# Chapter 10: Virtual Memory

- Background
- Demand Paging
- Process Creation
- Page Replacement
- Allocation of Frames
- Thrashing
- Demand Segmentation
- Operating System Examples

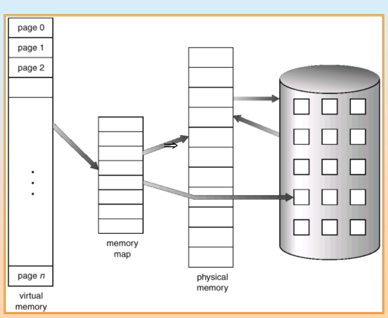


# Background

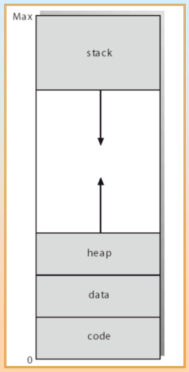
- **Virtual memory** – separation of user logical memory from physical memory.
  - Only part of the program needs to be in memory for execution.
  - Logical address space can therefore be much larger than physical address space.
  - Allows address spaces to be shared by several processes.
  - Allows for more efficient process creation.
- Virtual memory can be implemented via:
  - Demand paging
  - Demand segmentation



# Virtual Memory That is Larger Than Physical Memory



## Virtual-address Space



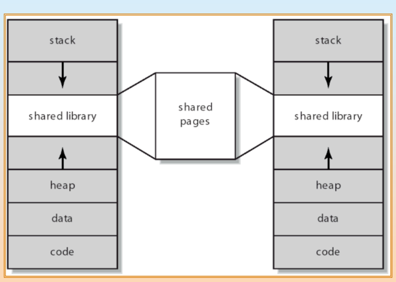



## Virtual Memory has Many Uses

- It can enable processes to so share memory



## Shared Library Using Virtual Memory

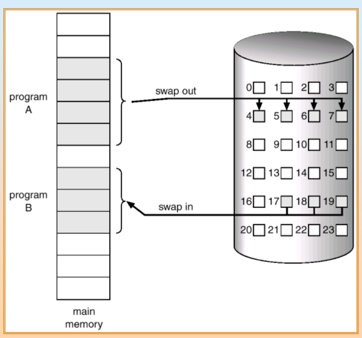


# Demand Paging

- Bring a page into memory only when it is needed
  - Less I/O needed
  - Less memory needed
  - Faster response
  - More users
- Page is needed ⇒ reference to it
  - invalid reference ⇒ abort
  - not-in-memory ⇒ bring to memory



# Transfer of a Paged Memory to Contiguous Disk Space






# Valid-Invalid Bit

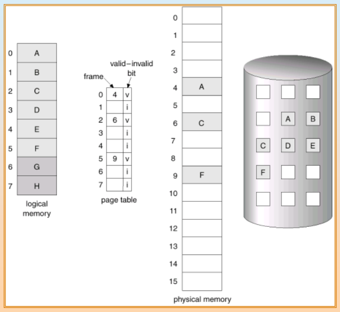
- With each page table entry a valid–invalid bit is associated (1 ⇒ in-memory, 0 ⇒ not-in-memory)
- Initially valid–invalid but is set to 0 on all entries
- Example of a page table snapshot:

| Frame # | valid-invalid bit |
|---|---|
| | 1 |
| | 1 |
| | 1 |
| | 1 |
| | 0 |
| ⋮ | |
| | 0 |
| | 0 |

page table

- During address translation, if valid–invalid bit in page table entry is 0 ⇒ page fault

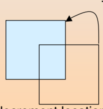
## Page Table When Some Pages Are Not in Main Memory






## Page Fault

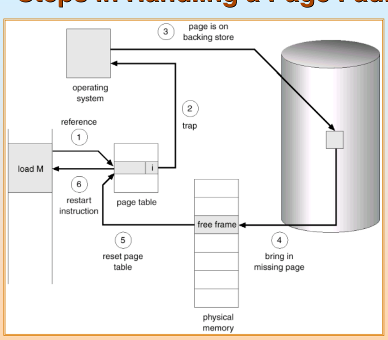
- If there is ever a reference to a page, first reference will trap to OS ⇒ page fault
- OS looks at another table to decide:
  - Invalid reference ⇒ abort.
  - Just not in memory.
- Get empty frame.
- Swap page into frame.
- Reset tables, validation bit = 1.
- Restart instruction: Least Recently Used
  - block move



  - auto increment/decrement location



## Steps in Handling a Page Fault



## What happens if there is no free frame?

- Page replacement – find some page in memory, but not really in use [i.e., “least recently used”], swap it out
  - algorithm (logic process for deciding which to choose)
  - performance – want an algorithm which will result in minimum number of page faults
- Same page may be brought into memory several times [if page faults are occurring]



## Performance of Demand Paging

- Page Fault Rate $0 \le p \le 1.0$
  - 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)

“swap page out” = “swap page in” x “probablity it has been changed”



## Demand Paging Example

- Memory access time = 1 microsecond (usec)
- 50% of the time the page that is being replaced has been modified and therefore needs to be swapped out
- Swap Page Time = 10 msec = 10,000 usec

EAT = (1 – p) x 1usec + p (1+ 0.50) 10000 usec
1 + 14999 x p (in usec)

If page fault rate p = 0.1% (0.001), then
EAT = 16 usec (16 times the memory access time)
Page faults can be zero for small data sizes that fit in memory.

[Why will adding more memory speed up your PC?]

## Process Creation

- Virtual memory allows other benefits during process creation:

  - Copy-on-Write

  - Memory-Mapped Files (later)



## Copy-on-Write

- 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, only then is the page copied [parent and child processes use different versions]

- COW allows more efficient process creation as only modified pages are copied

- Free pages are allocated from a **pool** of zeroed-out pages



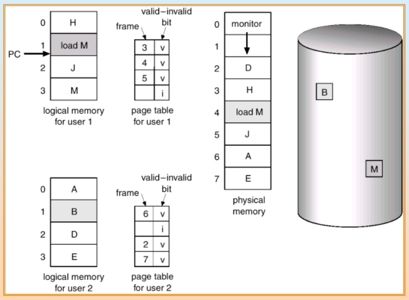
## Page Replacement

- Prevent over-allocation of memory by modifying page-fault service routine to include page replacement

- Use **modify (dirty) bit** to reduce overhead of page transfers – only modified pages are written to disk

- 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



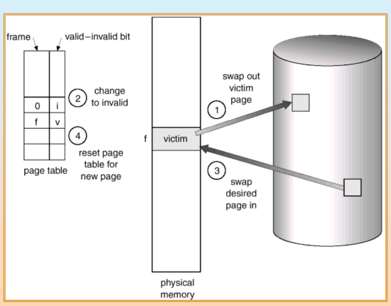



## Basic Page Replacement

- 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 (newly) free frame. Update the page and frame tables.
- Restart [ continue] the process



## Page Replacement



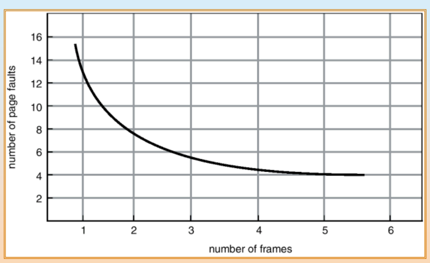
# Page Replacement Algorithms

- Want 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

  2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5 [ 1 is LRU ]



# Graph of Page Faults Versus The Number of Frames






# First-In-First-Out (FIFO) Algorithm

- Reference string: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5
- 3 frames (3 pages can be in memory at a time per process)

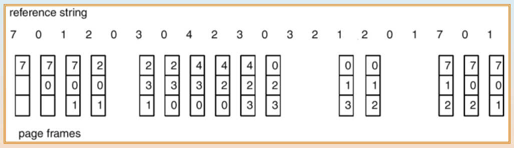
| | | | | |
|---|---|---|---|---|
| 1 | 1 | 4 | 5 | |
| 2 | 2 | 1 | 3 | 9 page faults |
| 3 | 3 | 2 | 4 | |

- 4 frames

| | | | | |
|---|---|---|---|---|
| 1 | 1 | 5 | 4 | |
| 2 | 2 | 1 | 5 | 10 page faults |
| 3 | 3 | 2 | | |
| 4 | 4 | 3 | | |

- FIFO Replacement – Belady's Anomaly
  - more frames (can) ⇒ more page faults (but not generally)

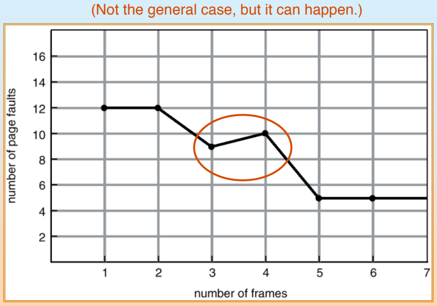
# FIFO Page Replacement






# FIFO Illustrating Belady's Anomaly

(Not the general case, but it can happen.)

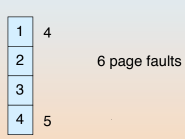





# Optimal Algorithm

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

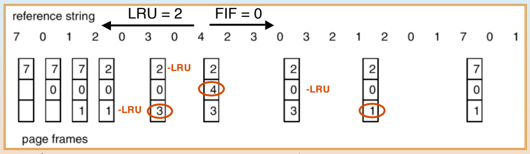
1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5




- How do you know this?
- Used for measuring how well your algorithm performs

# Optimal Page Replacement

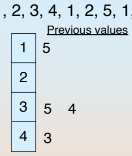
( Look Ahead - FIF = Farthest in Future )






# Least Recently Used (LRU) Algorithm

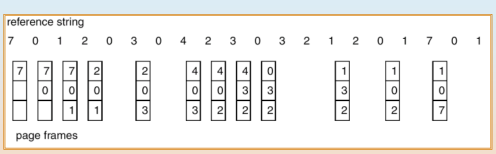
- Reference string: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5




- Counter 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. [inefficient -why?]



# LRU Page Replacement

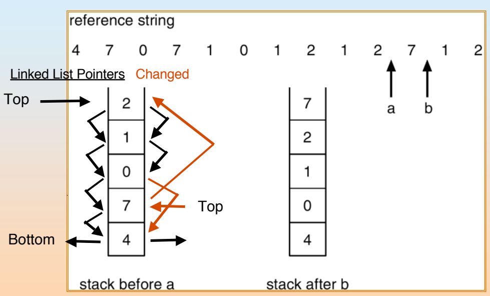


# LRU Algorithm (Cont.)

- Stack implementation – keep a stack of page numbers in a double link form:
  - Page referenced:
    - move it to the top
    - requires 6 pointers to be changed
  - No search for replacement (page at bottom of stack replaced)



## Use Of A Stack to Record The Most Recent Page References



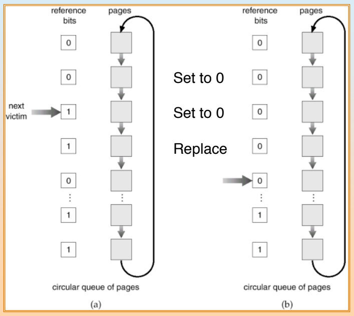



# LRU Approximation Algorithms

- Reference bit
  - With each page associate a bit, initially = 0
  - When page is referenced bit set to 1 [indicates a second reference]
  - Replace the first one which is 0 (if one exists). We do not know the order, however. [ move through pages in a circular manner]
- Second chance
  - 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

## Reference Bit Page-Replacement Algorithm

"2nd Chance" replaces oldest (by clock) rather than "circular pointer"






## Counting Algorithms

- Keep a counter of the number of references that have been made to each page
- **LFU Algorithm**: replaces page with smallest count
- **MFU Algorithm**: based on the argument that the page with the smallest count was probably just brought in and has yet to be used



## Allocation of Frames

- Each process needs *minimum* number of pages
- Example: IBM 370 – 6 pages to handle SS MOVE instruction:
  - instruction is 6 bytes, might span 2 pages
  - 2 pages to handle *from*
  - 2 pages to handle *to*
- Two major allocation schemes
  - fixed allocation
  - priority allocation

## Fixed Allocation

- Equal allocation – e.g., if 100 frames and 5 processes, give each 20 pages
- Proportional allocation – Allocate according to the size of process
  - $s_i$ = size of process $p_i$
  - $S = \sum s_i$
  - $m$ = total number of frames
  - $a_i$ = allocation for $p_i = \frac{s_i}{S} \times m$

$m = 64$

$s_i = 10$

$s_2 = 127$

$a_1 = \frac{10}{137} \times 64 \approx 5$

$a_2 = \frac{127}{137} \times 64 \approx 59$



## Priority Allocation

- Use a proportional allocation scheme using priorities rather than size
- If process $P_i$ generates a page fault,
  - select for replacement one of its frames - or -
  - select for replacement a frame from a process with lower priority number



## Global vs. Local Allocation

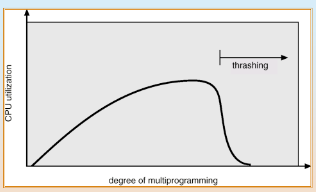
- **Global replacement** – process selects a replacement frame from the set of all frames; one process can take a frame from another
- **Local replacement** – each process selects from only its own set of allocated frames

## Thrashing

- If a process does not have “enough” pages, the page-fault rate is very high. This leads to:
  - low CPU utilization
  - operating system thinks that it needs to increase the degree of multiprogramming
  - another process added to the system
- **Thrashing** ≡ a process is busy swapping pages in and out



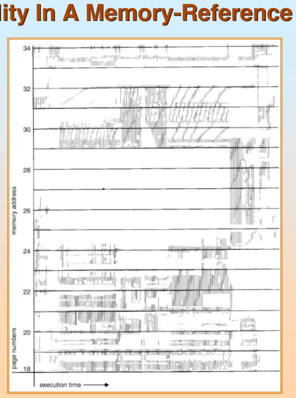
## Thrashing




- Why does paging work?
  Locality model
  - Process migrates from one locality to another
  - Localities may overlap
- Why does thrashing occur?
  $\Sigma$ size of locality > total memory size



## Locality In A Memory-Reference Pattern

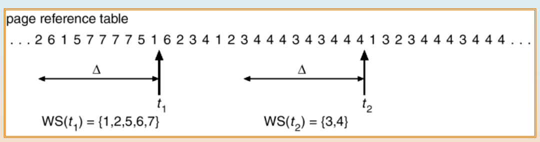


## Working-Set Model

- Δ ≡ working-set window ≡ a fixed number of page references
  Example: 10,000 instruction
- $WSS_i$ (working set of Process $P_i$) =
  total number of pages referenced in the most recent Δ (varies in time)
  - if Δ too small will not encompass entire locality
  - if Δ too large will encompass several localities
  - if Δ = ∞ ⇒ will encompass entire program
- $D = \Sigma\ WSS_i \equiv$ total demand frames
- if $D > m \Rightarrow$ Thrashing
- Policy if $D >$ m, then suspend one of the processes



## Working-set model

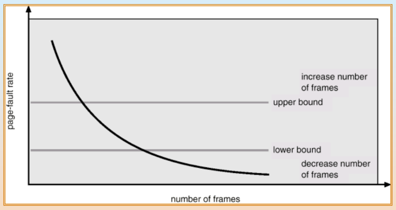





## Keeping Track of the Working Set

- Approximate with interval timer + a reference bit
- Example: Δ = 10,000
  - Timer interrupts after every 5000 time units
  - Keep in memory 2 bits for each page
  - Whenever a timer interrupts copy and sets the values of all reference bits to 0
  - If one of the bits in memory = 1 ⇒ page in working set
- Why is this not completely accurate?
- Improvement = 10 bits and interrupt every 1000 time units

## 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

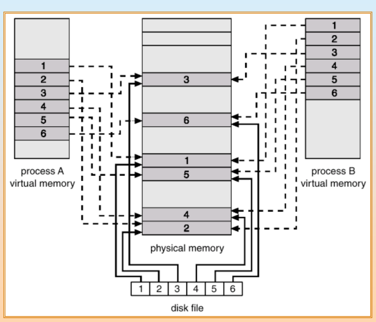


## Memory-Mapped Files

- Memory-mapped file I/O allows file I/O to be treated as routine memory access by *mapping* a disk block to a page in memory
- A file is initially read using demand paging. A page-sized portion of the file is read from the file system into a physical page. Subsequent reads/writes to/from the file are treated as ordinary memory accesses.
- Simplifies file access by treating file I/O through memory rather than **read() write()** system calls
- Also allows several processes to map the same file allowing the pages in memory to be shared



## Memory Mapped Files



## Memory-Mapped Files in Java

```
import java.io.*;
import java.nio.*;
import java.nio.channels.*;
public class MemoryMapReadOnly
{
    // Assume the page size is 4 KB
    public static final int PAGE SIZE = 4096;
    public static void main(String args[]) throws IOException {
        RandomAccessFile inFile = new RandomAccessFile(args[0],"r");
        FileChannel in = inFile.getChannel();
        MappedByteBuffer mappedBuffer =
          in.map(FileChannel.MapMode.READ ONLY, 0, in.size());
        long numPages = in.size() / (long)PAGE SIZE;
        if (in.size() % PAGE SIZE > 0)
                ++numPages;
```



## Memory-Mapped Files in Java (cont)

```
        // we will "touch" the first byte of every page
        int position = 0;
        for (long i = 0; i < numPages; i++) {
                byte item = mappedBuffer.get(position);
                position += PAGE SIZE;
        }
        in.close();
        inFile.close();
    }
}
```

- The API for the map() method is as follows:

map(mode, position, size)



## Other Issues

- Prepaging
  - To reduce the large number of page faults that occurs at process startup
  - Prepage all or some of the pages a process will need, before they are referenced
  - But if prepaged pages are unused, I/O and memory was wasted
  - Assume $s$ pages are prepaged and $\alpha$ of the pages is used
    - Is cost of $s * \alpha$ save pages faults > or < than the cost of prepaging $s * (1- \alpha)$ unnecessary pages?
    - $\alpha$ near zero $\Rightarrow$ prepaging loses
- Page size selection must take into consideration:
  - fragmentation
  - table size
  - I/O overhead
  - locality

## Other Issues (Cont.)

- **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.

TLB is Translation Look-aside Buffer



## Other Issues (Cont.)

- **Increase the Page Size**. This may lead to an increase in fragmentation as not all applications require a large page size.
- **Provide Multiple Page Sizes**. This allows applications that require larger page sizes the opportunity to use them without an increase in fragmentation.



## Other Issues (Cont.)

- Program structure
  - **int A[][] = new int[1024][1024];**
  - Each row is stored in one page [page size = 4096 bytes]
  - Program 1

```
for (j = 0; j < A.length; j++)
    for (i = 0; i < A.length; i++)
        A[i,j] = 0;
```

1024 x 1024 page faults

  - Program 2

```
for (i = 0; i < A.length; i++)
    for (j = 0; j < A.length; j++)
        A[i,j] = 0;
```

1024 page faults

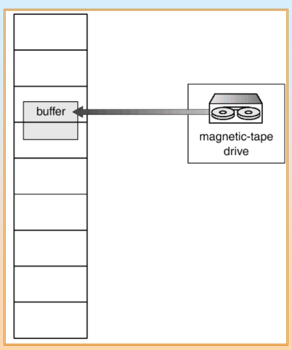
[ Moral: Inner loop should be over left-most array index.]

## Other Considerations (Cont.)

- **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.



## Reason Why Frames Used For I/O Must Be In Memory






## Demand Segmentation

- Used when insufficient hardware to implement demand paging.
- OS/2 allocates memory in segments, which it keeps track of through segment descriptors
- Segment descriptor contains a valid bit to indicate whether the segment is currently in memory.
  - If segment is in main memory, access continues,
  - If not in memory, segment fault.

## Operating System Examples

- Windows NT
- Solaris 2



## Windows XP

- Uses demand paging with **clustering**. Clustering brings in pages surrounding the faulting page.
- Processes are assigned **working set minimum** and **working set maximum**
- Working set minimum is the minimum number of pages the process is guaranteed to have in memory
- A process may be assigned as many pages up to its working set maximum
- When the amount of free memory in the system falls below a threshold, **automatic working set trimming** is performed to restore the amount of free memory
- Working set trimming removes pages from processes that have pages in excess of their working set minimum



## Solaris

- Maintains a list of free pages to assign faulting processes
- *Lotsfree* – threshold parameter (amount of free memory) to begin paging
- *Desfree* – threshold parameter to increasing paging
- *Minfree* – threshold parameter to being swapping
- Paging is performed by *pageout* process
- Pageout scans pages using modified clock algorithm
- *Scanrate* is the rate at which pages are scanned. This ranges from *slowscan* to *fastscan*
- Pageout is called more frequently depending upon the amount of free memory available

# Solaris 2 Page Scanner