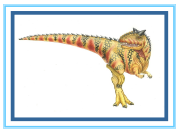
Chapter 10: Virtual Memory



Chapter 10: Virtual Memory

- Background
- Demand Paging
- Copy-on-Write
- Page Replacement
- Frame Allocation
- Thrashing
- Other Considerations

Objectives

- Define virtual memory and describe its benefits.
- Illustrate how pages are loaded into memory using demand paging.
- Apply the FIFO, optimal, and LRU page-replacement algorithms.
- Describe the working set of a process, and explain how it is related to program locality.

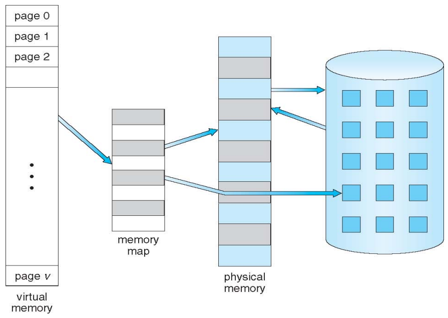
Background

- Codes need to be in memory to execute, but not necessarily the entire program.
  - Error code, unusual routines. Some errors seldom, if ever, occur in practice, this code is almost never executed
  - Large data structures such as arrays, lists and tables are often allocated more memory than they actually need. For example, an array may be declared 100x100 elements, even though it is seldom larger than 10x10
  - Certain options and features of a program may be used rarely
- Even if the entire program is needed, it may not all be needed at the same time
- Consider ability to execute partially-loaded programs
  - Programs no longer constrained by limits of physical memory. Programs can be written with an extremely large virtual memory address, simplifying the programming task
  - Each user program could take less physical memory, more programs could be run at the same time, which increases CPU utilization (**degree of multiprogramming**) and throughput
  - Less I/O would be needed to load or swap user programs into physical memory, so each user program would run faster.

Background

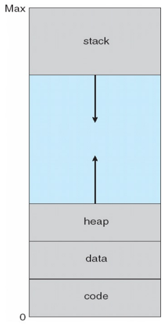
- **Virtual memory** – separation of user logical memory perceived by programmers from physical memory
  - Only part of the program needs to be in memory for execution
  - Logical address space can therefore be much larger than the actual physical address space
  - Allows address spaces to be shared by several processes. For instance, system libraries can be shared by several processes
  - Allows more efficient process creation, as pages can be shared during process creation, thus speeding up the process creation
  - More programs running concurrently – increase the degree of multiprogramming
  - Less I/O needed to load or swap processes
- Virtual memory can be implemented via:
  - Demand paging or demand segmentation – in principle, they are similar, details are different with respect to fix-sized frame/page and variable-sized segment

Virtual Memory That is Larger Than Physical Memory

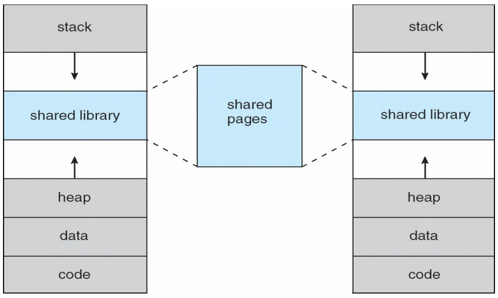


Virtual-address Space

- Virtual address space – logical view of how process is stored in memory
  - Usually start at address 0, contiguous addresses until the end of address space
  - Meanwhile, physical memory organized in frames
  - MMU must map logical to physical address
- Heap can grow upward in memory, used in dynamic memory allocation. Stack can grow downward in memory through successive function calls
- The large blank space (or hole) between the heap and stack is part of the virtual address space, but will require actual physical pages (space) only if the heap or stack grows.
- Enables sparse address spaces with holes left for growth, dynamically linked libraries, and etc
- System libraries can be shared via mapped into virtual address space
- Pages can be shared during process creation with the fork() system call, speeding up process creation

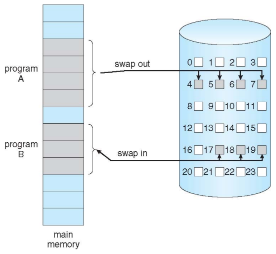


Shared Library Using Virtual Memory



Demand Paging

- Could bring entire process into memory at load time
- Or bring a page into memory only when the page is actually needed - referenced
  - Less I/O needed, no unnecessary I/O
  - Less memory needed
  - Faster response
  - More users to be running
- Similar to paging system with swapping (diagram on right)
- Page is needed ⇒ reference to it
  - invalid reference (illegal memory address) ⇒ abort
  - not-in-memory ⇒ bring to memory
- Lazy swapper – never swaps a page into memory unless page will be needed
  - Swapper that deals with pages is a pager

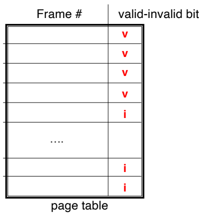


Basic Concepts

- Pager brings in only those “needed” pages into memory
- How to determine the set of pages brought inside memory?
  - Need new MMU functionality to implement demand paging
- If pages needed are already memory-resident
  - No difference from non demand-paging MMU
- If pages needed are not memory resident
  - Need to detect and load the page into memory from a secondary storage device
    - Without changing program behavior
    - Without programmer needing to change code – application not aware of this

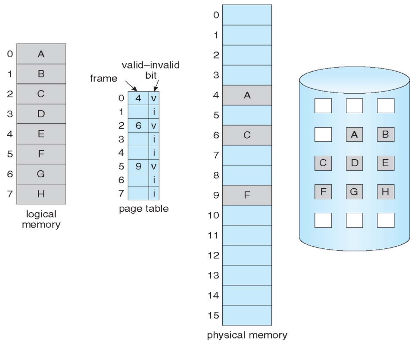
Valid-Invalid Bit

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



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

Page Table When Some Pages Are Not in Main Memory



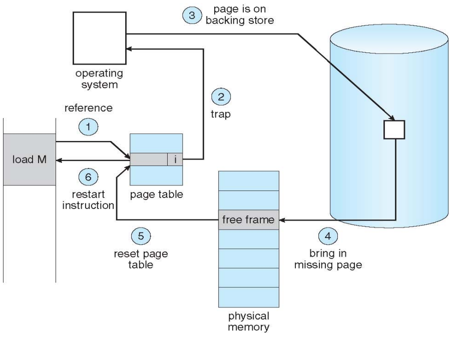
Page Fault

- If there is a reference to a page, first reference to that page will trap to operating system:

  Page Fault

1. Operating system looks at the corresponding table entry to decide:
   - Invalid reference (illegal address) ⇒ abort
   - Just not in memory
2. Get an empty frame if any - OS maintains free-frame list
3. Swap the page into the frame via scheduled disk operation
4. Reset tables to indicate page now in memory
   Set validation bit = **v**
5. Restart the instruction (depending on CPU scheduling) that caused the page fault

Steps in Handling a Page Fault



Aspects of Demand Paging

- The extreme case – start process with *no* pages in memory
  - OS sets instruction pointer to first instruction of process, non-memory-resident -> page fault
  - And for every other process pages on the first access
  - This is referred as **Pure demand paging**
- Actually, a given instruction could access multiple pages -> result in multiple page faults
  - Consider fetch and decode of instruction which adds two numbers from memory and stores result back to memory
  - Pain caused by page faults decreases after process starts running for some time because of locality of memory reference
- Hardware support is needed for demand paging
  - Page table with valid / invalid bit as indication
  - Secondary memory (swap device with swap space) for page in and page out
  - Instruction restart

Free-Frame List

- When a page fault occurs, the operating system must bring the desired page from the secondary storage into main memory.
- Most operating systems maintain a free-frame list -- a pool of free frames for satisfying such requests (a kernel data structure that only OS can access)

head → 7 → 97 → 15 → 126 ··· → 75

- Operating system typically allocate free frames using a technique known as zero-fill-on-demand -- the content of the frames zeroed-out before being (re)-allocated.
  - The technique of the writing of zeros into a page before it is made available to a process - thus erasing their previous contents or to keep any old data from being available to the process
  - Consider the potential security implications of not clearing out the contents of a frame before reassigning it.
- When a system starts up, all available memory is placed on the free-frame list.

Performance of Demand Paging

- **Stages in Demand Paging – handle page faults**

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 (if available) in physical memory:
   1. Wait in a queue for this device until the read request is serviced
   2. Wait for the device seek and/or latency time
   3. Begin the transfer of the page to a free frame
6. While waiting, allocate the CPU core to some other processes
7. Receive an interrupt from the disk I/O subsystem (I/O completed)
8. Save the registers and process state for the other process (depending on the CPU scheduling)
9. Determine that the interrupt was from the disk
10. Update the page table and other tables to show 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

Performance of Demand Paging (Cont.)

- There are three major task components of the page-fault service time:
  - Service the interrupt – careful coding might result in several hundred instructions
  - Read the page – lots of time (accessing the secondary storage, typically a hard disk)
  - Restart the process – a small amount of time
- The page switch time will probably be close to 8 milliseconds (for a typical hard disk)

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

- Effective Access Time (EAT)

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

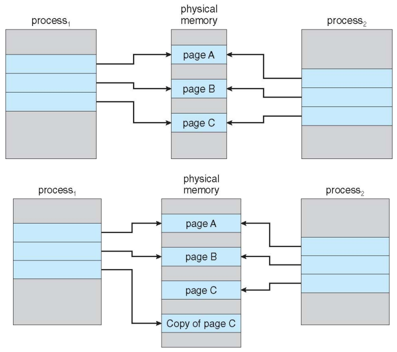
Demand Paging Example

- Memory access time = 200 nanoseconds
- Average page-fault service time = 8 milliseconds
- EAT = (1 – p) x 200 + p (8 milliseconds)
  = (1 – p) x 200 + p x 8,000,000
  = 200 + p x 7,999,800
- If one access out of 1,000 causes a page fault, then
  EAT = 8.2 microseconds.
  This is a slowdown by a factor of 40!!
- If want performance degradation < 10 percent
  - 220 > 200 + 7,999,800 x p
    20 > 7,999,800 x p
  - p < .0000025
  - < one page fault in every 400,000 memory accesses
- Fortunately, the memory locality usually satisfies this, as each memory miss brings an entire page

Copy-on-Write

- Traditionally, fork() worked by creating a copy of the parent's address space for the child, duplicating the pages belonging to the parent
- Copy-on-Write (COW) allows both parent and child processes to initially ***share*** the same pages in memory
  - These shared pages are marked as copy-on-write pages, meaning that if either process writes to a shared page, a copy of the shared page is created
- COW allows more efficient process creation as only modified pages are copied or duplicated
- This technique provides rapid process creation and minimizes the number of new pages that must be allocated to the newly created process
  - Considering that many child processes invoke the exec() system call immediately after creation, the copying of the parent's address space may be unnecessary.

Before and After Process 1 Modifies Page C



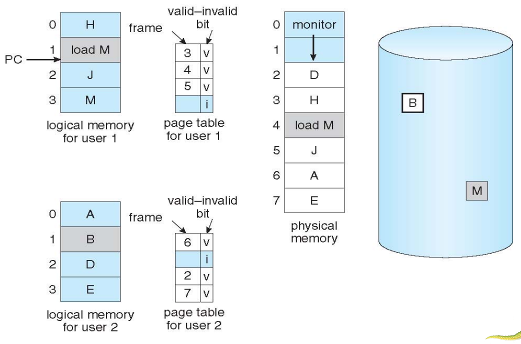
What Happens if There is no Free Frame?

- Used up by process pages
- Also in demand from the kernel, I/O buffers, etc.
- How much memory to allocate to each process? - frame-allocation algorithm
- Page replacement – find some page in memory, but not really in use, page it out
  - Algorithms – terminate the process? swap out the entire process image? replace the page?
  - Performance – want an algorithm which will result in the minimum number of page faults
  - This needs to be transparent to a process
- It may be inevitable that same page may be brought into memory several times

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 back to disk
- Page replacement completes separation between logical memory and physical memory – large virtual memory can be supported on a smaller physical memory

Need For Page Replacement

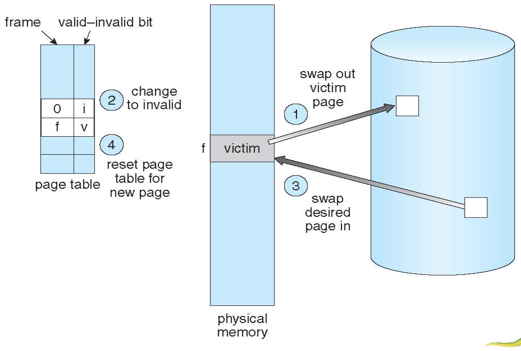


Basic Page Replacement

1. Find the location of the desired page on disk
2. 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
   - Write victim frame to disk if “dirty” (modified since last time it was brought into the memory)
3. Bring the desired page into the (newly) free frame; update the page table
4. Continue the process by restarting the instruction that caused the trap

Note now potentially 2 page transfers for a page fault – which can significantly increase EAT

Page Replacement



Page and Frame Replacement Algorithms

- Page-replacement algorithm
  - Decide which frames to replace – the objective is the lowest page-fault rate on both first access and re-access
- Frame-allocation algorithm determines
  - How many frames allocated to each process – which is decided by how a process utilize or access the memory

Page and Frame Replacement Algorithms

- Evaluate algorithms by running on a particular string of memory references - reference string and computing the number of page faults on that string
  - First, for a given page size, we need to consider only the page number, rather than the complete memory address.
  - If we have a reference to a page **p**, then any references to page **p** that immediately follow will never cause a page fault. Page **p** will be in memory after the first reference, so the immediately following references will not have page fault.
- For example, for a particular process, we might record the following address sequence:

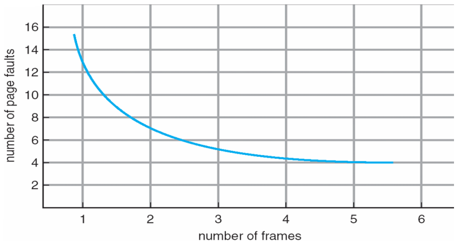
  0100, 0432, 0101, 0612, 0102, 0103, 0104, 0101, 0611, 0102, 0103,

  0104, 0101, 0610, 0102, 0103, 0104, 0101, 0609, 0102, 0105
- At 100 bytes per page, this sequence is reduced to the following reference string:

  1, 4, 1, 6, 1, 6, 1, 6, 1, 6, 1
- In all our examples, the reference string is

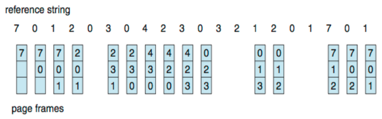
  7,0,1,2,0,3,0,4,2,3,0,3,0,3,2,1,2,0,1,7,0,1

Graph of Page Faults Versus The Number of Frames



First-In-First-Out (FIFO) Algorithm

- Reference string: **7,0,1,2,0,3,0,4,2,3,0,3,0,3,2,1,2,0,1,7,0,1**
- 3 frames (3 pages can be in memory at a time per process)



15 page faults

- Can vary by reference string: consider 1,2,3,4,1,2,5,1,2,3,4,5
  - Adding more frames can cause more page faults!
    - **Belady’s Anomaly**
- How to track ages of pages? – implementation easy
  - Just use a FIFO queue (the time this page brought into the memory)

FIFO Page Replacement

reference string

3 frames

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

Page fault:
9

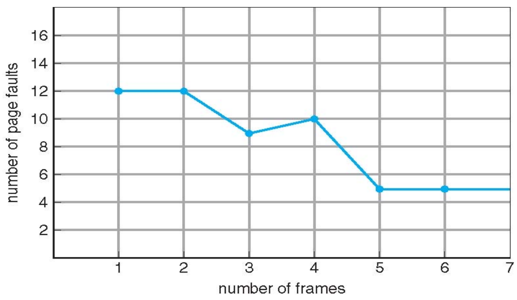
reference string

4 frames

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

Page fault:
10

FIFO Illustrating Belady's Anomaly



Optimal Algorithm

- Replace page that will not be used for longest period of time in the future
  - If possible, ideally select a page that will not be used at all in the future. In practice, this may not always be feasible, so a page can be brought into the memory multiple times
  - 9 is the optimal for the example
- How do you know this?
  - Can' t read the future
- Used for measuring how well your algorithm performs as a comparison

reference string

7	0	1	2	0	3	0	4	2	3	0	3	2	1	2	0	1	7	0	1
7	7	7	2		2		2			2			2				7		
	0	0	0		0		4			0			0				0		
		1	1		3		3			3			1				1		

page frames

Least Recently Used (LRU) Algorithm

- Use the past knowledge rather than future as an approximation for OPT
- Replace page that has not been used in the most amount of time
- Associate the time of last use with each page – complex, as this need to be updated with each memory reference

reference string

7	0	1	2	0	3	0	4	2	3	0	3	2	1	2	0	1	7	0	1
7	7	7	2		2		4	4	4	0			1		1		1		
	0	0	0		0		0	0	3	3			3		0		0		
		1	1		3		3	2	2	2			2		2		7		

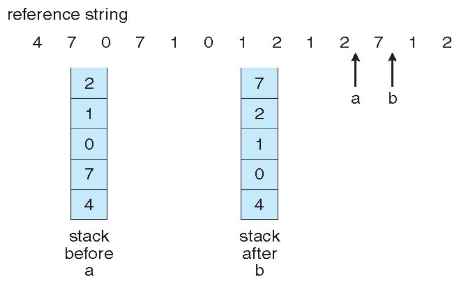
page frames

- 12 faults – better than FIFO but worse than OPT
- Generally a good algorithm and frequently used
- But how to implement? - An LRU page-replacement algorithm may require substantial hardware assistance. The problem is to determine an order for the frames defined by the time of last use.

LRU Algorithm Implementation

- **Counters** implementation
  - Every page entry adds a time-of-use field recording a logical clock or counter. The clock is incremented for every memory reference.
  - Whenever a reference to a page is made, the contents of the clock register are copied to the time-of-use field in the page-table entry for that page.
  - When a page needs to be replaced, look for the counters to find the smallest value
    - Search through table needed to find the LRU page and a write to memory (to the time-of-use field in the page table) for each memory access
- **Stack** implementation
  - Keep a stack of page numbers
  - Whenever a page is referenced, it is removed from the stack and put on the top. In this way, the most recently used page is always at the top of the stack, and the least recently used page is always at the bottom
  - This requires multipel pointers to be changed upon each reference
  - Each update more expensive, but no need to search for replacement

Use Of A Stack to Record The Most Recent Page References



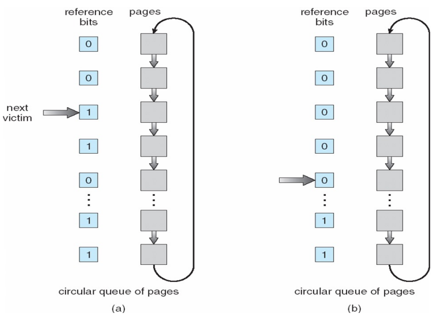
LRU Algorithm Discussions

- LRU and OPT are cases of stack algorithms that don't suffer from Belady's Anomaly
  - A stack algorithm can be shown that the set of pages in memory for **n** frames is always a subset of the set of pages that would be in memory with **n+1** frames allocated
  - For LRU replacement, the set of pages in memory would be the **n** most recently referenced pages. If the number of frames allocated is increased to (**n+1**), these **n** pages will still be the most recently referenced and so will still be in memory
- Both the implementation of LRU requires extra hardware assistance
- The updating of the clock fields or stack must be done for every memory reference
  - If we were to use an interrupt for every reference to allow software to update such data structures, it would slow every memory reference by a factor of at least ten!

LRU Approximation Algorithms

- Reference bit
  - With each page associate a bit, initially = 0, associated with each entry in the page table
  - When page is referenced (read or write), the reference bit set to 1
  - Replace any with reference bit = 0 (if one exists)
    - Corse-grained approximation, but do not know the order of use
- Second-chance algorithm
  - Generally FIFO, plus hardware-provided reference bit
  - Clock replacement
  - If page to be replaced has
    - Reference bit = 0 -> replace it (select it as the victim)
    - reference bit = 1 then:
      - set reference bit 0, leave page in memory (second chance)
      - replace next page, subject to same rules (FIFO and clock)

Second-Chance (Clock) Page-Replacement Algorithm



Counting Algorithms

- Keep a counter of the number of references that have been made to each page
- The least frequently used (**LFU**) Algorithm: replaces the page with the smallest count
- The most frequently used (**MFU**) Algorithm: replace the page with the largest count based on the argument that the page with the smallest count was probably just brought in and has yet to be used
- Neither LFU nor MFU replacement is commonly used. The implementation of such algorithms is expensive, and they do not approximate OPT replacement well

Allocation of Frames

- How do we allocate memory among different processes?
  - Does every process get the same fraction of memory, or different fractions?
  - Should we completely swap some processes out of memory?
- Each process needs certain minimum number of frames in order to execute its program
- 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*
- The maximum, of course, is the total frames required for a process
- Two major allocation schemes
  - fixed allocation
  - priority allocation
- Many variations

Fixed Allocation

- Equal allocation – For example, if there are 100 frames (after allocating frames for the OS) and 5 processes, give each process 20 frames
- Proportional allocation – Allocate according to the size of process
  - Dynamic as the degree of multiprogramming and process sizes change over the time

$s_i = \text{size of process } p_i$

$S = \sum s_i$

$m = \text{total number of frames}$

$a_i = \text{allocation for } p_i = \frac{s_i}{S} \times m$

$m = 64$

$s_1 = 10$

$s_2 = 127$

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

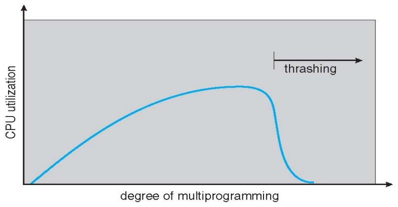
$a_2 = \frac{127}{137} \times 64 \approx 59$

Global vs. Local Allocation

- Global replacement – process selects a replacement frame from the set of all frames, even if that frame is currently allocated to some other process; thus, one process can take a frame from another process
  - For instance, this can be based on priority – priority allocation in which a process can preempt memory from a lower priority process
  - This can result in better system throughput
  - But process execution time can vary greatly, as a process cannot control its own page-fault rate.
- Local replacement – each process selects from only its own set of allocated frames
  - What we used in the page replacement algorithms earlier
  - The set of page for a process is only affected by the paging behaviour of only that process
  - More consistent per-process performance
  - But possibly underutilized memory, since pages allocated to a process can not be utilized by another process, even if this page is not currently used by the process holding it

Thrashing

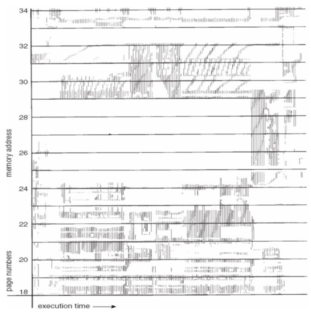
- If a process does not have "enough" pages, the page-fault rate would be very high
  - Page fault to get page, and replace an existing frame, but quickly need replaced frame back
  - This leads to low CPU utilization – OS might think "by mistakes" that it needs to increase the degree of multiprogramming in order improve the CPU utilization – aggravate the problem
- Thrashing ≡ a process or a set of processes is busy swapping pages in and out
- This high paging activity is called thrashing. A process is thrashing if it is spending more time paging than executing, which results in serious performance problems



Demand Paging and Thrashing

- Why does demand paging work?
  Locality model
  - A locality is a set of pages that are actively used together. A running program is generally composed of several different localities, which may overlap
  - Memory access or subsequent memory access tends to stay in the same set of page(s)
  - Process migrates from one locality to another, e.g., operating on a different set of data or call a function (different code segment)
  - Localities may overlap, instructions or part of the data being manipulated
- Why does thrashing occur?
  Σ size of locality (of all processes) > total memory size
  - If we do not allocate enough frames to accommodate the size of the current locality, the process will thrash, since it cannot keep in memory all the pages that it is actively using.
  - We can limit effects by using local or priority page replacement, as thrashing in one process can not steal frames from another process and cause the latter to thrash as well

Locality In A Memory-Reference Pattern

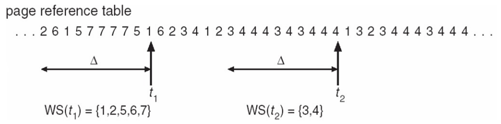


- Recall program memory access patterns exhibit temporal and spatial locality
- The left Figure illustrates the concept of locality and how a process's locality changes over time. At time (a), the locality is the set of pages {18, 19, 20, 21, 22, 23, 24, 29, 30, 33}. At time (b), the locality changes to {18, 19, 20, 24, 25, 26, 27, 28, 29, 31, 32, 33}. Notice the overlap, as some pages (for example, 18, 19, and 20) are part of both localities.

Working-Set Model

- Δ ≡ working-set window ≡ a fixed number of page references
  Example: 10,000 instructions
- 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
- $D = \Sigma\ WSS_i$ ≡ total demand frames
  - Approximation of the current locality in the system (of all processes)
- if $D > m$ ⇒ Thrashing – at least one process is short of memory
- Policy if $D > m$, then suspend or swap out one of the processes
- The working-set strategy prevents thrashing while keeping the degree of multiprogramming as high as possible, thus optimizes CPU utilization
- The difficulty with the working-set model is how to keep track of the working set.

Working-Set Model (Cont.)

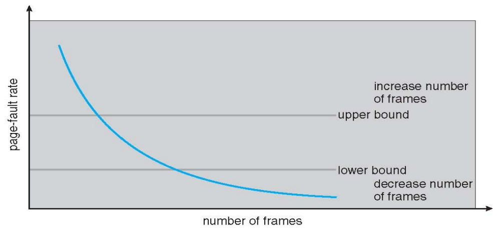


Keeping Track of the Working Set

- It is difficult to keep track of the working set, as working-set window is a moving window which needs to be updated for each memory reference
- Approximate with interval timer + a reference bit
- Example: $\Delta = 10{,}000$
  - Timer interrupts after every 5000 time units
  - Keep in memory 2 bits for each page, (0,0), (0,1),(1,0),(1,1)
  - 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
- This is of course not accurate, as we cannot tell where, within an interval of 5,000, a reference occurred
- Improvement = 10 bits and interrupt every 1000 time units, more accurate but cost is higher
- Accuracy versus complexity

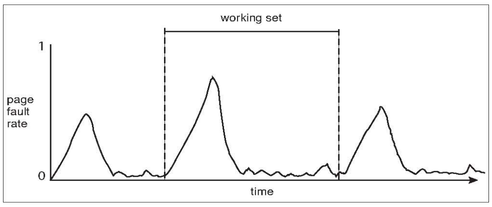
Page-Fault Frequency

- More direct approach than WSS
- Establish “acceptable” page-fault frequency (PFF) rate and use local replacement policy
  - If actual rate too low, process loses frame
  - If actual rate too high, process gains frame



Working Sets and Page Fault Rates

- Direct relationship between working set of a process and its page-fault rate
- Working set changes over time
- The page-fault rate of a process will transition between peaks and valleys over time.



Other Considerations

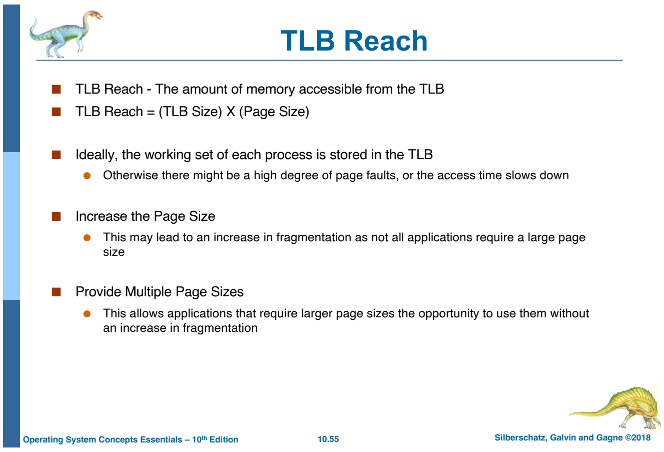
- Prepaging
- Page size
- TLB reach
- Program structure

Prepaging

- To reduce the large number of page faults that occurs at process startup
- Prepage 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 α of the pages is used
  - Is cost of $s * \alpha$ save pages faults > or < than the cost of prepaging $s * (1- \alpha)$ unnecessary pages?
  - α near zero ⇒ prepaging loses

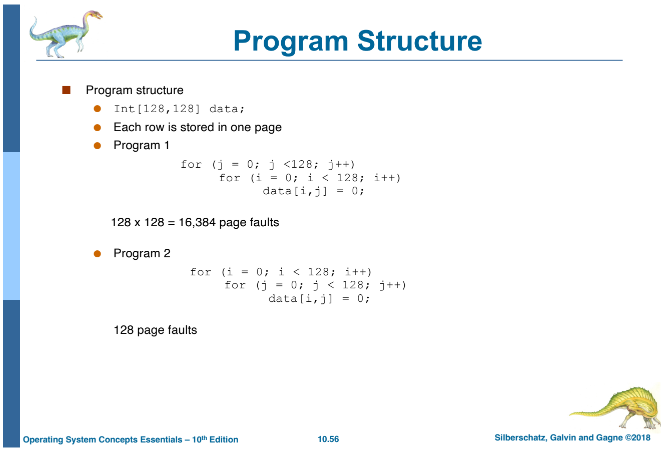
Page Size

- Sometimes OS designers have a choice
  - Especially if running on custom-built CPU
- Page size selection must take into consideration a conflicting set of criteria:
  - Fragmentation – calls for smaller page size
  - Page table size – calls for larger page size
  - Resolution – isolate the memory actually be used
  - I/O overhead – larger page size requires longer I/O time
  - Number of page faults – smaller page size can increase the number of page faults
  - Locality – ideally each page should match the current locality
  - TLB size and effectiveness – larger page size improves the TLB reach
- Always power of 2, usually in the range 2^{12} (4,096 bytes) to 2^{22} (4,194,304 bytes)
- On average, growing over time



TLB Reach

- 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 might be a high degree of page faults, or the access time slows down
- 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



Program Structure

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

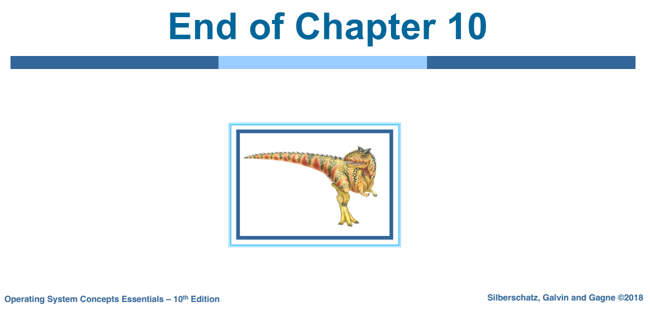
```
for (j = 0; j <128; j++)
     for (i = 0; i < 128; i++)
           data[i,j] = 0;
```

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



End of Chapter 10