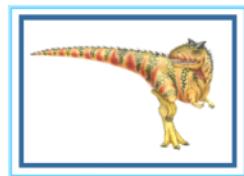




Chapter 10: Virtual Memory

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Chapter 10: Virtual Memory

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

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10.2



Objectives

- Describe virtual memory and 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.

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10.3



MMU translates logical \rightarrow physical addy.

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 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** \rightarrow **only load what is needed**
 - 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.

\rightarrow reduce mem. footprint of each program
 \rightarrow program is not the bottleneck
 \rightarrow increase throughput

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10.4



Background

- **Virtual memory** – separation of user logical memory (referred as **address space** earlier) 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 \hookrightarrow **share segments/ pages**
 - 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**
- \rightarrow cover the program footprint
- 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
- \rightarrow only load when needed.

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10.5



Virtual Memory That is Larger Than Physical Memory



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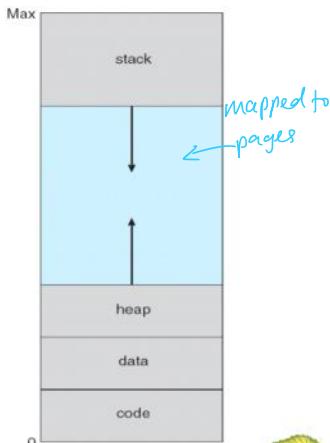
10.6





Virtual-address Space

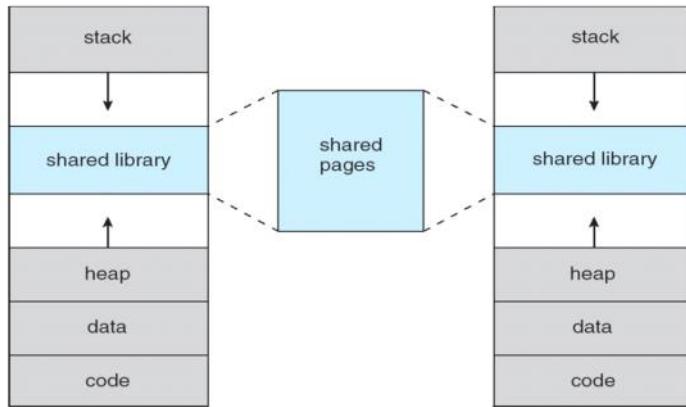
- **Virtual address space** – logical view of how process is stored in memory
 - Usually start at address 0, contiguous addresses until the end of address space
 - Meanwhile, physical memory organized in frames
 - **MMU must map logical to physical address**
- **Heap can grow upward** in memory, used 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

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10.7



Shared Library Using Virtual Memory

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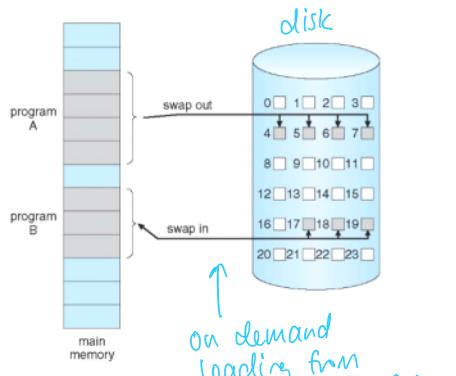


Demand Paging

→ only load page when needed

- Could bring entire process into memory at load time
- Or bring a **page** into memory only **when the page is needed or 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**

→ Predictive swapping: pre fetch pages into memory.

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10.9



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** → in mem.
 - 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

→ if main mem. has no room, must swap out unneeded page and replace with wanted page.

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10.10



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:

Frame #	valid-invalid bit
	v
	v
	v
	v
	i
....	
	i
	i

page table

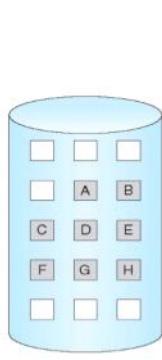
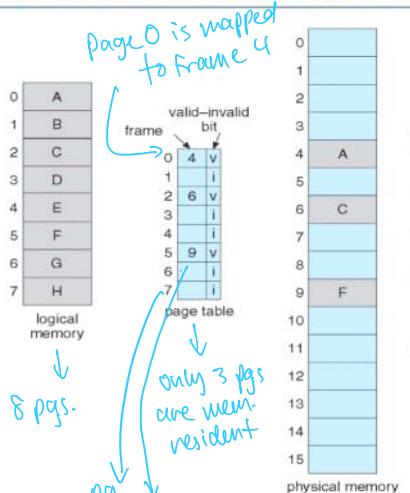
- During address translation, if valid–invalid bit in page table entry is **i** → page fault

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10.11



Page Table When Some Pages Are Not in Main Memory

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10.12



Page Fault

os kernel will check

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

Page Fault

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

if no free frame; find victim frame to swapout.

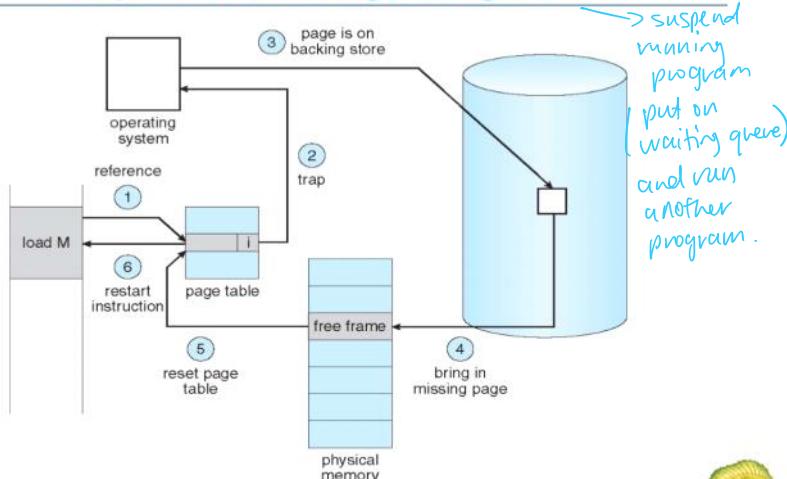


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Steps in Handling a Page Fault



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10.14



Aspects of Demand Paging

- The extreme case – start process with **no pages in memory** \leftarrow cold start problem
 - OS sets instruction pointer to first instruction of process, non-memory-resident \rightarrow page fault
 - And for every other process pages on the first access
 - This is referred as **Pure demand paging** \leftarrow time consuming
- A given instruction could access multiple pages \rightarrow result in multiple page faults \leftarrow extreme case
 - Consider fetch and decode of instruction which adds two numbers from memory and stores result back to memory \leftarrow time consum.
 - Pain caused by page faults decreases after process starts running for some time because of locality of memory reference \leftarrow once pgs brought into main mem. it is unlikely that the process will access random page
- 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

guarantees that page fault won't occur after pages have been loaded in



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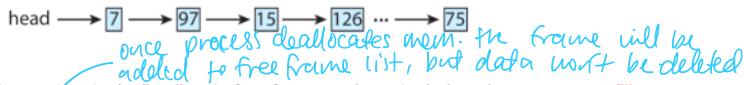


Free-Frame List \leftarrow page fault

- When a page fault occurs, the operating system must bring the desired page from the secondary storage into main memory.



- 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)



- Operating system typically allocates 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 writing 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. → **content leakage, BAD!**
- When a system starts up, all available memory is placed on the free-frame list.



← Frame clear out only happens if it is reallocated
→ so it lowers the overhead since the frame might not be used.



HERE Performance of Demand Paging



- Stages in Demand Paging – handle page faults**
 - Trap to the operating system ← **raise page fault**
 - Save the user registers and process state ← **suspend program**
 - Determine that the interrupt was a **page fault** ← **if is fault, check what kind**
 - Check that the page reference was legal and determine the location of the page on the disk
 - Issue a read from the disk to a free frame (if available) in physical memory:
 - Wait in a queue for this device until the read request is serviced ← **since it'll take time to get free frame**
 - Wait for the device seek and/or latency time
 - Begin the transfer of the page to a free frame
 - While waiting, allocate the CPU core to some other processes
 - Receive an interrupt from the disk I/O subsystem (I/O completed) ← **when requested frame is brought into main mem.**
 - Save the registers and process state for the other process (depending on the CPU scheduling)
 - Determine that the interrupt was from the disk
 - Update the page table and other tables to show page is now in memory ← **update valid bit**
 - Wait for the CPU to be allocated to this process again ← **context switching**
 - 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 tasks in 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) ← **dominates mem access time**
 - 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 $0 \leq p \leq 1$** ← chance to encounter page fault.
 - if $p = 0$ no page faults ← we want to minimise P
 - if $p = 1$, every reference is a fault
- Effective Access Time (EAT)**

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





Demand Paging Example

- Memory access time = 200 nanoseconds *if no page fault*
- Average page-fault service time = 8 milliseconds
- $EAT = (1 - p) \times 200 + p$ (8 milliseconds)

$$= (1 - p) \times 200 + p \times 8,000,000$$

$$= 200 + p \times 7,999,800$$
- If one access out of 1,000 causes a page fault, then
 $EAT = 8.2 \text{ microseconds}$ *= 8.2 / 1,000,000 micro = 100 ns*
 This is a slowdown by a factor of 40!!
- If want performance degradation < 10 percent
 - $220 > 200 + 7,999,800 \times p$
 - $20 > 7,999,800 \times p$
 - $p < .0000025$
 - < one page fault in every 400,000 memory accesses
- Fortunately, the memory locality usually satisfies this, as each memory miss brings an entire page
unlikely to make a req. to a pg. far away

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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 *duplicating takes time*
- **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 must be created for that process**
- **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.

→ reduce start up latency for child to be created.
 → only duplicate when needed.

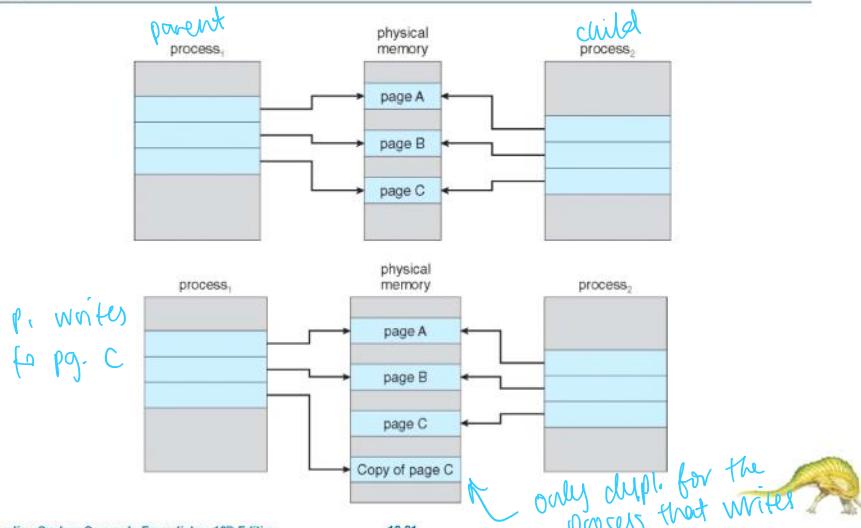


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Before and After Process 1 Modifies Page C



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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 or program execution

- Noticing that it may be inevitable that same page may be brought into memory several times

→ neg. additional disk access time
→ can waste CPU cycles



Page Replacement

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

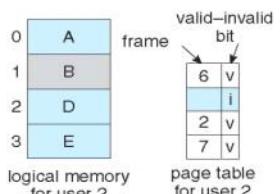
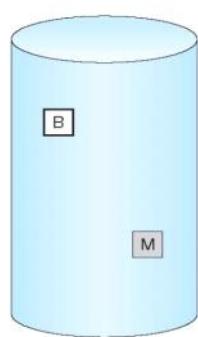
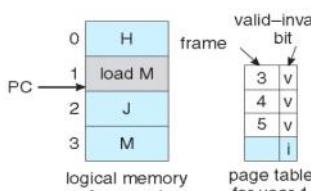
- Use modify (dirty) bit to reduce overhead of page transfers – only modified pages are written back to disk
→ if dirty bit is 1, must be written back to the disk, if not, can

- Page replacement completes separation between logical memory and physical memory – **replace**.
large virtual memory can be supported on a smaller physical memory

→ use an algor. to choose which pg. to swap out.
→ logical mem. can be bigger than real
→ logical mem. footprint doesn't incr.
→ i.e. if want to alloc. mem. for prog. much larger than physical mem., then will end up w/
out of memory error.



Need For Page Replacement





HERE

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 two page transfers for a page fault – which can significantly increase EAT

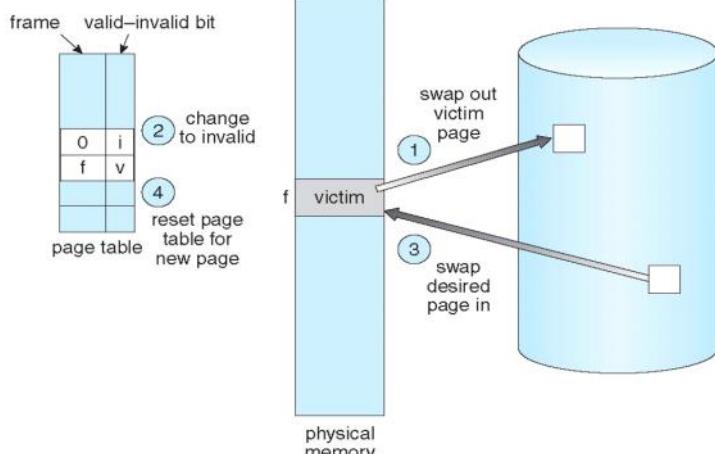


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Page Replacement



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Page and Frame Replacement Algorithms

- Page-replacement algorithm
 - Decide which frames to replace – the objective is to minimize the page-fault rate
 - Frame-allocation algorithm determines - how many frames allocated to each process – which is decided by how a process accesses the memory, locality

→ Attempting to min page fault rate (P)



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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 physical 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
4 1's into single 1
- In all our examples, the reference string is

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

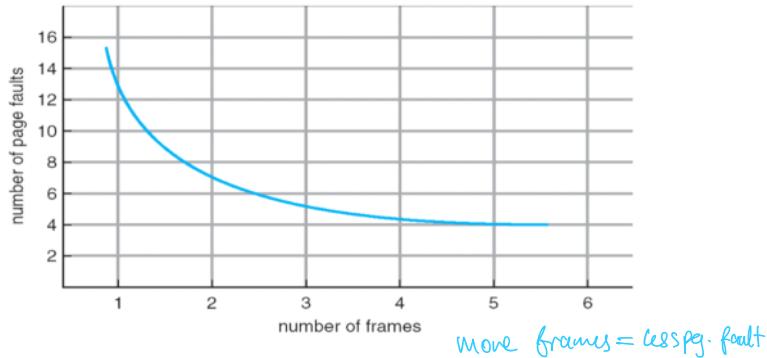
seq. of mem addresses
it wants to access

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Graph of Page Faults Versus The Number of Frames



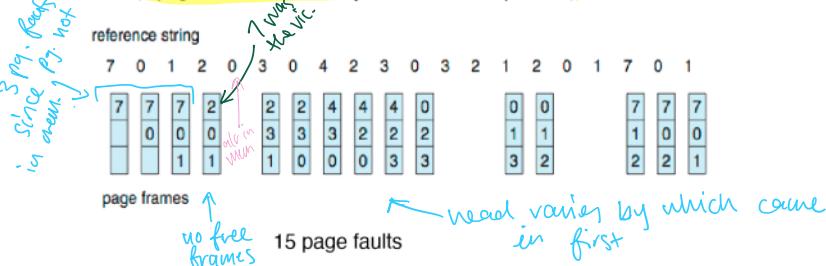
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First-In-First-Out (FIFO) Algorithm

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



- 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)

→ Simple, but Not good choice



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FIFO Page Replacement

reference string

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

Page fault:
9

reference string

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

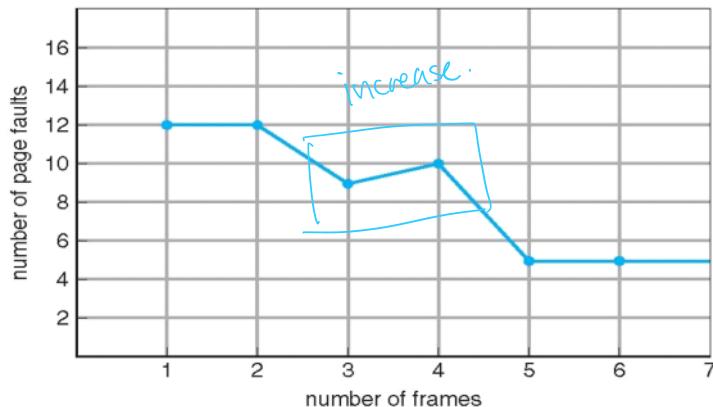
Page fault:
10

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10.31



FIFO Illustrating Belady's Anomaly



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

9 pg-faults

→ ideal benchmark.

→ can't be implemented LOL!



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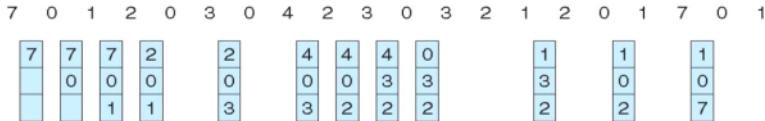
Least Recently Used (LRU) Algorithm

→ most common

- 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 → unlikely that the pg. will be used
- Associate the time of last use with each page – complex, as this need to be updated with each memory reference

→ doesn't suffer from Belady's Anomaly

reference string

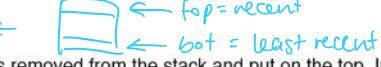


page frames

- 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.



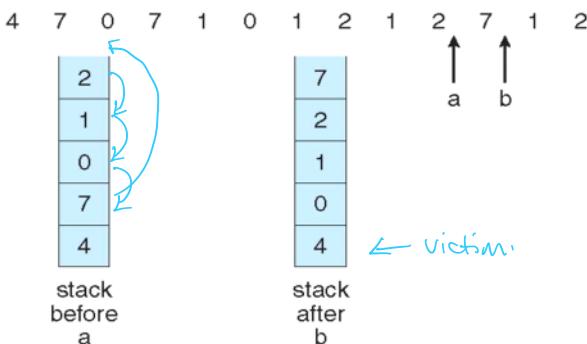
LRU Algorithm Implementation

- Counters implementation** ← expensive → read time w/ sys call
 - 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 multiple pointers to be changed upon each reference
 - Each update more expensive, but no need to search for replacement
- better than counter, but still slow.



Use of A Stack to Record the Most Recent Page References

reference string





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 same **n pages** will still be part of the **$n+1$ most recently referenced**, so will still be in memory
- Both the implementation of LRU A(counter and stack) 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!



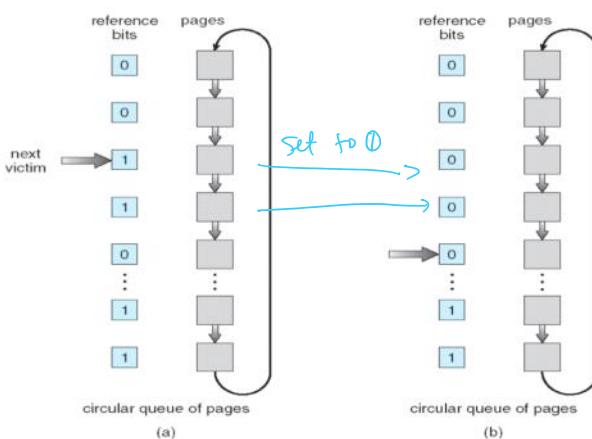
LRU Approximation Algorithms

- **Reference bit**
 - 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)
 - ▶ Coarse-grained approximation, but do not know the **order of use**
 - Not ideal
- **Second-chance algorithm** → **circular queue of reference bit**
 - FIFO order, 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)

→ both req. hard were support (ref bit)



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
→ Since it's been accessed a lot, it will be accessed in future
- Neither LFU nor MFU replacement is commonly used. The implementation of such algorithms is expensive, and they do not approximate OPT replacement well

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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

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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
→ may lead to low CPU utilisation.
- Proportional allocation – Allocate according to the size of process
 - Dynamic as the degree of multiprogramming and process sizes change over the time

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

$$S = \sum S_i$$

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

$$a_f = \text{allocation for } p_i = \frac{S_i}{S} \times m$$

$$m = 64$$

$$s_1 = 10$$

$$S_1 + S_2 = 137$$

$$s_2 = 127$$

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

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

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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.

→ bad isolation

- **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 pages for a process is only affected by the paging behaviour of 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

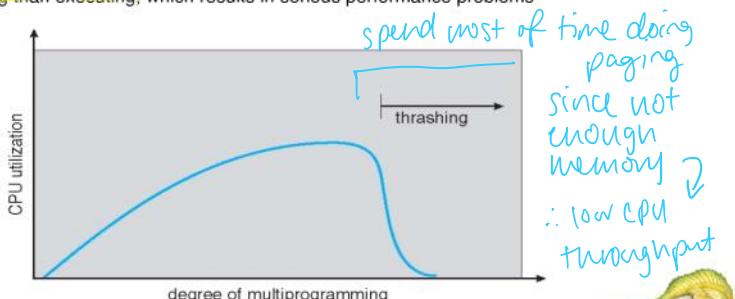
→ to choose victim frames only choose from itself

→ good isolation of program.



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 to 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

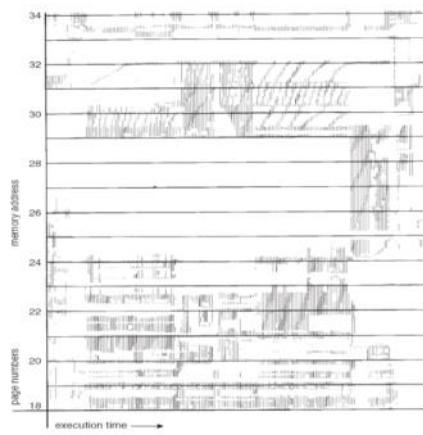
- Why does demand paging work? ← don't need to preload pages into memory
Locality model
 - A locality is a set of pages that are actively used together. A running program is generally composed of several different localities over the time, which may overlap
 - Memory access or subsequent memory access tends to stay in the same set of pages
 - 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 the effects by using local replacement, this way thrashing in one process can not steal frames from another process and cause the latter to thrash as well

→ larger the LHS, the more severe thrashing is.





Locality In A Memory-Reference Pattern



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- 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.

→ can expect process to request spatially local pages.



Working-Set Model

- $\Delta \equiv$ working-set window = a fixed number of page references
Example: 10,000 instructions.
- WSS_i (working set of Process P_i) = total number of distinctive pages referenced in the most recent Δ - this varies in time
 - if Δ too small will not encompass entire locality
 - if Δ too large will encompass several localities
 - if $\Delta = \infty$ will encompass entire program
- $D = \sum WSS_i$ = total demand frames
 - Approximation of the current locality in the system (of all processes)
- if $D > m \Rightarrow$ 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 a working-set model is how to keep track of the working set.



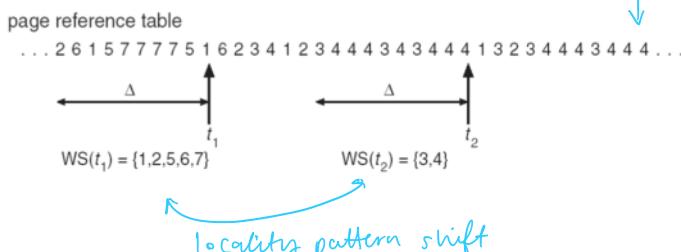
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Working-Set Model (Cont.)

pg. ref string



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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** ← don't upd. after each mem. req.
- Approximate with interval timer + a reference bit ← upd. according to finer req. ↓ too exix.
- 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 \Rightarrow page in working set
- This is of course not accurate, as we cannot tell where, within an interval of 5,000, a reference occurred
→ course-grained
- Improvement = 10 bits and interrupt every 1000 time units, more accurate but cost is higher
- Accuracy versus complexity

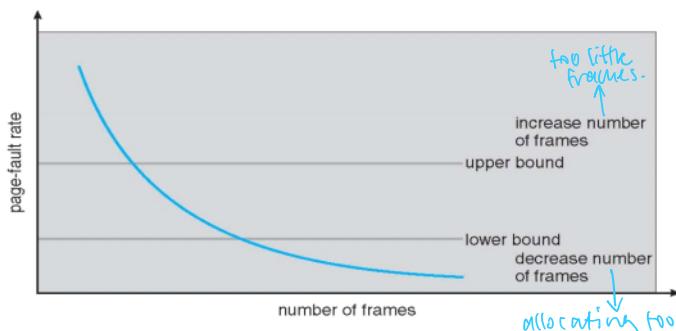
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Page-Fault Frequency

- working set**
- 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

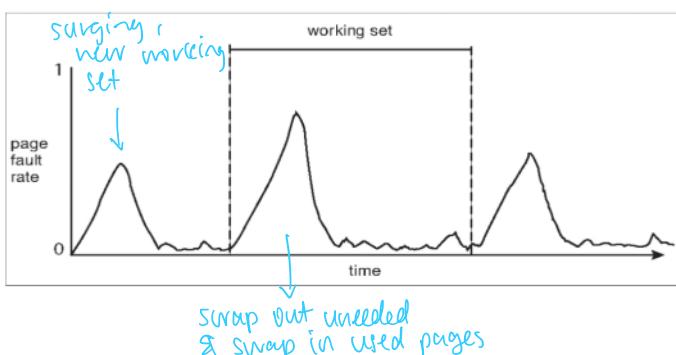
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Working Sets and Page Fault Rates

- Relationship between working set of a process and its page-fault rate
- Working set changes over time
- The page-fault rate of a process transitions between peaks and valleys over time.
→ periodic

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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 a of the pages is used
 - expensive
 - Is cost of $s * a$ save pages faults > or < than the cost of prepaging
 $s * (1-a)$ unnecessary pages?
 - a near zero ⇒ prepaging loses

→ can reduce I/O latency if prediction accuracy (δ) is high.
→ saving = $s \times a$ time
→ cost = $s \times (1-\delta)$
→ for recurring programs:
→ can accurately prepage
→ for non-recurring prog. → a is low



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:
 - *Internal 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)
4 KB 4 MB
- On average, growing over time

→ large page table caused by page size too small.





Cache ← TLB Reach

can save 1 mem. access

- TLB Reach - The amount of memory accessible from the TLB
- TLB Reach = (TLB Size) X (Page Size)
- Want TLB reach to = phys. mem. 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 ← only way to incr. TLB reach is to incr. pg. 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 ← Initialise all element to 0


```
for (j = 0; j < 128; j++)
    for (i = 0; i < 128; i++)
        data[i, j] = 0;
```
- 128 x 128 = 16,384 page faults ← switching to diff. row
 - ↳ switch to diff. page
 - ↳ pg. fault.
- Program 2


```
for (i = 0; i < 128; i++)
    for (j = 0; j < 128; j++)
        data[i, j] = 0;
```
- 128 page faults ← iterate row by row in outer loop.



End of Chapter 10

