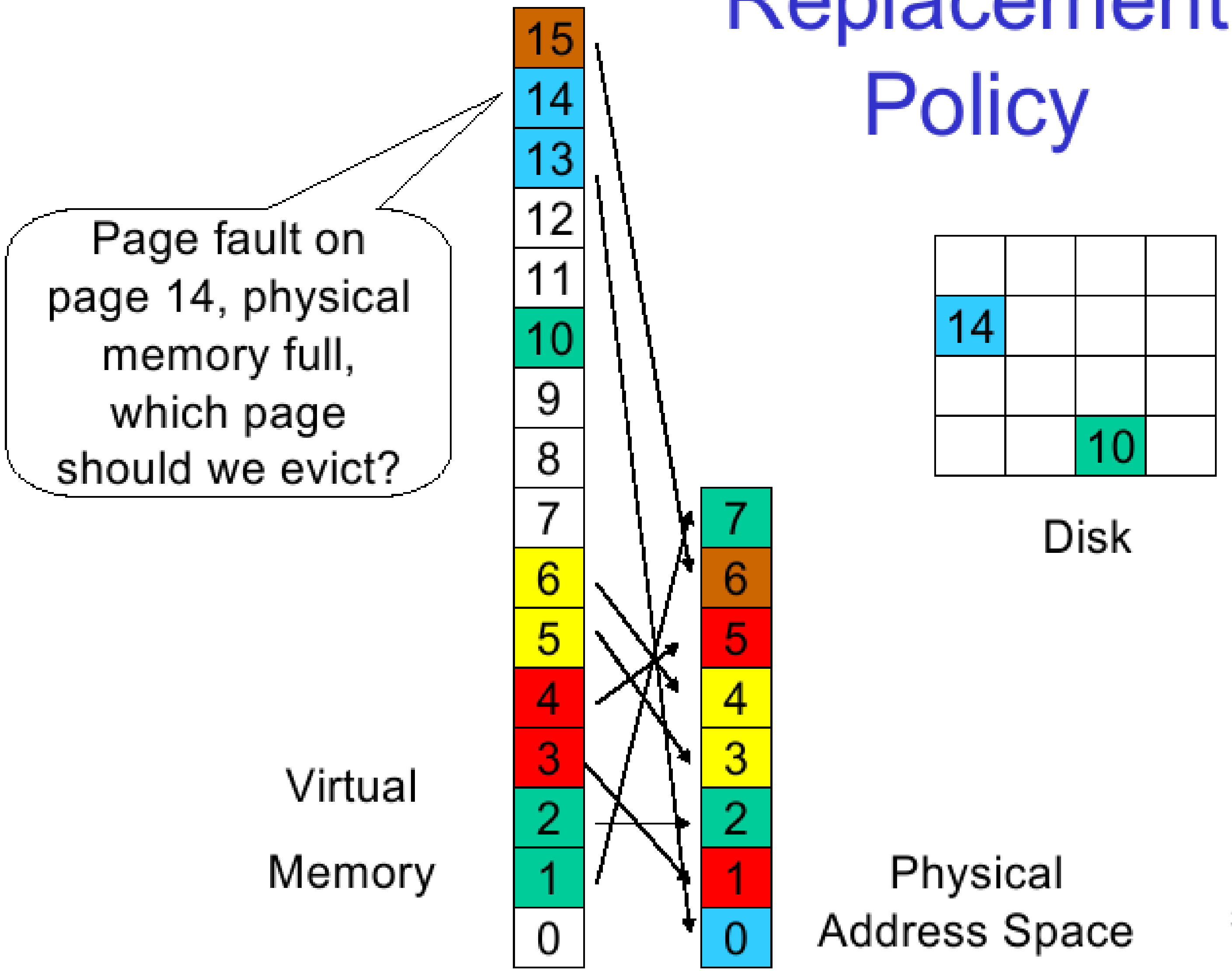
Page Size

- Multiple page sizes provide flexibility to optimise the use of the TLB
- Example:
  - Large page sizes can be use for code
  - Small page size for thread stacks
- Most operating systems support only a single page size
  - Dealing with multiple page sizes is hard!

Fetch Policy

- Determines *when* a page should be brought into memory
  - *Demand paging* only loads pages in response to page faults
    - Many page faults when a process first starts
  - *Pre-paging* brings in more pages than needed at the moment
    - Improves I/O performance by reading in larger chunks
    - Pre-fetch when disk is idle
    - Wastes I/O bandwidth if pre-fetched pages aren't used
    - Especially bad if we eject pages in working set in order to pre-fetch unused pages.
    - Hard to get right in practice.

Replacement Policy



Replacement Policy

- Which page is chosen to be tossed out?
  - Page removed should be the page least likely to be references in the near future
  - Most policies attempt to predict the future behaviour on the basis of past behaviour
- Constraint: locked frames
  - Kernel code
  - Main kernel data structure
  - I/O buffers
  - Performance-critical user-pages (e.g. for DBMS)
- Frame table has a *lock* bit

Optimal Replacement policy

- Toss the page that won't be used for the longest time
- Impossible to implement
- Only good as a theoretic reference point:
  - The closer a practical algorithm gets to *optimal*, the better
- Example:
  - Reference string: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5
  - Four frames
  - How many page faults?

FIFO Replacement Policy

- First-in, first-out: Toss the oldest page
  - Easy to implement
  - Age of a page is isn't necessarily related to usage
- Example:
  - Reference string: 1,2,3,4,1,2,5,1,2,3,4,5
  - Four frames
  - How many page faults?
  - Three frames?

Belady's Anomaly

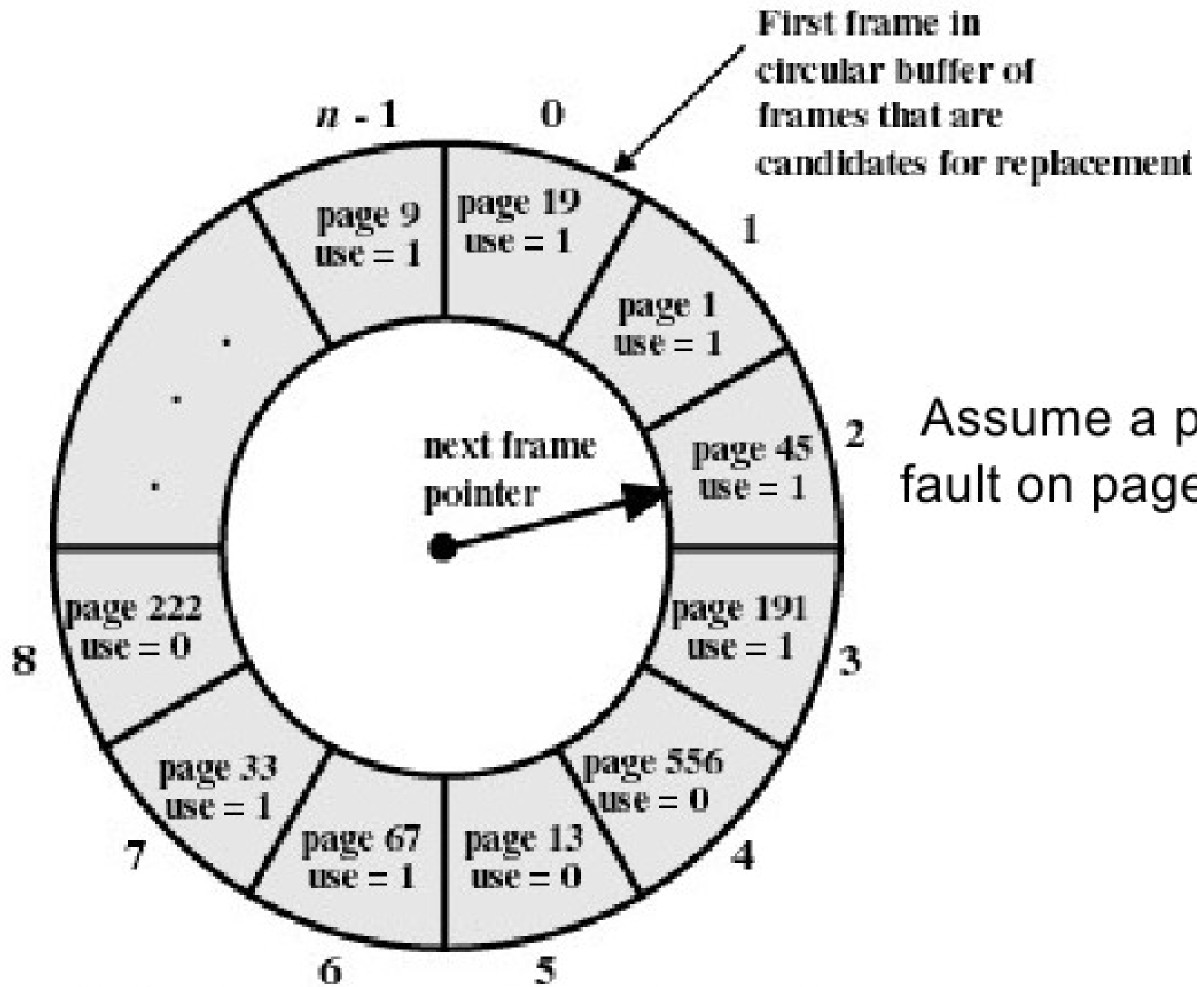
- More frames does not imply fewer page faults

Least Recently Used (LRU)

- Toss the least recently used page
  - Assumes that page that has not been referenced for a long time is unlikely to be referenced in the near future
  - Will work if locality holds
  - Implementation requires a time stamp to be kept for each page, updated **on every reference**
  - Impossible to implement efficiently
  - Most practical algorithms are approximations of LRU

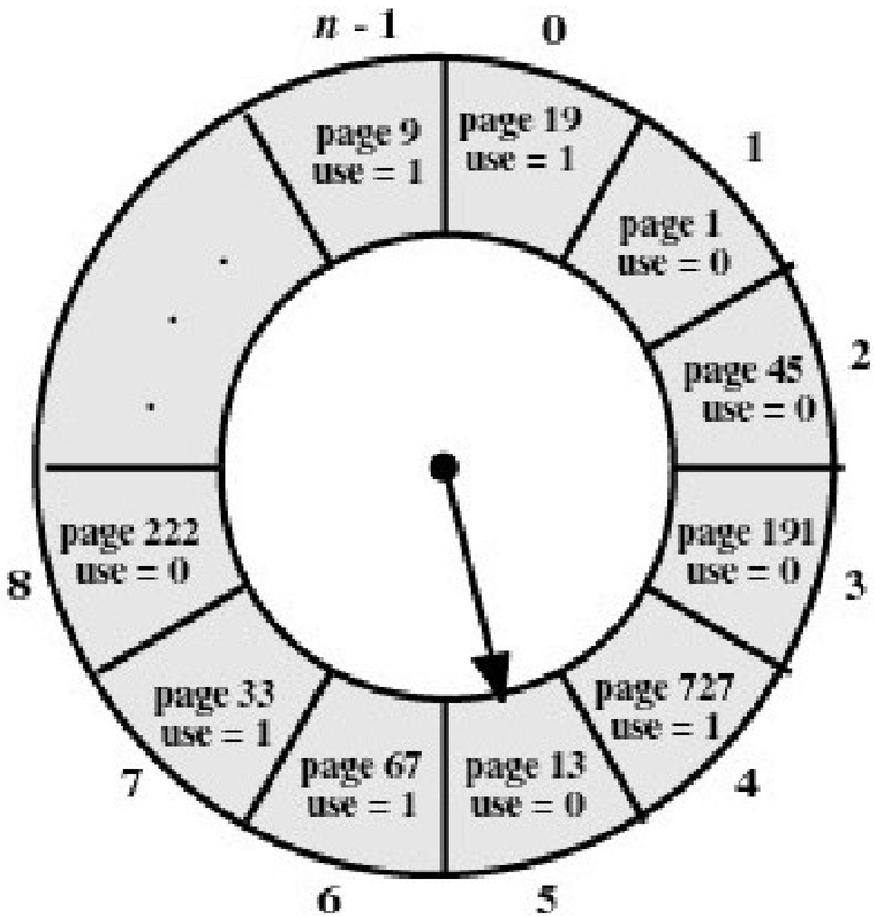
Clock Page Replacement

- Clock policy, also called *second chance*
  - Employs a *usage* or *reference* bit in the frame table.
  - Set to *one* when page is used
  - While scanning for a victim, reset all the reference bits
  - Toss the first page with a zero reference bit.



(a) State of buffer just prior to a page replacement

Assume a page fault on page 727



(b) State of buffer just after the next page replacement

Issue

- How do we know when a page is referenced?
- Use the valid bit in the PTE:
  - When a page is mapped (valid bit set), set the reference bit
  - When resetting the reference bit, invalidate the PTE entry
  - On page fault
    - Turn on valid bit in PTE
    - Turn on reference bit
- We thus simulate a reference bit in software

Performance

- It terms of selecting the most appropriate replacement, they rank as follows
  1. Optimal
  2. LRU
  3. Clock
  4. FIFO
- – Note there are other algorithms (Working Set, WSclock, Ageing, NFU, NRU)
  - – We don't expect you to know them in this course

Resident Set Size

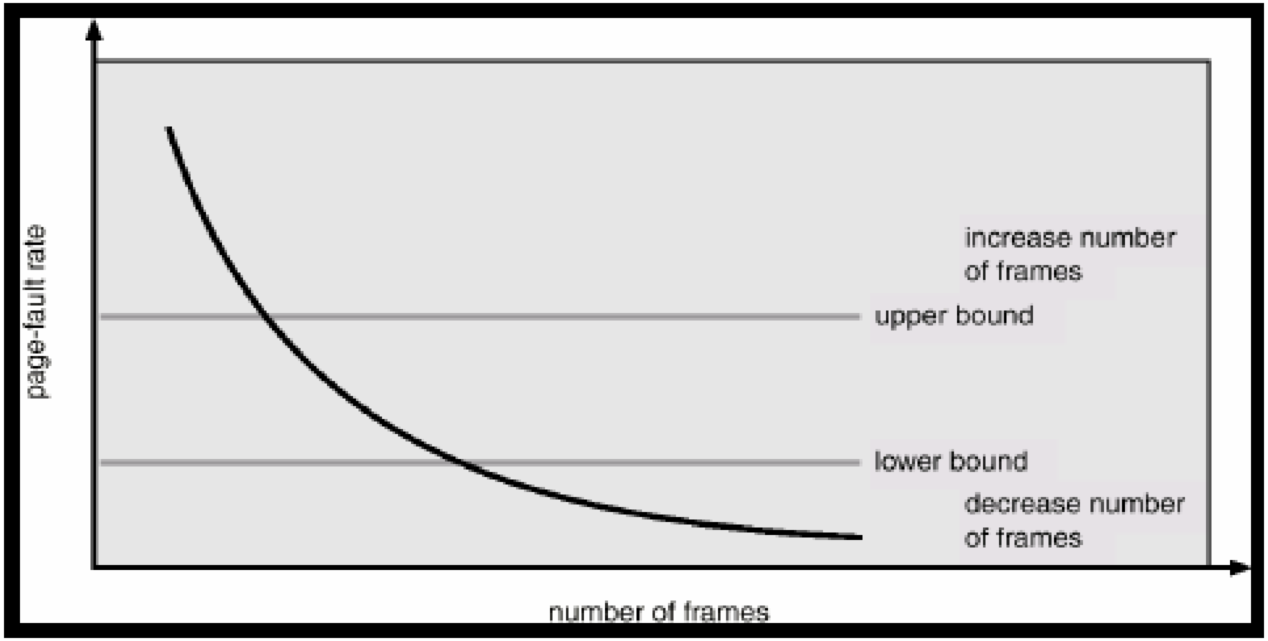
- How many frames should each process have?
  - *Fixed Allocation*
    - Gives a process a fixed number of pages within which to execute.
    - When a page fault occurs, one of the pages of that process must be replaced.
    - Achieving high utilisation is an issue.
      - Some processes have high fault rate while others don't use their allocation.
  - *Variable Allocation*
    - Number of pages allocated to a process varies over the lifetime of the process

- Variable Allocation, Global Scope
  - Easiest to implement
  - Adopted by many operating systems
  - Operating system keeps global list of free frames
  - Free frame is added to resident set of process when a page fault occurs
  - If no free frame, replaces one from any process

Variable Allocation, Local Scope

- Allocate number of page frames to a new process based on
  - Application type
  - Program request
  - Other criteria (priority)
- When a page fault occurs, select a page from among the resident set of the process that suffers the page fault
- *Re-evaluate allocation from time to time!*

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.

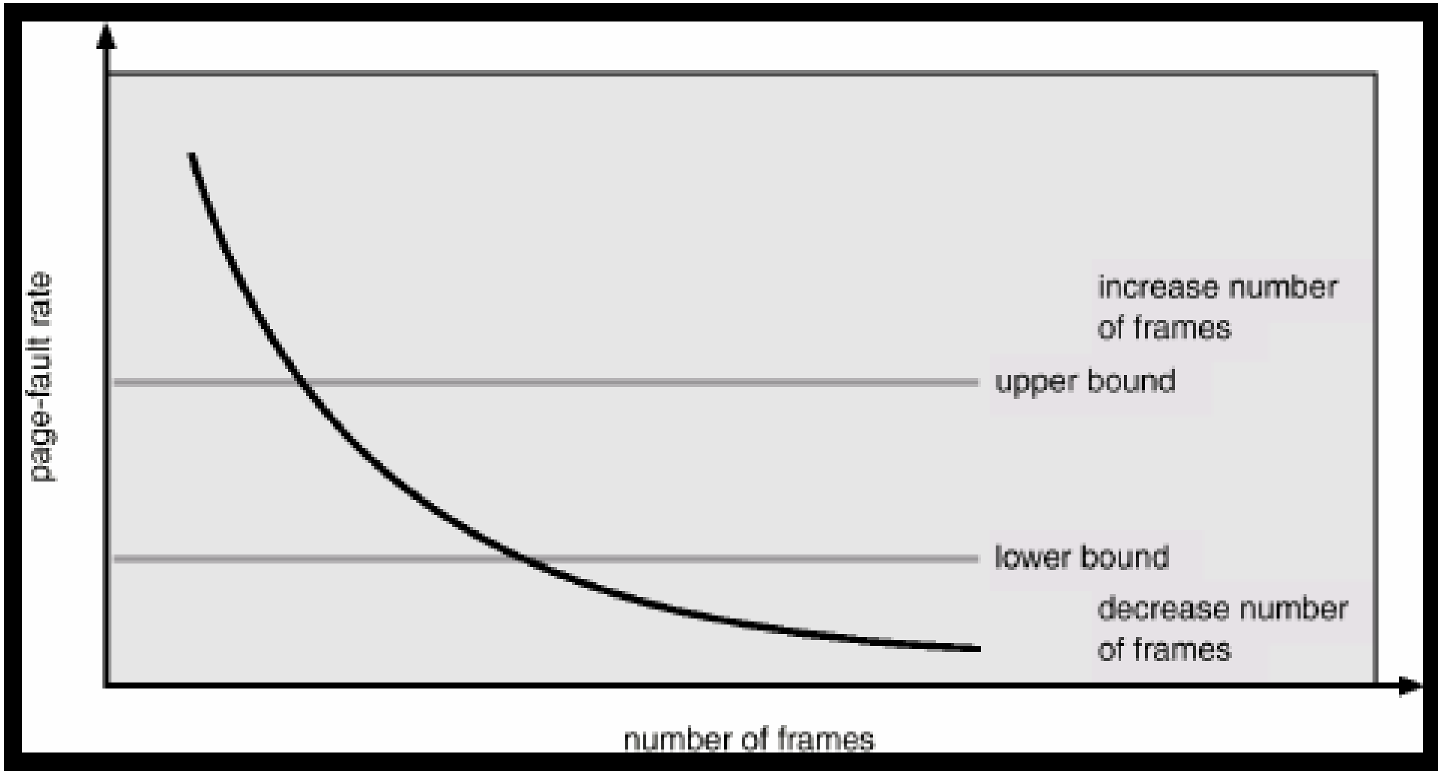
Cleaning Policy

- Observation
  - Clean pages are much cheaper to replace than dirty pages
- Demand cleaning
  - A page is written out only when it has been selected for replacement
  - High latency between the decision to replace and availability of free frame.
- Precleaning
  - Pages are written out in batches (in the background, the *pagedaemon*)
  - Increases likelihood of replacing clean frames
  - Overlap I/O with current activity

Load Control (Degree of multiprogramming)

- Determines the number of runnable processes
- Controlled by:
  - Admission control
    - Only let new process's threads enter *ready* state if enough memory is available
  - Suspension:
    - Move all threads of some process into a special *suspended* state
    - Swap complete process image of suspended process to disk
- Trade-off
  - Too many processes will lead to thrashing
  - Too few will lead to to idle CPU or excessive swapping

Load Control Considerations



- Can use page fault frequency.